Building Technology Master Thesis

Scalable façade renovation solution for Dutch system-built houses

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2024

MSc in Architecture, Urbanism, and Building Science Building Technology Track
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ABSTRACT

The building sector significantly impacts the environment, consuming 42% of the EU's energy and producing 36% of its greenhouse gas emissions. To achieve its climate objectives, the Netherlands must accelerate its home renovation rate to 200,000 annually by 2030. This research addresses the scalability and circularity of façade renovation for these system-built houses, aiming to balance immediate energy efficiency improvements with long-term sustainability.

This research focuses on designing a scalable and circular façade renovation system for post-war Dutch system-built houses. These homes, built between 1945 and 1975, represent around 30% of the Dutch housing stock and are in critical need of energy efficiency upgrades. However, the embodied energy involved in renovations presents a significant challenge to meeting climate goals.

The study's primary focus is answering: "How can a scalable and circular façade renovation system be designed for Dutch system-built houses from the post-war period?" The research investigates current façade renovation systems, their limitations, and the potential role of circularity in creating sustainable renovation strategies. It also examines building typologies, highlighting similarities and differences among system-built houses to develop design criteria for scalable and circular renovation.

Although time constraints prevented the development of a complete design, the research reveals that many existing façade components, such as brick slip systems and prefabricated frames, already perform well. However, achieving flexibility and scalability remains challenging, particularly in balancing cost, energy efficiency, and building-specific constraints. This work lays the groundwork for future research into developing standardized, adaptable façade renovation systems for the Dutch housing stock, contributing to more sustainable and efficient building practices while addressing the challenges posed by post-war system-built houses.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Martin Tenpierik, my main mentor from the Board of Climate Design, for his support and availability from the beginning. His expertise in building climate, regulations, and building laws in the Netherlands, as well as the invaluable documents he provided during the research, have been essential to this thesis.

I would also like to thank Jan Jongert from Superuse Studios, who recently joined the Board of Facade Design, for our insightful discussions and for sharing his expertise in the circularity of renovations. His contributions have greatly inspired the direction of this work.

Finally, I am deeply grateful to my family and friends for their constant support and encouragement throughout my struggles during this thesis. Their belief in me kept me motivated and resilient during the most challenging times.

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ABBREVIATIONS

CBS - Centraal Bureau voor de Statistiek

DGBC – Dutch Green Building Council

EPBD - Energy Performance of Buildings Directive

KNMI - Koninklijk Nederlands Meteorologisch Instituut

Prefab - Prefabricated

RVO - Rijksdienst voor Ondernemend Nederland

Rc - Resistance coefficient (related to insulation value)

IEBB - Industrial Energy Efficiency Building

NTA - Nederlandse Technische Afspraak (Dutch Technical Agreement)

GBO – Gebruiksoppervlak (Usable area)

COP - Coëfficiënt Of Performance

DUTCH WORDS

Systeemwoningen – Dutch system-built houses

Galerijwoningen - Gallery apartments

Portiekwoningen - Porch apartments

Grondgebonden woning - Ground-based house or row house

Appartementen – Apartments

Bouwbesluit - Dutch Building Code

Besluit Bouwwerken en Leefomgeving - Buildings and Living Environment Code (New Bouwbesluit)

Gietbouw – Concrete cast construction

Montagebouw – Prefabricated assembly construction

Stapelbouw - Stacked block construction

Kopgevel – Gable end (the shorter side of a building)

Langsgevel – Longitudinal wall (the longer side of a building)

Spouwmuur – Cavity wall

Traveematen - The distance between two structural supports

Penanten – Piers or Pilasters (vertical supports between windows or door openings)

Borstwering – Parapet or Dwarf wall (a low wall between the structural supports)

1 INTRODUCTION

1.1 Background

In the face of global climate challenges, the European Union has embarked on an ambitious journey to become the first climate-neutral continent by 2050, as illustrated by the European Green Deal. (Fetting, 2020). The EU's commission has adopted a set of proposals to make the EU's climate policies fit for reducing greenhouse gas emissions. The framework sets out a bold vision for a 55% reduction in greenhouse gas emissions by 2030 and a commitment to achieve net-zero emissions by 2050. In 2021, a revision of the Energy Performance of Buildings Directive was proposed to gradually improve the energy performance of buildings in Europe. This is a critical component in the EU's strategy, considering that buildings significantly contribute to energy consumption and greenhouse gas emissions.

The building sector is responsible for 42% of the EU's total energy consumption and 36% of greenhouse gas emissions. This substantial environmental impact underlines the sector's urgent need for renovation and modernization strategies. About 85% of the EU's existing building stock was constructed before 2000, and 75% is considered energy inefficient (European Commission, 2010). The repercussions of this inefficiency are impacting the lives of citizens. In 2022, around 40 million Europeans could not afford proper home heating (Eurostat, 2023). This makes renovation not just a sustainability measure but also a social necessity.

In the Netherlands, about 30% of the total building stock is considered post-war, which means it was built between 1945 and 1975 (Platform31, 2013). After the oil crisis of 1970, most new building policies on energy use and insulation requirements were coming up. Post-war buildings, however, were predominantly constructed with a focus on speed and standardization, often neglecting energy efficiency. Most of these buildings are now reaching an age where major renovations are necessary if they have not already been done. This presents an opportunity to integrate energy renovations cost-effectively with façade refurbishment.

A critical element in addressing the energy efficiency of buildings is the façade, which is the primary part of energy loss. In Europe, approximately 80% of household energy is consumed for heating, cooling, and hot tap water (European Commission, 2010). In a moderate maritime climate like the Netherlands, façade renovation and insulation are necessary and among the most cost-effective strategies for energetic renovation. As indicated, in colder climates, four of the ten most cost-effective building modifications involve adding insulation, and most energy-saving strategies involve modifications to the building envelope (Gelfand & Duncan, 2011).

To meet these challenges, focusing on the quality and quantity of building renovations is essential. According to the Dutch Climate Agreement, the renovation rates of buildings must increase to 200.000 homes per year by 2030 to reach the climate goals from the EU (Klimaatakkoord, 2019). This increase is necessary to renovate the entire building stock by 2050.

One promising solution is industrial prefabrication for renovation; this is the production and design of new building elements in a controlled factory environment rather than being constructed on-site. The benefits of industrial prefabrication are higher precision and standardization, improved quality control, reduction of waste, and the potential to reduce costs if sufficient scale is achieved (Glicker et al., 2022).

1.2 Problem statement

The building renovation process can be scaled up with industrial prefabrication and standardization. However, scaling up the renovation process faces several challenges. One significant challenge is the non-uniform building stock; each building has different energy demands and architectural aspects, making it difficult to find a single solution. Additionally, large-scale renovations require a high upfront investment to set up factories and production systems.

Another challenge in the renovation industry is the embodied energy of renovations. If we want to renovate the entire building stock, the renovation industry will be the most polluting sector of the construction industry in the Netherlands in the short term (Copper8 et al., 2024). The materials, transport, and construction will be responsible for these CO_2 emissions. It is not just about increasing the number of renovations, but also decreasing the CO_2 emissions per renovation to decrease their CO_2 footprint.

Despite these challenges, the Dutch system-built houses constructed between 1945 and 1975, which represent approximately 450,000 houses in the Netherlands (Platform31, 2013), have more similarities in their construction methods. This similarity offers the potential for scalable renovation solutions. Creating demand for industrial prefabrication is essential for ensuring its success. Bundling demand, project aggregation, and other measures to stimulate demand can encourage manufacturers to pursue industrial prefab solutions (Glicker et al., 2022). While some newer systems have industrialized prefabrication, little research has been conducted on scalable renovation systems specifically for Dutch system-built houses.

1.3 Objectives

1.3.1 General objective

The primary goal of this research is to develop a scalable façade renovation system for Dutch post-war system-built houses. These houses, representing a significant portion of the Dutch building stock, offer substantial renovation potential. Focusing on these system-built houses, the research addresses the need for efficient and large-scale renovation solutions to improve these homes' overall condition and sustainability.

The main criteria for this renovation system are scalability and circularity. Scalability enables the application of renovation techniques on a large scale, thus increasing the renovation rate of Dutch post-war homes. Circularity ensures the system is sustainable through material reuse, recycling, and waste reduction.

The final goal is to design a standardized renovation system that can be adapted to various façade types with different characteristics, creating a flexible yet uniform approach to façade renovation that meets the needs of the Dutch system-built houses.

1.3.2 Sub-objectives

To achieve the main objective of developing a scalable and circular façade renovation system for Dutch post-war system-built houses, the following sub-objectives have been defined:

1. Comprehensive Façade Analysis: Analyze the façades of system-built houses from the post-war period. This includes identifying the key material and structural characteristics that impact renovation potential.
2. Circular Renovation Potential: Explore how circularity can be integrated into the renovation system. This involves investigating opportunities for material reuse, recycling, and waste reduction within the renovation process, contributing to the system's sustainability.
3. Classification of System-Built Houses: Develop a rational categorization of system-built houses based on their design, materials, and structural components. This classification will facilitate the adaptation of the renovation system to various façade types, ensuring the system can be standardized while retaining flexibility to accommodate different characteristics.
4. Development of a façade renovation system: Design of a façade renovation system, including the buildup of the layers and the connections.

1.4 Research question

From the problem statement and research objectives, the following research question is formed:

"How can a **scalable** and **circular** façade renovation system be designed for Dutch system-built houses from the post-war period?"

Literature review:

1. How is the current Dutch building stock distributed?
2. What are the current façade renovation systems and newer technologies in the field, and what are the limitations of these existing systems or strategies?
3. How does circularity play a role in the design of a façade renovation system?
4. Why does the system need to be scalable, and what are the requirements for scalability?

Analysis of system-built houses:

5. What are the similarities and differences between Dutch system-built houses, and what are the critical components that influence the performance of façade renovation systems?

Design:

6. What are the design criteria for a scalable and circular façade renovation system?
7. How should the layers and structure of the façade renovation system be organized?

Discussion:

8. What are the limits of a facade renovation system in practice?

1.5 Research approach and methodology

The process of this research can be carried out in 5 phases:

Phase 1: Literature review

The literature research creates a framework and further elaborates on the research question. It will explain the question's relevance and set some of the main criteria for the research. This phase will cover:

1. The current Dutch building stock distribution and the relevance of Dutch system-built houses. This section will explain the focus on Dutch system-built houses.
2. Energy efficiency in the building industry and the importance of climate and comfort.
3. The current façade renovation systems and review their limitations and challenges.
4. Circularity in façade renovation and explain the relevance of carbon emissions in the short term.
5. Scalability requirements and outline the critical requirements for achieving scalable solutions.

Phase 2: Building analysis

This research phase examines the Dutch post-war building stock, specifically the system-built houses. The objective is to find the building characteristics that can impact a standardized design approach. At this stage, collecting these buildings' research materials and technical drawings is important to ensure a comprehensive understanding of the respective building systems.

Phase 3: Design criteria

Based on the literature review and building analysis findings, this phase will develop the design criteria for the façade renovation system. In the first part, this will be the design criteria for achieving scalability and circularity for a system that can fit the Dutch system-built houses. Furthermore, the energy performance and comfort of the renovation solutions should have certain standards.

Phase 4: Design solutions

With the design criteria in place, different design solutions for system-built houses can be explored. With the help of Ubakus and THERM, the façade types can be tested and compared to test their hygrothermal performance. The design solutions should be adaptable to various housing types and standardized to ensure cost-effectiveness and feasibility for large-scale implementation. There needs to be a balance between mass production and mass customization.

Phase 5: Case study (Validation)

The proposed renovation solutions will be tested on different building cases to validate the research. This involves selecting buildings with varying structural elements, energy needs, and other relevant factors to evaluate the feasibility and performance of the standardized solutions. Considering the case studies' findings, the phase will also discuss the practical limits of the façade renovation system in real-world applications.

2 EXISTING BUILDING STOCK

Understanding the characteristics and energy performance of the existing building stock is crucial for implementing effective energy-saving measures and policies. The Netherlands has diverse building ages and types, each with unique energy profiles and renovation needs. By assessing the existing stock, the research can identify specific weaknesses and opportunities for improvement in different categories of buildings.

2.1 Residential stock

The Dutch building stock consists of residential and non-residential stock. To improve the performance of existing buildings, the EPBD requires EU member states to develop long-term renovation strategies for residential and non-residential buildings. However, there is limited data available for non-residential buildings compared to residential buildings (European Commission, 2023). Moreover, non-residential buildings are far more diverse, have different regulations and functional requirements, and typically involve more stakeholders. This makes renovating them far more complex than renovating residential stock.

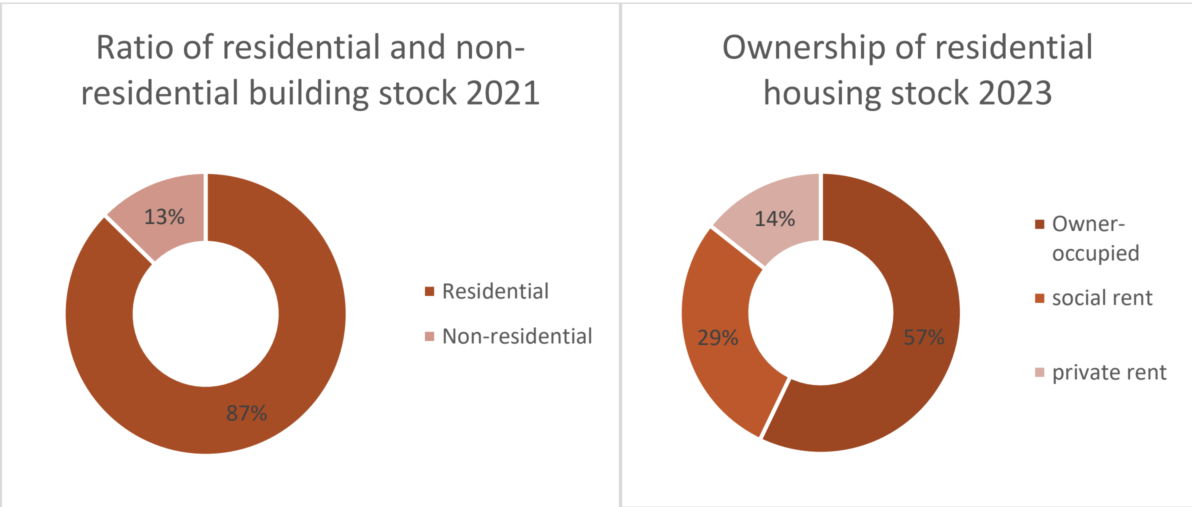


Figure 1 Dutch housing stock (CBS, 2023)

Meanwhile, the residential stock accounts for 87% of the national stock (CBS, 2023). This much more significant presence necessitates a targeted approach to the residential stock to achieve significant impacts in energy reduction. Even though the residential stock still poses many challenges for renovation because of its diversity, the buildings have many similarities as they are built with the same function.

The residential building stock is divided into three main categories: owner-occupied, social rented, and private rented. Owner-occupied houses represent 57% of the total housing stock (CBS, 2023). This has some advantages for renovation as the owner will get the direct advantages. Research shows that the main drivers towards Energy Efficient Renovation for home-owners are ‘saving on energy bills’ and ‘improving comfort’ (Ebrahimigharehbaghi et al., 2019). These drivers are less present in the rental sector because the owners do not receive direct benefits from the renovation.

Between 1945 and 1975, around 1.3 million units of social housing were realized, which indicates that most of the social housing stock stems from that period (Platform31, 2013). Currently, this is 29% of the national stock. In 2020, the Ministry of Internal Affairs started the 'renovation accelerator' program cooperating with Dutch housing associations. This program aims to scale up the market through demand bundling of similar projects with multiple homeowners, creating more demand for large-scale renovations (Ministry of Internal Affairs, 2020). Targeting the social housing stock has the potential to achieve fast renovations on a larger scale.

2.2 Housing types

For the Dutch climate agreement, the Dutch housing stock has been categorized into four different construction periods (Nieman, 2021). These construction periods represent similar aspects of the residences built in that period. The following periods have been identified:

1. Period before 1945: Mostly stone walls in combination with wooden floors
2. Period 1945 - 1975: Uninsulated cavity walls in combination with wooden floors
3. Period 1975 - 1995: Insulated cavity walls in combination with concrete floors, poorly insulated
4. Period after 1995: Relatively well-insulated cavity walls

It is divided into four housing categories:

1. Dutch terraced house
2. Corner houses / semi-detached houses
3. Detached houses
4. Galerij- / portiek apartments

In combination with the construction periods, 16 housing typologies can be created, under which most of the existing Dutch houses can be categorized. The following image gives examples of the typologies.

Tabel 2: Voorbeelden (ter illustratie) van de 16 woningtypen per bouwjaar en woning categorie

Figure 2 Examples of the 16 housing types (Nieman, 2021)

Based on the WOon 2018 research Nieman has identified the number of dwellings per housing category. More than 30% of the residential stock can be identified as galerij- / portiekwoningen. This can also be referred to as apartment or multi-family houses. The post-war households (1945-1975) are particularly interesting because of the potential for renovation. These houses were often built in a prefab manner to generate a large volume of residences. Their age reaches a point where the building envelope starts to reach its end of life, while the structure is usually still in a good state. Table 1 shows the amount of housing units per category.

Table 1 Amount of housing units per category (Nieman, 2021)

	<1945	1945-1975	1975-1995	>1995	Totaal
Tussen-woningen	202 eenheden 332.881 woningen	363 eenheden 643.490 woningen	398 eenheden 626.759 woningen	213 eenheden 380.789 woningen	1.176 eenheden 1.983.919 woningen
Hoek-woningen/ 2^1 kap-woningen	187 eenheden 307.992 woningen	375 eenheden 635.489 woningen	422 eenheden 668.358 woningen	186 eenheden 341.177 woningen	1.170 eenheden 1.953.015 woningen
Vrijstaande woningen	157 eenheden 281.028 woningen	176 eenheden 265.258 woningen	203 eenheden 248.300 woningen	163 eenheden 245.625 woningen	699 eenheden 1.040.211 woningen
Galerij-/ portiekwoningen	273 eenheden 491.643 woningen	439 eenheden 780.881 woningen	360 eenheden 599.558 woningen	389 eenheden 621.791 woningen	1.461 eenheden 2.493.873 woningen
TOTAAL	453 eenheden 1.413.543 woningen	1.353 eenheden 2.325.118 woningen	1.383 eenheden 2.142.975 woningen	951 eenheden 1.589.382 woningen	4.506 eenheden 7.471.018 woningen

2.3 Energy consumption

CBS data indicates that households in newer buildings tend to consume less gas, which aligns with the progressive implementation of energy efficiency regulations over time. Specifically, buildings constructed from 2006 and onwards exhibit a marked decrease in gas usage.

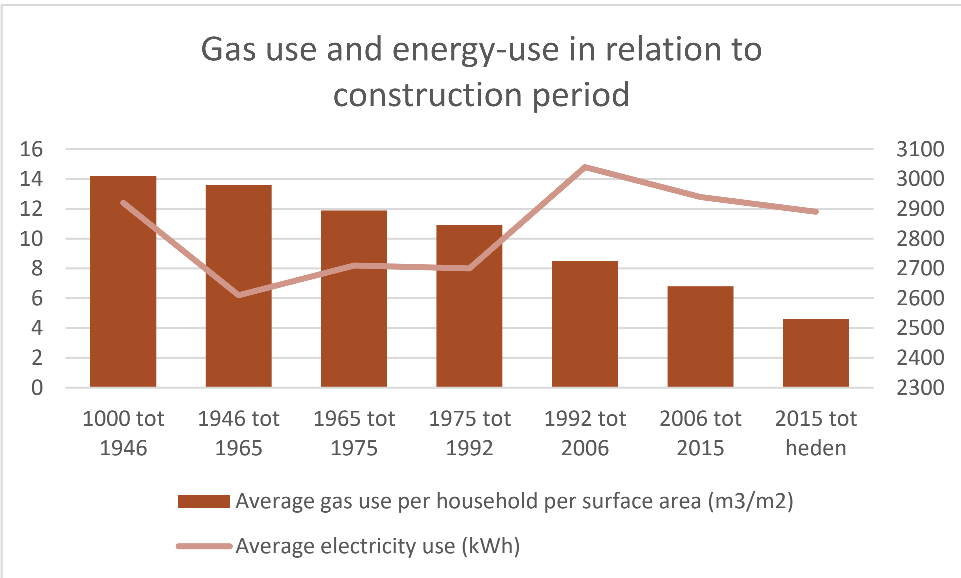


Figure 3 Gas use and energy-use in relation to construction period (CBS, 2023)

Conversely, the trend in electricity consumption increases for newer buildings. This could reflect the greater integration of electrical appliances and devices in modern living or the difference in the behavior of occupants in newer buildings (Delzendeh et al., 2017).

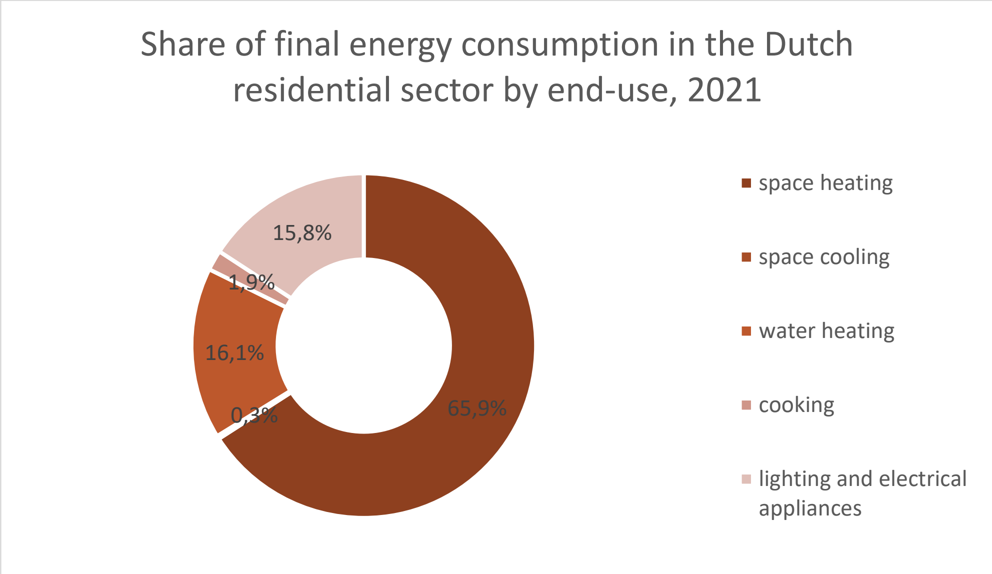


Figure 4 Share of final energy consumption in the Dutch residential sector by end-use (Eurostat, 2023)

In Dutch households, the energy balance is predominantly tipped towards space heating, which accounts for 65.9% of the energy consumption in 2021. This large share is mainly due to heat loss through various means, such as transmission through walls, windows, and roofs, especially in the colder months. In contrast, energy for space cooling remains minimal due to the mild summers. Other energy expenditures, like water heating and powering appliances, also contribute to the overall energy consumption but are more controlled and thus represent a smaller fraction of the total energy use. Even though the Dutch climate is slowly changing, the need for space heating is still at large and will still be a high priority for the next couple of years.

2.4 Dutch system-built houses

The Dutch system-built houses represent over 400,000 residences in the Netherlands, almost 15% produced between 1945 and 1975. Due to the fast-growing Dutch population and shrinking household size (CBS, 2024), around 2.9 million houses were built in a period of 30 years. During this period, two new developments were made to meet the growing housing demand. First, strict quality standards and the limited availability of diverse building materials led to much uniformity in housing design. Second, there was a significant standardization in the construction methods of residences. Many Dutch housing factories started popping up with the rise of prefabrication for new construction. As a result, these houses still have pretty rigid construction because they were built from prefabricated concrete and designed to minimize failure (Platform31, 2013). The uniformity and quality of the construction indicate that these houses have considerable potential for renovation.

The architectural quality of the system-built houses was not the best. The facades were often dull and repetitive, and in that period, there were no strict energy standards, so their energy performance was very poor. Currently, the facades of these houses are about to reach the end of their lifespan, while the construction is still in a good state.

The plans were quite well designed (in some systems) and have the flexibility to be reused. The plans were pretty small for families, ranging from 45m^2 to 75m^2, but with the current household sizes decreasing in the Netherlands, they could be transformed into smaller apartments. According to CBS data (2024) the average household size in 1964 was 3.49 people, which shrunk to 2.11 people per household in 2024.

2.5 Conclusion

The residential stock, accounting for 87% of the Dutch national stock, is a critical target for energy renovations due to its vast presence and direct impact on the country's energy consumption. Because of their uniform function, residential buildings present better opportunities for large-scale energy efficiency improvements than the more diverse non-residential buildings.

Post-war residences, a substantial portion of the residential stock built between 1945 and 1975, are particularly ripe for renovation. Their construction techniques and aging thermal envelopes make them suitable for standardized retrofitting processes, which can be effectively scaled up. This focus can leverage the volume of these buildings to achieve substantial energy reductions quickly.

The energy performance of post-war residences is currently suboptimal, mainly due to the age of their building envelopes, which often leads to significant heat loss. Renovating the building envelopes is essential, as space heating accounts for most energy end-use in Dutch households. Especially the Dutch system-built houses, which show much uniformity between them and have the potential for scaling up the renovation industry. Targeting the thermal envelope of post-war buildings can drastically reduce energy consumption, directly addressing the residential sector's primary source of energy inefficiency.

Dutch system-built houses have great potential for renovation. The core building structures and plans are solid and functional, making them suitable for modern upgrades. The uniformity in building systems across these homes offers scalable renovation solutions, making system-built houses ideal candidates for large-scale renovation.

3 ENERGY EFFICIENCY AND COMFORT

This chapter explores the energy efficiency and comfort of residential buildings. Its main goal is to understand the requirements needed to reach climate goals and the challenges that come with energetic renovation. The Trias Energetica (shown in the figure 5) is central to this research, where the main goal is to decrease energy demand, the use of green energy is second, and the efficient use of fossil fuels is last.

Figure 5 Trias Energetica (van de Sande, 2021)

3.1 Energy labels

In the Netherlands, a building's energy efficiency can be determined by its assigned energy label. This labeling system provides transparency about the energy performance of residential buildings, encourages energy-saving measures, and helps reduce CO_2 emissions. Energy performance is also an important factor in the real estate market, influencing properties' selling and rental prices (NOS, 2022). Additionally, the current energy performance determines the potential for improvement. Buildings that perform worse have the opportunity to reduce more energy with renovations.

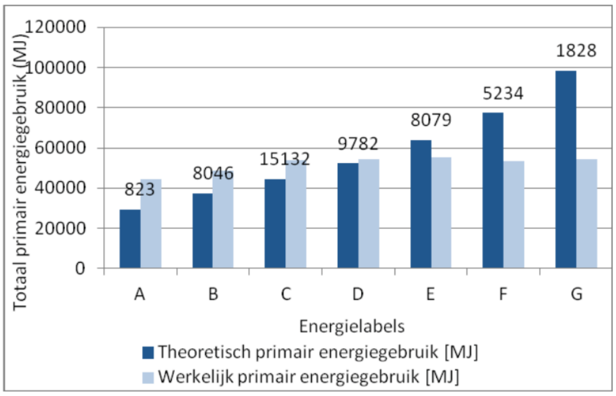


Figure 6 Theoretical energy use vs actual energy use per energy label (Majcen & Itard, 2014)

The initial energy label in the Netherlands provided a basic indication of the energy efficiency of a building, but it was not very accurate. Figure 6 shows the expected and actual energy use per label for social rent housing in Amsterdam; it shows that labels D, E, F, and G have almost similar energy use. In 2015, the energy index was introduced as a more comprehensive measure. Since January 1, 2021, a new methodology called NTA 8800 has been used to determine the energy performance of Dutch residences. This method is more detailed and accurate than the previous ones, requiring an on-site inspection by a certified expert to assess various aspects of the building's energy efficiency (RVO, 2021). The NTA 8800 also emphasizes a building's compactness in the calculations, which the previous methods excluded. The compactness of a building is defined by the ratio between the floor area and the area of the building's outer shell (A_{ls} / A_g). This is an important variable when comparing different housing typologies on energy performance. The method also aligns with the Energy Performance of Buildings Directive (European Commission, 2010).

3.2 Energy Performance Gap

Despite this more advanced calculation method, the energy efficiency in the residential sector presents a complex problem between theoretical and actual energy consumption. While energy renovations are implemented with expectations of significant efficiency gains, the actual performance often reveals a gap between predicted and realized energy outcomes. This phenomenon, known as the 'Energy Performance Gap,' highlights the differences in energy savings following renovations (van den Brom, 2020). An analysis of a large number of houses within the Dutch social housing stock undergoing thermal energy renovations, for instance, showed that actual energy savings frequently deviated from the expected results (Guerra-Santin et al., 2021).

Research shows that 50% of this deviation is attributed to occupant behavior, including ventilation habits, appliance usage, and temperature settings. The remaining 50% is linked to building envelope features, including thermal resistance and air infiltration, as well as external factors like location and shading (Cozza et al., 2021; De Wilde, 2014; van den Brom, 2020).

3.3 Deep renovations

In energy-efficient building renovations, the Buildings Performance Institute Europe (BPIE) defines deep renovations as transformative processes achieving a minimum of 60% energy savings. This sets deep renovations apart from incremental upgrades, emphasizing their significant role in energy efficiency research (BPIE, 2021). Deep renovations yield substantial energy savings for building owners and tenants and prevent the 'lock-in' effect typical in multi-staged shallow renovations. This approach aligns with the EU's current need to intensify efforts in building renovations to meet climate targets, positioning deep renovations as a pivotal strategy for sustainable and energy-efficient building practices.

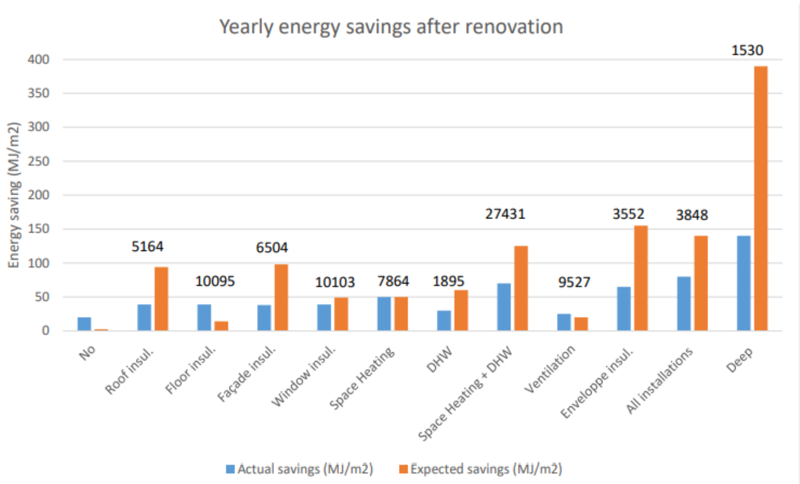


Figure 7 Actual savings vs expected energy savings in renovation projects (Guerra-Santin et al., 2021)

The image above shows the influence of small and big renovation interventions and the energy performance gap between them. The report from the IEBB shows that deep renovations often result in lower energy savings than expected (Guerra-Santin et al., 2021). This poses a massive challenge for the renovation industry.

According to the Dutch Green Building Council and Project Circulaire Energierenovaties (2024), the existing Dutch buildings do not have to become completely net-zero energy. The climate agreement states that the Netherlands should be climate-neutral by 2050. This will be done by generating more green energy and decreasing energy demand.

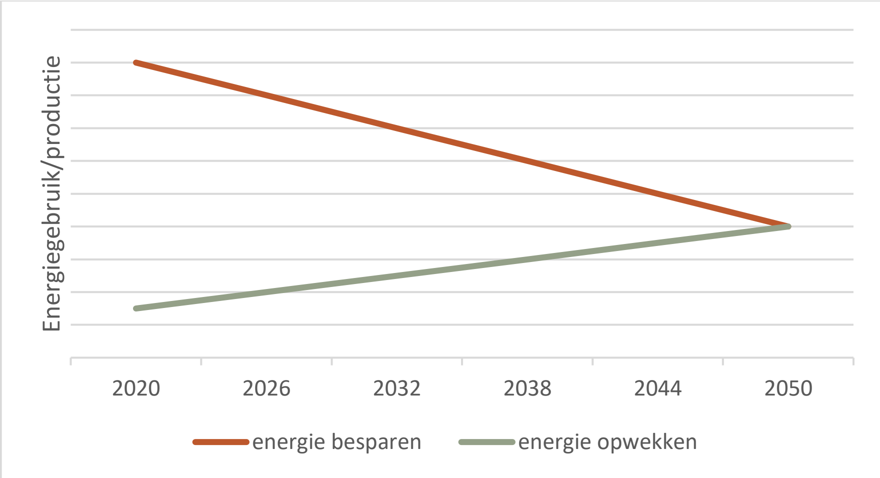


Figure 8 CO_2 neutral by energy savings and green energy production (van Bruggen, 2023)

The assumption can be made that the green energy produced in 2050 should also be enough to cover minimal building energy requirements. This is called the Paris Proof standard and sets the following requirements for operational energy use per year:

- Grondgebonden woning 35 kWh/m2
- Appartementen 45 kWh/m2

The average Dutch building uses about 150-200 kWh/m2 of operational energy per year (Schootstra, n.d.); for post-war buildings, this is even higher. To reach this value of 35 kWh/m2 would require a deep renovation. This research focuses on energy losses through the envelope, making it hard to assess how much total operational energy use is allowed as losses through the facade. It also stands out that ground-based homes have stricter standards than apartments, which initially seems counterintuitive because single-family houses usually have more surface area for energy loss. Nieman (2021) have provided insight into the net heating demand of the Dutch building stock. This is done to establish building-specific target values for energy efficiency. Table 2 shows these values.

Table 2 Voorstel energie standaard renovatie

Woningtype	voorstel standaard	
	Compactheid (A_{ls}/A_g)	Netto warmtevraag (kWh/m²)
Eengezinswoningen, voor 1945	< 1,00	≤ 60
	≥ 1,00	≤ 60 + 105 * (A_{ls}/A_g -1,0)
Eengezinswoningen, na 1945	< 1,00	≤ 43
	≥ 1,00	≤ 43 + 40 * (A_{ls}/A_g -1,0)
Meergezinswoningen, voor 1945	< 1,00	≤ 95
	≥ 1,00	≤ 95 + 70 * (A_{ls}/A_g -1,0)
Meergezinswoningen, na 1945	< 1,00	≤ 45
	≥ 1,00	≤ 45 + 45 * (A_{ls}/A_g -1,0)

The main division is between single-family and multi-family homes, and there is a division between the built years. Compactness is assessed separately because single-family homes are usually expected to have a lower compactness value and, therefore, more surface energy loss than multi-family homes. The net heating demand is lower for single-family homes, assuming they have more space for building systems and solar panels. Then there are stricter standards for buildings after 1945 as they generally have better energy performance.

3.4 Energy savings requirements

The required Rc-value for the façade of new buildings in the Netherlands is 4.7 m2K/W. This value has increased over the years as buildings need to be more sustainable. In 2021, it was 4.5 m2K/W. Due to increased energy costs and sustainability measures, it has been increased in the Dutch building code (Rijksoverheid, 2024). The Rc-value for renovation is only 1.4 m^2K/W, is reasonable because not every renovation needs to be extensive. Deep renovations can be especially difficult for monumental buildings because elements that contribute to energy loss, like windows and doors, often need to be preserved. However, renovating these buildings is becoming easier through websites such as monumenten.nl and restauratiefonds.nl. The Dutch government is also working on “Routekaart Verduurzaming Monumenten” exploring the possibilities for renovating monumental buildings (Duurzaam Erfgoed, 2024).

Achieving the required Rc-value of 4.7 m^2K/W in the facades of system-built houses can be challenging. Applying such high insulation standards can raise questions about cost-effectiveness, particularly for older buildings with a limited lifespan in terms of durability and functionality. Deep renovations involving extensive upgrades can be expensive for these buildings, and their economic viability may not support such investments. However, some companies/organizations have been proven successful in providing economical payback times as low as 15-20 years, together with a business model that supports it. These will be examined more in the next chapter.

3.5 Climate

The climate in which a building is situated affects its energy consumption. The Netherlands has a temperate and maritime climate, which means temperatures generally vary between -5 and 20 degrees Celsius. The yearly average temperature is around 10 degrees Celius, with an annual slow increase in the past few years (KNMI, n.d.). These numbers have been used for most theories on climate-proofing and designing houses in the Netherlands. Most newer homes, designed to be more energy-neutral, consider these outside temperatures.

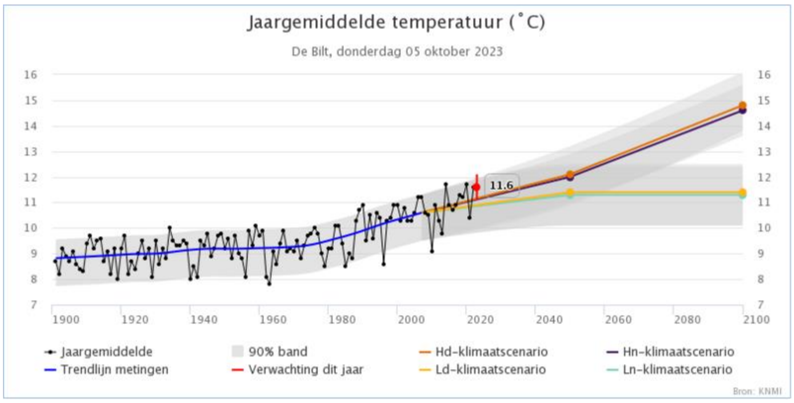


Figure 9 Yearly average temperature in the Netherlands (KNMI, n.d.)

Given the current situation, it is crucial to consider the impact of climate change, especially on home insulation. As the number of warm days per year continues to rise, even with existing climate control measures, all plausible future scenarios fall between 2 – 3 degrees temperature increase by 2100 (Pielke Jr et al., 2022). Increasing warm days relative to cold days can result in less comfortable temperatures for fully insulated homes. Thus, it is necessary to adjust home renovation approaches to future-proof them.

The defining property of insulation materials is their low thermal conductivity. This means that they work as an excellent barrier to temperature differences. In theory, this should keep inside temperatures more constant and keep out the outside cold or heat. However, in practice, it becomes difficult for the heat to escape once it gets inside, especially in many improperly designed newer homes with no cooling or ventilation. Multiple news articles indicate that people with new insulated homes complain about overheating in summer (Peter Koelewijn, 2024; Roos van Bijnen, 2024).

3.6 Comfort

Establishing temperature and ventilation standards is essential when setting the requirements for indoor comfort in Dutch homes for renovation projects. The Dutch building code (*Bouwbesluit* or *Besluit Bouwwerken en Leefomgeving*), uses the NTA 8800 for calculations. Although there are no requirements for indoor temperature in the BBL, the NTA 8800 uses a minimum indoor temperature 20°C for winter, and 24°C as maximum indoor temperature for summer. Peeters et al. (2009) researches the comfortable indoor temperatures in relation to outdoor temperatures. Figure 10 shows the upper and lower limits as a function of the average outdoor temperature.

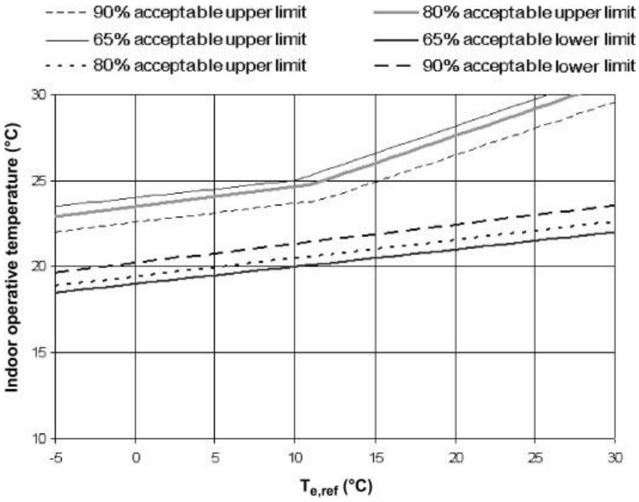


Figure 10 Temperature limits as a function of the outdoor temperature (Peeters et al., 2009)

At an outdoor temperature of 0°C (average winter temperature in Dutch climate), the 90% lower limit is at an indoor temperature of 20°C. At an outdoor temperature of 20°C (average summer temperature in Dutch climate), the 90% upper limit is around 26°C.

According to Hogen (2019) the ideal indoor temperature for living rooms and offices is around 18 to 20 degrees Celsius, sometimes rising to 22 degrees. The suggested bedroom temperature is slightly lower, between 15 and 18 degrees Celsius. Bathrooms and shower areas are typically warm, between 20 and 25 degrees Celsius. Other spaces, such as toilets, hallways, and study rooms, can maintain a comfortable temperature of 18 to 20 degrees. This research will use the adaptive comfort model, which means that the allowed comfortable indoor temperature can be adjusted depending on the outside temperature. This can save much energy as the temperature difference between outdoor and indoor environments is lowered. The focus should be on maintaining a comfortable living environment, which includes preventing overheating in summer and ensuring adequate warmth in winter.

3.7 Conclusion

The chapter underlines the critical role of façade renovation in reducing energy losses, which is essential for improving the energy efficiency of residential buildings, as emphasized by the Trias Energetica. Reducing passive energy losses through façade improvements is fundamental because it minimizes the need for active energy systems to maintain comfortable indoor conditions.

The compactness of buildings is important for their total energy use. Without compactness as a variable, buildings' energy labels are inaccurate. The current way of calculating building energy use is through the NTA 8800 method, which considers this and can lead to more accurate projections of the building stock's energy consumption. However, it is important to consider that the energy performance gap remains a challenge, partly due to occupant behavior and building characteristics.

Deep renovations especially show a big difference between theoretical and expected energy savings, which is true for most energy measures. Deep renovations are not always necessary for older buildings, but at least reaching Paris Proof values is required to reach our climate goals and implement regret-free renovations.

The chapter also considers climate change and its influence on renovation solutions. Given this, there might be a greater need for cooling buildings instead of heating them. Furthermore, the comfortable indoor temperatures for residential buildings are explored. According to the adaptive comfort model, there can be more flexibility for the required indoor temperatures, but there must be proper summer ventilation.

4 FAÇADE RENOVATION

This chapter explains the term renovation and mentions the barriers and challenges in renovating post-war households. It also addresses the different strategies for façade refurbishment and the various degrees of industrialization in the building industry.

4.1 Definition of renovation

In the context of this research, "renovation" refers to enhancing the buildings' exteriors, often referred to as the building's "skin." However, the research explicitly emphasizes "energetic renovation”, which means improving the buildings' energy efficiency and sustainability.

This approach includes measures to significantly upgrade the buildings' energy performance, such as enhancing insulation, installing energy-efficient windows and doors, optimizing ventilation systems, and incorporating sustainable building materials.

While "retrofit" is a more technically precise term often used to describe these energy-focused improvements (Shahi et al., 2020), this research chooses to continue using the term "renovation". This decision is made to maintain consistency with the widely recognized and used terminology in building renovation despite recognizing "retrofit" as a more specific term.

4.2 Barriers and challenges

The Building Performance Institute Europe has analyzed the most prominent barriers to energy renovations, highlighting financial barriers as one of the highest-ranking across-country responses in their survey.

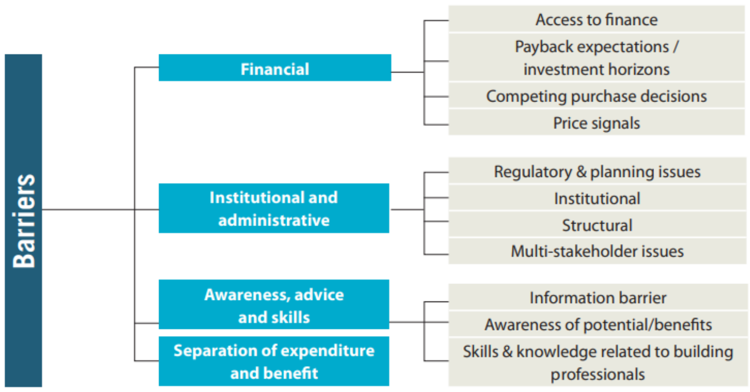


Figure 11 Main barriers in energy renovations of buildings (BPIE, 2011)

Financial constraints include limited access to financing and the problem of long-term benefits with immediate costs. Energy renovations usually have a long payback time, which lowers the Return on investment. This is further complicated by market prices that fail to reflect the long-term savings of energy efficiency.

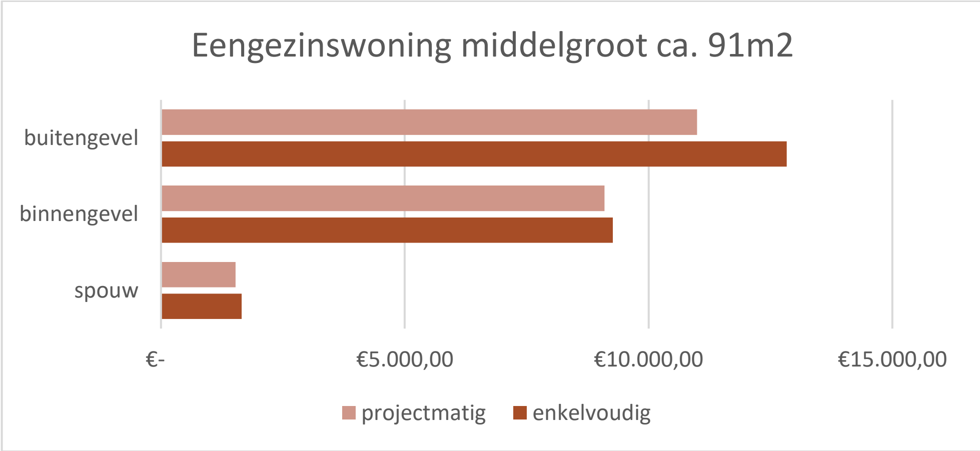


Figure 12 Facade insulation costs for single-family homes (RVO, 2023)

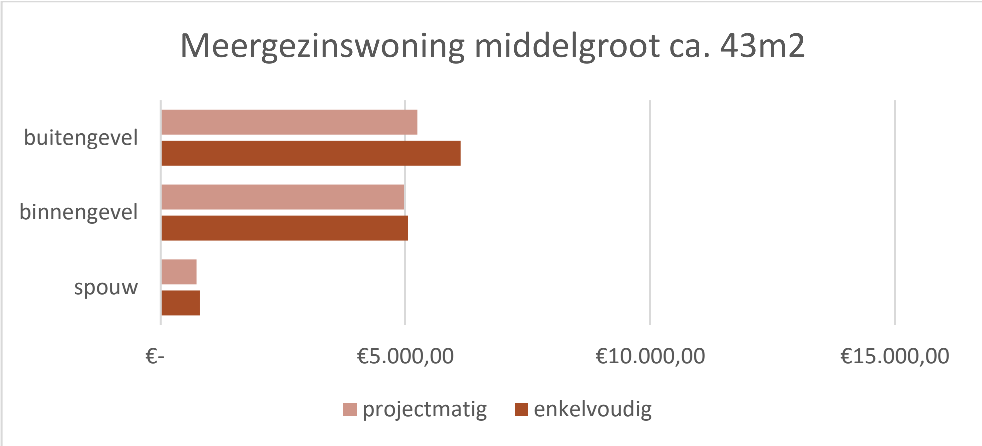


Figure 13 Facade insulation costs for multi-family home (RVO, 2023)

The RVO's website provides an in-depth overview of costs associated with different renovation approaches in the Netherlands. In Figures 12 and 13, there is a comparison of costs between simple cavity insulation, complete internal insulation, and complete external insulation. There is a 15% difference between internal and external insulation. Furthermore, an almost 50% difference exists between insulating a multi-family home/apartment and a single-family home. This is primarily because a multi-family home usually gets renovated with multiple homes simultaneously, which decreases the overall costs compared to a single-family home (RVO, 2023).

Administrative and institutional barriers also impose significant hurdles, with regulatory complexities and the need for multi-stakeholder coordination often slowing progress. Moreover, a lack of awareness and advice and a shortage of skilled professionals undermine the capacity for implementing energy-efficient renovations (BPIE, 2011).

Finally, there is a misalignment between who invests in renovations and who benefits – often seen between tenants and property owners. Addressing these barriers requires streamlined financial support mechanisms, simplified regulatory frameworks, skill-building initiatives, and a realignment of incentives to ensure that energy renovations are attractive and feasible investments (BPIE, 2011).

4.3 Basics of façade renovation

The Facade Refurbishment Toolbox categorizes refurbishment strategies into the following categories: Replace, Add-in, Wrap-it, Add-on, and Cover-it. Each of these strategies has its unique advantages and disadvantages (Konstantinou, 2014).

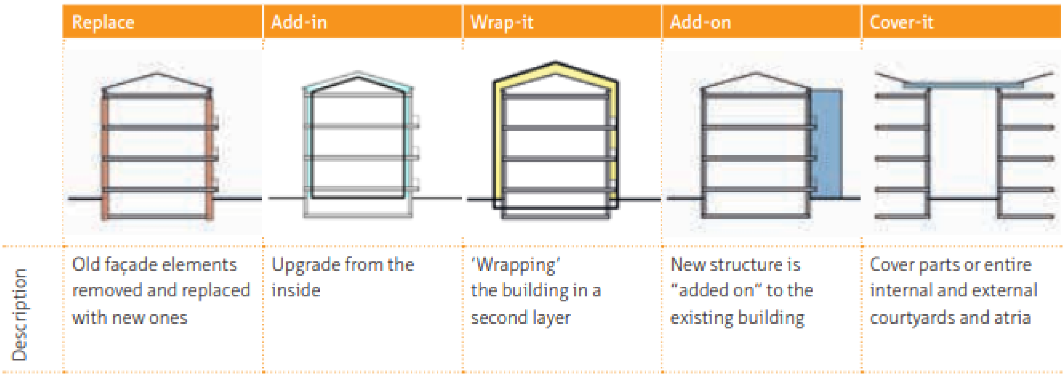


Figure 14 Facade refurbishment strategies (Konstantinou, 2014)

1. **Replace Strategy**: The "Replace" strategy involves removing and replacing the existing facade elements with new components. This approach eliminates the issue of aging older components. However, it can be more expensive due to removing the old facade. This strategy can be disruptive to occupants, necessitating relocation during construction.
2. **Add-in Strategy**: The "Add-in" strategy focuses on adding insulation to the inside of the building and is mainly used when the exterior appearance should remain unchanged or when dealing with protected monuments. While it can enhance energy efficiency, it does not effectively address thermal bridging. Construction works inside the building can be disruptive to occupants and reduce usable interior space.
3. **Wrap-it Strategy**: The "Wrap-it" strategy entails adding a second layer to the building, which can include external insulation, cladding of balconies, or a second facade. This approach effectively resolves thermal bridging issues while increasing thermal resistance. It is less intrusive and disruptive to occupants compared to complete replacement. Moreover, it can provide additional living space and opportunities for design enhancements. However, it may impact the building's appearance, and it could be argued that the old façade's potential is wasted.
4. **Add-on Strategy**: The "Add-on" strategy involves adding new structures to the existing building, ranging from small interventions like balconies to entire extensions. This strategy enhances climate control and resolves technical problems, but it can be complex. It may also necessitate additional surrounding space and a precise design approach.
5. **Cover-it Strategy**: The "Cover-it" strategy emphasizes upgrading buildings by enclosing internal and external courtyards and atria, often with transparent elements. This approach can provide functional space and change the relationship between the interior and exterior. However, its feasibility depends on the building's shape and suitability for this intervention. Proper shading and ventilation are essential to avoid overheating in the newly covered spaces.

The "Wrap-it" strategy is often optimal for large-scale renovation projects. This approach offers several advantages, including reduced disruption to occupants, potential for additional space, cost-effectiveness, and minimized structural impact. This strategy also has the potential for scaling up the renovation process, as few changes need to be made to the building.

4.4 Heat and moisture management

To answer this chapter's question, "What is energetic façade renovation?”. Some background research is required on insulation and its properties, including how it performs and can be applied in buildings. It is crucial to consider the materials' properties when choosing insulation materials and placing the insulation and other layers of the façade system.

4.4.1 Heat transport

Heat transfer through a façade can occur in three primary ways: conductive heat transfer, convective heat transfer, and radiative heat transfer.

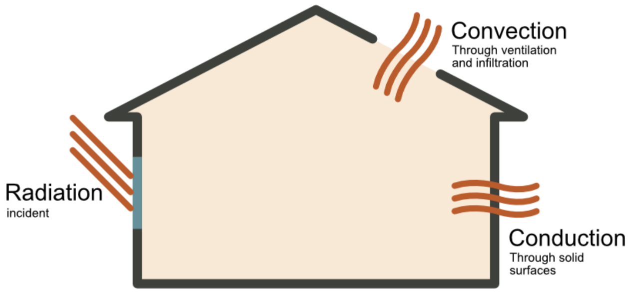


Figure 15 Different ways of heat transfer through building envelope modified from (Archi-Monarch, n.d.)

Conduction typically results in the highest energy loss due to the large surface area of the façade. Insulating materials primarily aim to reduce conductive heat loss by creating a thermal barrier, which helps keep the indoor temperature stable. However, while this reduces heating and cooling demands, convection and radiation remain significant contributors, particularly in well-insulated homes. Convection can cause many heat losses, especially in buildings with air leaks. These leaks can result in increased energy loss and moisture transport. Solar radiation absorbed by the building’s envelope can raise indoor temperatures, especially in homes with large glass areas or insufficient shading. As mentioned before, this can trap the heat inside the building and cause heating problems. Shading devices, reflective materials, and glazing treatments can be installed to prevent overheating.

Although convection and air infiltration can significantly contribute to energy loss, most energy retrofitting methods focus on limiting heat transfer through conduction because this is usually responsible for most energy loss (Kamel & Memari, 2022).

The transfer formulas through a medium can be expressed for each type of transfer with a similar formula. The interaction between heat and moisture is critical within a building component, as this can be the leading cause of material degradation. Kumaran (1994), has written the following formula for most transport equations through a medium.

Equation 1 The basic formula for transport equations

$$J_B = -k \cdot grad\, \phi_B$$

where J_B denotes the rate at which entity B is transported, ϕ_B is the driving potential, and k is a quantity called transport coefficient, characteristic of the medium through which the transport occurs (Kumaran et al., 1994).

For heat, the formula for conductive heat transfer through materials can be written as the following:

Equation 2 Fourier’s law on conductive heat transfer through materials

$$J_q = -\lambda \cdot grad\, T$$

Where J_q is the heat flux, λ is the thermal coefficient of dry insulation, and T is the temperature difference (Kumaran et al., 1994). The driving force behind transport for heat is the temperature difference; heat will distribute from a warm temperature to a cold temperature to reach a balance. Completely stopping heat transfer is not possible, but it is possible to decrease it.

4.4.2 Moisture transport

Moisture must be prevented inside a building's construction because it can alter the properties of the insulating materials, making them less effective as water conducts heat more efficiently. It can also deteriorate the materials and their life span, not just the insulation but also the construction. Therefore, the building's construction is often preferred to be on the inside of the thermal barrier to extend its lifespan.

The driving force in water vapor transport is a difference in water vapor pressure. Equation 3 expresses the transport of water vapor through a building material.

Equation 3 Fick's law of water vapor diffusion

$$J_v = -\delta \cdot grad\, p$$

Where J_v is the water vapor diffusion flux density [kg/m^{2}s], δ is the water vapor diffusion coefficient [kg/msPa], and p is the water vapor partial pressure (Kumaran et al., 1994).

Construction materials can contain moisture in three states: liquid, vapor, and solid (ice), depending on the temperature. When it gets colder, moisture can freeze and turn into ice, which expands and can cause cracking in the materials, especially in building exteriors exposed to the weather. In regular conditions, moisture in building materials can exist in both liquid and vapor form. Liquid moisture can be absorbed or trapped, leading to potential swelling or rot. Simultaneously, moisture in vapor form can diffuse through porous materials and may condense into liquid upon reaching colder surfaces. This condensation can contribute to material degradation over time.

Temperature is crucial in determining how moisture behaves within building materials. When there is a significant temperature difference between the inside and outside of a building, the risk of condensation increases. As the temperature decreases, the air's capacity to hold moisture decreases, causing the relative humidity to rise. If indoor humidity surpasses a certain threshold, moisture can condense on colder surfaces, especially in poorly ventilated areas or places with thermal bridging. Over time, these fluctuations in moisture contribute to the deterioration of construction materials. This process is illustrated in Figure 16.

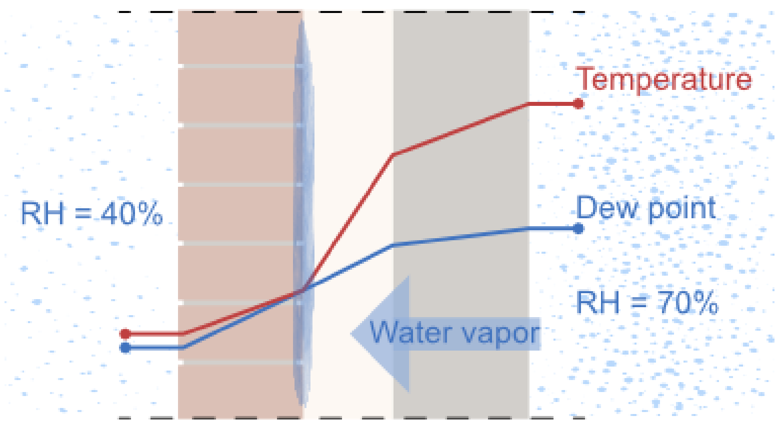


Figure 16 Water vapor transport in building facade (own work)

A psychrometric chart is a graphical tool used to visualize the properties of moist air, such as temperature, humidity, and dew point, and to understand how they interact. It helps in analyzing processes like heating, cooling, and humidification. The chart shows the relationship between dry bulb temperature, humidity ratio, and relative humidity, allowing users to track how air moves and changes its moisture content.

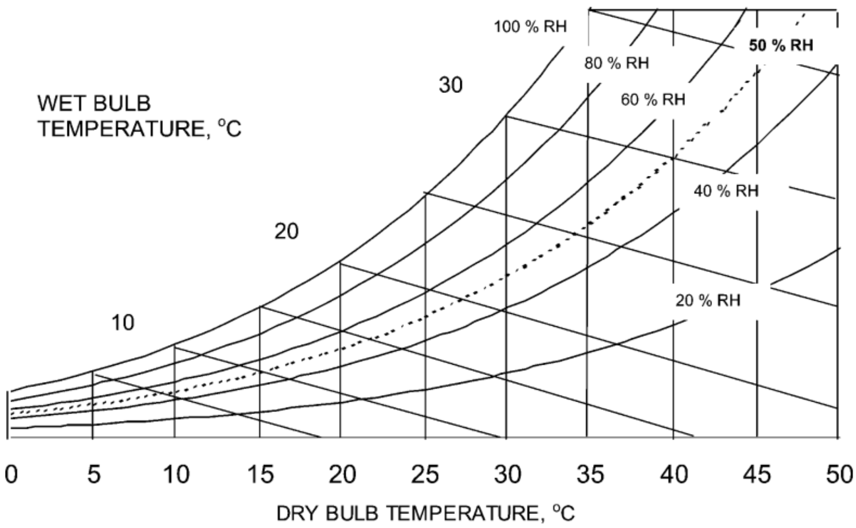


Figure 17 Simple psychrometric chart (Kumaran et al., 1994)

The Glaser or steady-state method (Kumaran et al., 1994) is a common way to calculate condensation within a building envelope. It uses temperature and humidity data and a psychrometric chart to identify areas where moisture may condense within the building layers. This method assumes steady-state conditions (no time-dependent changes) and calculates the risk of vapor diffusion and condensation based on differences in vapor pressure across the building structure.

To prevent moisture and temperature problems in the building, good structuring of the façade layers is required. The thermal insulation and vapor barrier should be placed correctly. In the Dutch climate, the vapor permeability of the layers often results in low vapor permeability on the outside and high vapor permeability on the inside. However, as mentioned in Chapter 3.5, climate change could cause problems if the outside temperatures are much higher than indoor temperatures. This could cause the vapor to move in the opposite direction. This is less likely due to water condensing less quickly at higher temperatures, but is important to keep in mind with the design of façade systems.

4.5 Development of façade renovation

Despite the growing recognition of the benefits of modern energy-efficient renovation methods, (around 75-80%) of renovation practices continue to be executed using traditional methods (Mohan, 2021). This persistence of conventional practices underlines the industry's resistance to change and the lack of awareness or access to newer renovation techniques.

4.5.1 Industrialization

The industrialization of the building industry represents a shift towards applying manufacturing principles and advanced technologies in construction processes. This approach is widely adopted in the construction of new buildings. However, it is still limitedly used for building renovation.

According to Richard (2005) industrialization can be classified into the five following degrees, each degree getting more automated:

1. **Prefabrication** involves manufacturing components or modules in factories or elsewhere, often using traditional processes and materials. It can reduce construction costs by up to 15% due to factors like climatic protection, task rationalization, specialized tooling, semiskilled labor, quality control, and bulk purchasing of raw materials.
2. **Mechanization** involves incorporating machinery, such as power tools, to facilitate labor-intensive tasks. It often accompanies prefabrication, with modular housing manufacturers using tools like pneumatic hammers.
3. **Automation**: Tools and machinery completely take over tasks previously performed by labor. Automation requires supervision, but industrial engineers and programmers play a critical role. Studies show potential cost savings of up to 27% compared to traditional construction methods.
4. **Robotics**: This involves highly flexible machinery capable of performing diverse tasks. While expensive, robotics is essential for computer-aided manufacturing (CAM) and mass customization.
5. **Reproduction**: Introduces innovative technology to simplify the multiplication of complex goods, bypassing repetitive linear operations typical of craftsmanship. Reproduction focuses on generating simplified processes through research and development.

Several companies are adopting innovative technologies such as robotics and prefabrication to streamline renovation and improve efficiency. Energiesprong is a network that facilitates collaboration between all involved stakeholders to enable Net Zero Energy renovations. Construction companies like RC Panels, VanWijnen, and BIKBouw collaborate with Energiesprong and are at the forefront of the industrialization of the renovation industry.

4.5.2 Rc Panels renovation process

The image shown from RC Panels highlights a typical process in their industrialized renovation approach, which consists of four key steps:

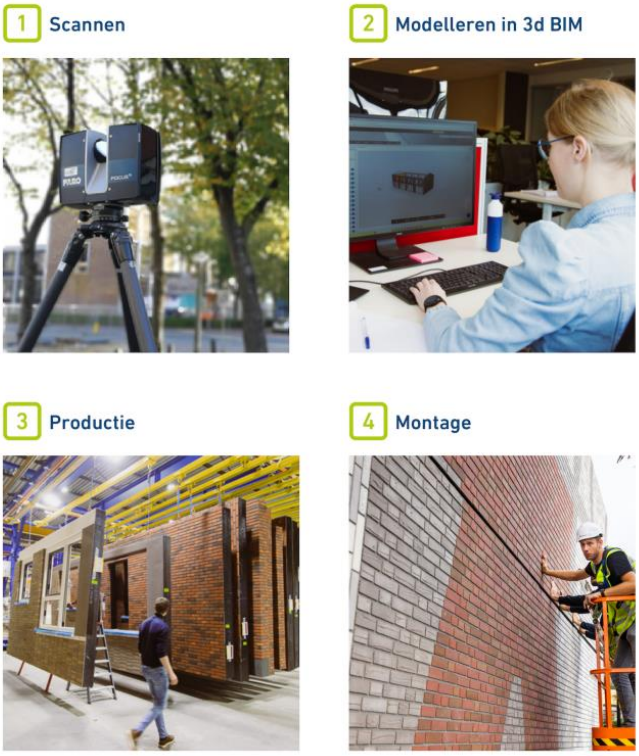


Figure 18 Modern renovation approach (RcPanels, 2023)

1. Scanning: The existing façade is scanned using 3D laser technology. This digital mapping, images, and a physical review of the building lead to a detailed digital model of the building's current condition. The scan ensures precision in the design and manufacturing stages.

2. Modeling in 3D BIM: After scanning, the data is processed to create a 3D model using Building Information Modeling (BIM) software. This model helps visualize the new façade and allows for detailed planning of every element, ensuring everything fits seamlessly during installation.

3. Production: Once the design is finalized, prefabricated façade elements are produced. These elements are manufactured in a controlled factory setting, ensuring high quality, precision, and faster production times. Companies like RC Panels and VanWijnen use robotic assembly lines to achieve consistent results.

4. Assembly: The prefabricated elements are transported to the site and installed on the building's exterior. The panels' modular nature allows for quick assembly, reducing the time needed for on-site work. This method reduces disruption to the occupants while ensuring high quality and thermal performance.

A future development for these companies could involve designing façades with disassembly in mind. Many prefabricated façades are built to be durable and long-lasting, but little attention is paid to how they can be deconstructed once they reach the end of their service life. Designing for easy disassembly would allow individual façade components to be removed, replaced, or recycled without causing damage to the building's structure. This approach could reduce waste and align with the growing emphasis on circular construction, where materials are reused and repurposed.

In addition to improving disassembly, enhancing material circularity could also be a focus. By selecting materials that can be more easily recycled or repurposed, companies can contribute to reducing the environmental impact of renovations. For example, using façade panels made from recycled materials or components that are easier to separate and reuse at the end of their lifecycle would help lower the carbon footprint of these renovations. Robotics could also play a role in the construction phase and the controlled disassembly process, ensuring precision and efficiency in material recovery.

Robotics, prefabrication, and digital tools like 3D scanning and BIM are transforming the façade renovation industry. These can increase the speed and efficiency of the renovation process and improve the quality and sustainability of the end product.

4.6 Conclusion

The chapter delves into the definition of renovation, opting for this term as it is more known to the general public. It reviews the barriers and challenges within the renovation industry, identifying financial constraints as the most significant obstacle. A comparison of common façade refurbishment strategies is also presented, focusing on the differences between internal and external renovation methods. According to RVO, the costs of external renovation are approximately 25% higher than internal renovation.

Despite the higher costs of external insulation, the theoretical research indicates that internal insulation poses more long-term risks, including cold-bridging, material degradation, and moisture-related problems. Furthermore, external insulation offers greater benefits by mitigating these issues and better adapting to potential climate change impacts. While internal renovation is sometimes the only option for certain homes, the chapter concludes that external façade systems are more viable and sustainable due to their long-term benefits.

5 CIRCULARITY IN FAÇADE RENOVATION

This chapter discusses the importance of circularity in designing new façade renovation systems and some drawbacks of speeding up the renovation rate. Ultimately, the need for renovation is driven by its potential to decrease the building sector's CO_2 emissions.

5.1 Defining circularity in construction

With the current construction and the need for new and comfortable homes, the CO_2 impact of Dutch buildings will be 113 Mtons of CO_2 emissions by 2030. This will even double to 297 Mtons of CO_2 until 2050. Considering current climate goals, renovating the entire building stock (8 million houses) will be responsible for 44% of these short-term CO_2 emissions. New building construction will be responsible for 15% of the emissions. (Copper8 et al., 2024)

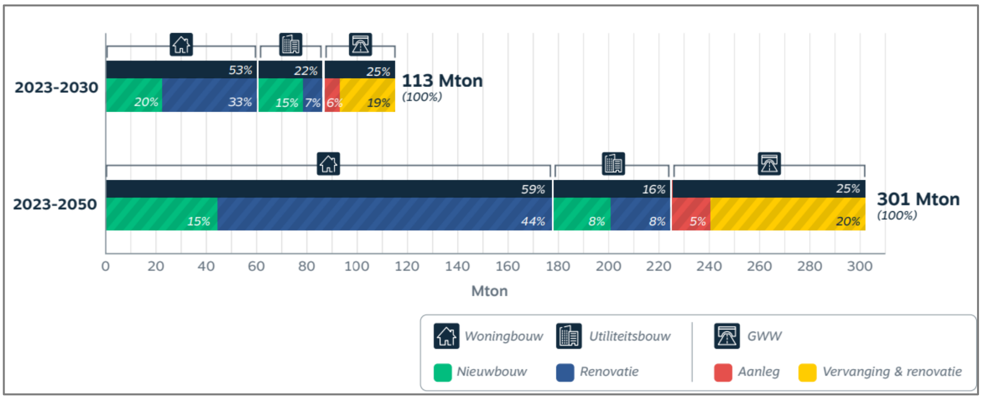


Figure 19 Emissions from Dutch construction with the current way of building (Copper8 et al., 2024)

As mentioned earlier in this research, a critical goal of the energy transition is renovating the Dutch building stock to be more sustainable. The consequence is that in the short term, the embodied energy of these renovations is responsible for enough CO_2 emissions that the primary climate goal of preventing a 1.5-degree global temperature rise may not be possible. Initially, two very opposite statements in this research need to be considered. On the one hand, we need to renovate as fast as possible. On the other hand, building stock renovation will also be one of the most significant contributors to not reaching the climate goals in the short term. How do we solve this issue?

First, it is essential to consider that renovation seems to have the highest energetic impact compared to new construction. However, renovation targets 8 million buildings, while new construction accounts for only 1 million. Considering this, completely re-constructing the entire stock would be responsible for significantly higher CO_2 emissions.

The main problem is that these renovations will not be enough to reach our climate goals in the short term. Copper8's research (2024) states that there are ways to reduce these short-term emissions. Unfortunately, the research shows that making the renovation industry more circular could reduce the total emissions of renovations by not more than 11.9%, which is still not enough even to reach a 2-degree global temperature increase.

Nonetheless, there are problems with the current methods of renovating. Little to no attention is paid to CO_2 emissions from building materials, and the renovation industry produces much waste. Renovation has the highest potential for improvement in the building industry regarding total future emissions. According to the report from Copper8 et al. (2024), making this industry more sustainable can save 13.4 Mtons of CO_2 in the short term. A renovation's CO_2 payback period is around seven years. Using more biobased or recycled materials and designing more circular renovation systems can reduce payback time.

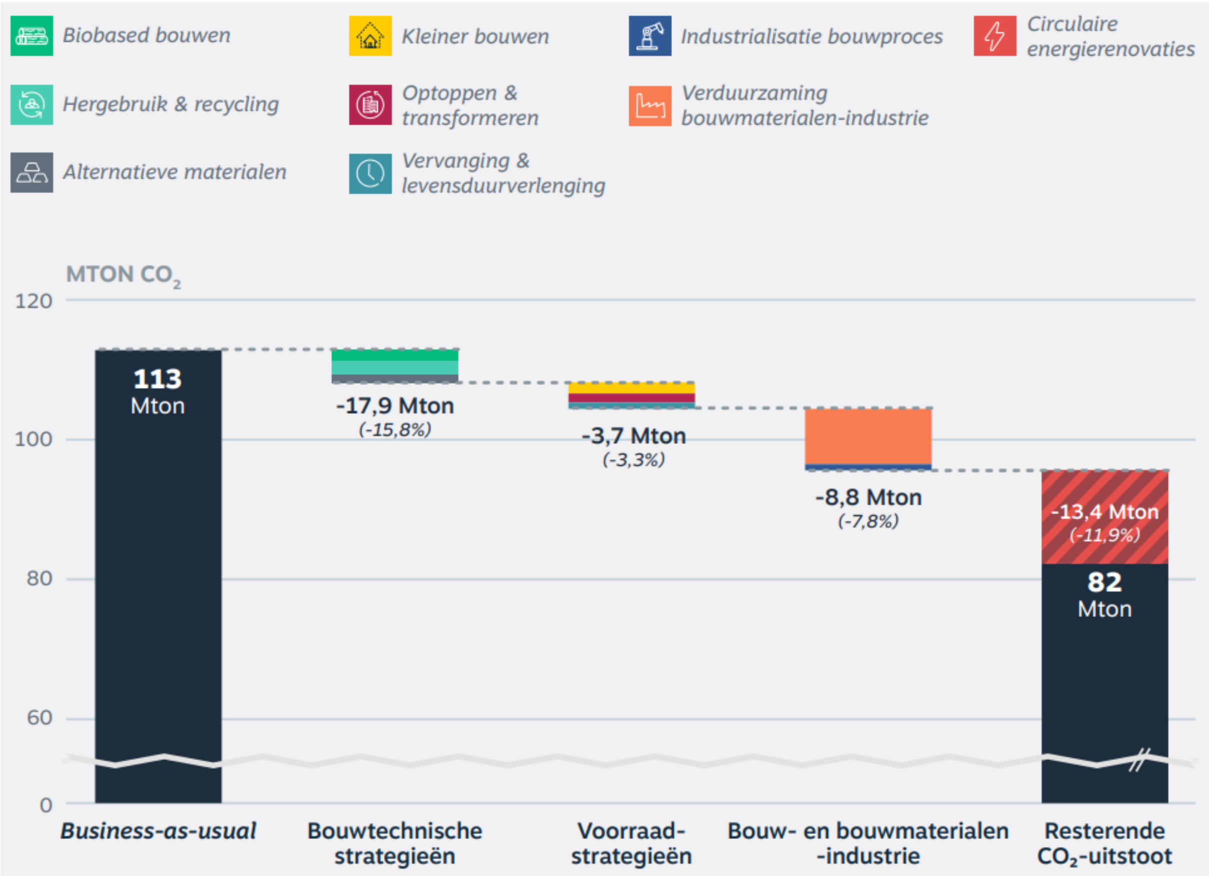


Figure 20 CO_2 reduction per circular strategy until 2030 (Copper8 et al., 2024)

5.2 Renovation vs demolition

Renovating existing housing often trumps demolition from a sustainability standpoint, conserving resources and reducing carbon emissions by preserving the embodied energy in building materials. Studies, like those from the Preservation Green Lab (2011), suggest that the energy efficiency gains from new buildings can take decades to offset the impacts of their construction. Furthermore, demolition generates substantial waste, and a building structure usually has the highest carbon footprint. Reusing this building structure in renovation can negate a big part of the embodied energy. There are buildings where the structure and layout are not functioning anymore and would need to be demolished. The European Union’s directive on building energy performance favors renovations to meet its climate and energy objectives (European Commission, 2010).

5.3 Design for disassembly

Design for disassembly is one essential part of moving towards a circular economy. This offers the opportunity to reduce the use of primary materials and their environmental impacts. According to Thormark (2001), material producers play a significant role in building projects, as they often provide complete systems, including the materials and products for assembly, which must be designed with disassembly. So, the target needs to be with the material or system producers and their manufacturing systems.

5.3.1 Recycling vs reuse

One of the primary benefits of design for disassembly is reducing the time, costs, and environmental risks associated with demolition and traditional end-of-life processes. Disassembly allows materials to be extracted with minimal damage, retaining their value for reuse. Construction and demolition waste in the Netherlands amounted to 18 million tonnes in 2001. Of this total, 40% was concrete waste (Durmisevic, 2005). As concrete has a high embodied energy, it is essential to reduce this waste by renovating and reusing existing building structures.

From a circularity perspective, reuse is preferred over recycling because no extra energy is required to smelt and change the material. Table 3 shows the energy required to produce some common building materials. For some materials, these energy savings can be more than 90%. To reduce landfilling and stimulate reuse, a tax on landfills and subsidies for circular construction can be introduced.

Table 3 Energy saved by using recycled materials (Durmisevic, 2005)

	Energy required to produce from virgin material (million Btu/ton)	Energy saved by using recycled materials (percentage)
Aluminum	250	95
Plastics	98	88
Newsprint	29.8	34
Corrugated Cardboard	26.5	24
Glass	15.6	5

Façade systems can be designed in layers, allowing individual components such as insulation, cladding, or structural supports to be separated and replaced without dismantling the entire system. The ability to disassemble at the material level, rather than just the system level, is particularly relevant for renovation, as the dimensions are pretty specific and some materials within the façade have different service life. For system-built houses, where the design and dimensions are more standardized, the potential for reusing parts of a disassembled façade on other projects is still limited. Recyclability on a material level can be better suited for these projects.

Table 4 Service life of insulation materials (Kono et al., 2016)

Insulation material	Service life (years)
Cellulose fibre	50
Fibreboard	50 / Building lifetime
Foamglass	100 / Unlimited
Stone wool	Building lifetime / unlimited
VIP	40
PUR	50
EPS	35-50
XPS	Building lifetime

Table 4 shows the service life for some of the most common insulation materials. Compared with the

Most of these materials have quite a long lifespan, especially fibreboard, which has a long service life for a biobased material. The products examined in the research from Kono et al. (2016) refer to Kronopoly and GUTEX materials, which show a long service life according to their EPD(Environmental Product Declaration). While there was no information about an 'unlimited' service life for these materials, it shows that insulation materials can still have a long service life.

It is essential to consider the functional service life compared to the technical service life. According to Durmisevic (2005) the technical and functional service life of a modern building is about 50 years. Most of the insulation materials in Table 4 can support this service life. Dumisevic also mentions that the functional service life can often be shorter than the technical service life.

5.3.2 Joints and Connections

When considering disassembly for façade systems, joints and connections become critical. The type of joints used must allow for easy removal and replacement of façade elements without compromising structural integrity during the building's life. Durmisevic (2005) divides buildings into three groups:

1. Building structures with low disassembly potential. Those are structures with standard construction waste stream (70-100% down-cycling and demolition).
2. Building structures with partial disassembly potential (30-70% of materials are down-cycled land filed or incinerated).
3. Building structures with high disassembly potential (0-30% of materials are down-cycled, land filled or incinerated).

Buildings' environmental efficiency can be drastically improved by optimizing design aspects for disassembly. This research aims to create a façade renovation system with high disassembly potential.

Furthermore, Durmisevic (2005) sets two main design criteria for the design of decomposable connections:

1. elements/components should be kept separated, to avoid penetration into other components or systems, and
2. dry-jointing techniques should replace chemical techniques.

Figure 21 shows different principles of connections, from fixed to flexible connections. Durmisevic classifies the chemical and direct material connections as more fixed. Moving towards more elements and components creates more flexible connections but increases the system's complexity. Additional fixing devices also add more different materials but allow for the reusability of each component. Therefore, the choice of the joint has to be made with a balance of flexibility and complexity.

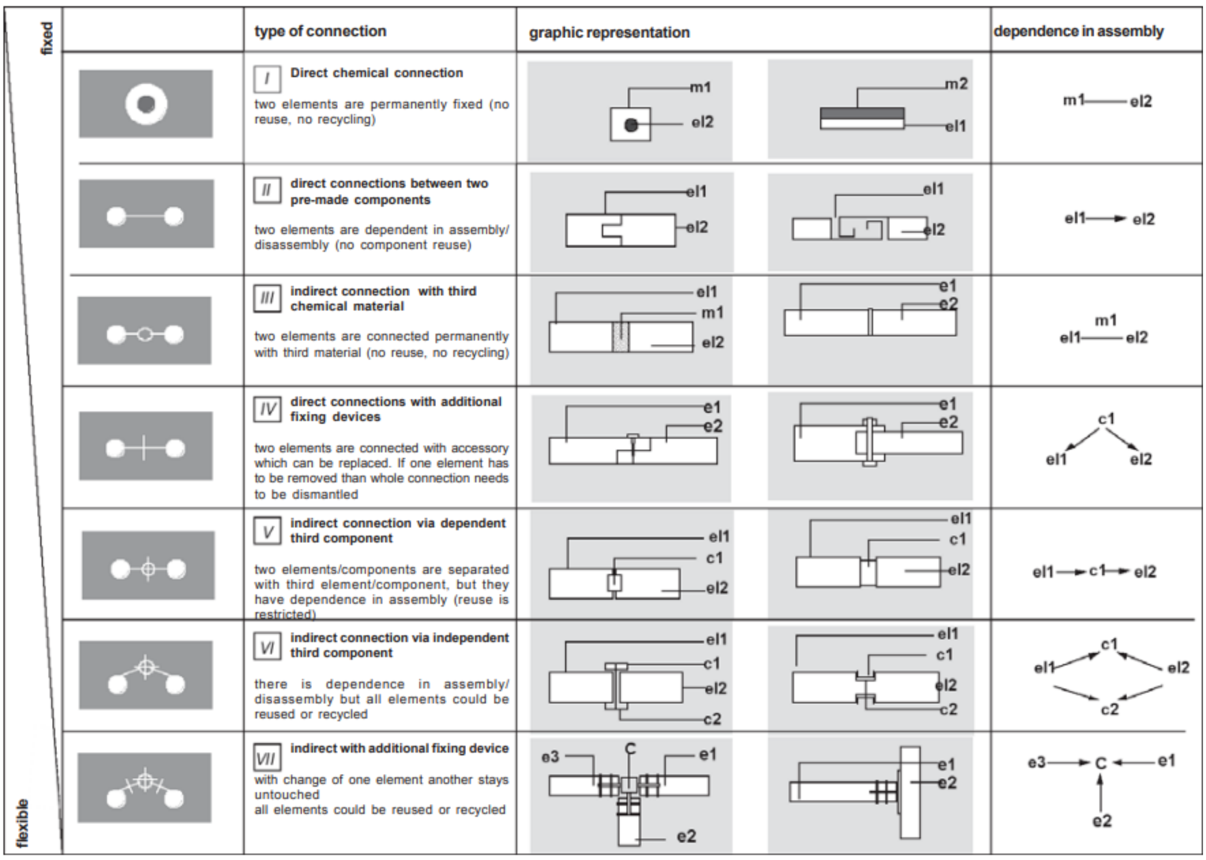


Figure 21 Seven principles of connections ranged from fixed to flexible connections (Durmisevic, 2005)

5.4 Benefits and consequences of circular systems

Circular façade systems can improve environmental performance and provide other benefits to the building industry. However, they can also have consequences for the quality and integrity of the façade.

5.4.1 Embodied energy

While the Dutch Green Building Council has not yet set standards for material-bound energy for renovation, there are standards for the limited values of new construction. NIBE (2023) in collaboration with other companies and the Dutch government, have made a detailed report on the embodied carbon for renovations. This report sets a limit of 100 kg CO_2-equivalent per square meter for renovating single-family and multi-family homes. The material-related CO_2 emissions are calculated using a life cycle assessment (LCA), focusing on the environmental impact of global warming potential (GWP), which accounts for all greenhouse gases expressed in CO_2 equivalents (kg CO_2e).

As mentioned in Chapter 5.1, the environmental payback time for current renovations is about seven years. According to NIBE (2023) Through circular renovation strategies, this can be reduced to two years. The report highlights the importance of biobased and circular approaches to lowering CO_2 emissions. The focus remains on reducing energy use and achieving circular economy targets by 2050.

Figure 22 shows the environmental shadow costs for these common insulation materials. Shadow costs are a more accurate representation of environmental impact than just carbon and consider other harmful and toxic emissions from material production. This research does not specifically choose the best and most sustainable insulation materials, nor does it for other façade components, such as windows, with a high carbon footprint. The goal is to create a flexible and demountable system; the infill of the materials can be changed based on the project and availability of the materials.

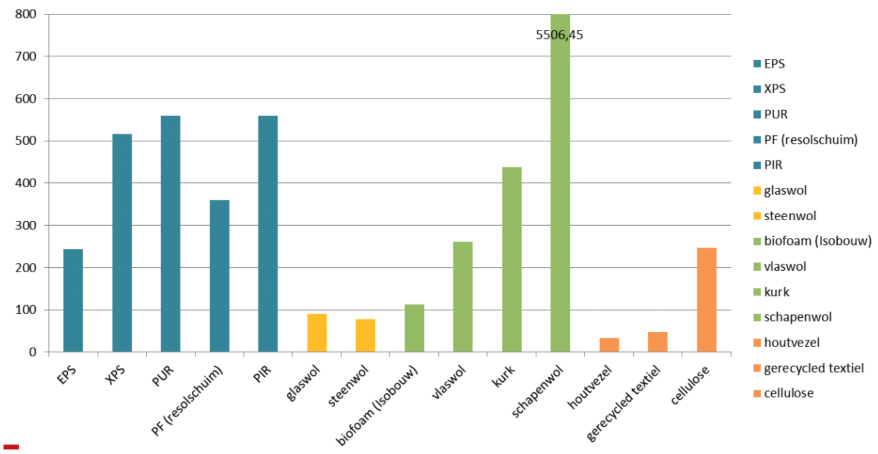


Figure 22 The shadow costs of different insulation materials (Muntinga, 2018)

Glass wool and mineral wool have great environmental performance. This is because they are made mainly from recycled materials and have recyclability potential at the end of their service life (Muntinga, 2018).

Wood fiber, recycled textiles, and bio-foam are also effective materials. Although environmental impact is a key consideration in material selection, other factors can also play a role. For example, the insulation's Rc value can be a problem in certain renovation solutions.

5.4.2 Practical implications and challenges

While circularity is an important part of the future building industry, there are challenges associated with it. Economic challenges: With the current way of design, demolition is often cheaper than disassembly. Moreover, the time required for disassembly must be considered during the design phase to ensure the process is economically viable. The speed and ease of disassembly can directly affect labor costs, making it a crucial factor in determining whether this approach is feasible for construction companies.

Then, there are technical challenges, such as the complexity of disassembly and careful removal of components without damaging others. Disassembly must be carefully managed to ensure materials can be reused without compromising quality. The system's structural integrity is a challenge if there cannot be any glued connections or strong material bonds.

Compatibility is a challenge for renovation; even within the system-built houses, there are many differences, and it could prove challenging to reuse the facades. Assuming the facades have a service life of 50 years or more, it is unknown how much functional service life the building has left, as it is already very old. Weatherproofing can also prove to be a challenge in the context of renovation. With joints that allow for disassembly, maintaining airtightness and waterproofing in the façade is more complex.

5.5 Conclusion

In conclusion, this chapter highlights the benefits and challenges of implementing circular façade renovation systems. While circularity is crucial for reducing CO2 emissions and improving environmental performance, the reuse potential of demountable systems in renovation projects is limited due to the specific dimensions of existing buildings. Therefore, disassembly on a material level is preferred so that the materials that reach their end of life can be recycled.

Furthermore, maintaining waterproofing and airtightness is a challenge, as joints allowing disassembly can complicate the façade's integrity. The economic viability of disassembly is also a concern, as demolition often remains cheaper and faster. While circular renovation strategies can reduce CO_2 payback periods from seven to two years, technical and practical considerations - such as weatherproofing, structural integrity, and compatibility - must be carefully addressed to maximize the potential of these systems. Ultimately, for the connections, there should be a balance between the complexity of the joint and the flexibility.

6 SCALABILITY OF FAÇADE RENOVATION SYSTEMS

Scalability depends on two factors in the renovation sector: adaptability (whether the system can fit any building) and product manufacturing. There should be a balance between mass production and mass customization.

6.1 Defining scalability in construction

Scalability in building construction, particularly in renovation, refers to applying renovation strategies across many buildings with consistent efficiency and quality. In the case of the Dutch housing stock, where large-scale renovation efforts are required to meet sustainability goals (Klimaatakkoord, 2019), scalability becomes a critical factor. For a façade renovation system to be scalable, it must be adaptable to various building types while maintaining standardized solutions that can be implemented across multiple projects with minimal changes required.

One of the critical factors driving scalability is standardization. By designing renovation systems that use standardized components, such as prefabricated façade elements, large-scale implementation becomes more feasible. This enables mass production, which reduces both material and labor costs.

Flexibility within standardization is another essential aspect of scalability. While standardization is critical, renovation solutions must also be flexible enough to address the unique characteristics of different buildings, such as variations in building materials, architectural styles, and thermal performance requirements. Buildings with similar structural and thermal characteristics can be grouped and addressed with similar renovation solutions. This clustering approach enables economies of scale and makes large-scale renovations more economically viable (Mohan, 2022).

6.2 Requirements for a scalable façade renovation system

Specific criteria must be established for standardization to enable large-scale renovations. These criteria help streamline the renovation process, making it feasible to produce building elements in bulk and implement them efficiently. From research conducted as part of the IEBB project (Mohan, 2021), the following criteria have been set to support scalability in renovation projects:

1. **Uniform Characteristics within Clusters:** To facilitate mass production and standardized renovation solutions, the dwellings within each cluster must exhibit similar physical and structural characteristics. Homogeneity within clusters is crucial for effectively applying uniform renovation strategies.
2. **Standardized Renovation Solutions**: The renovation solutions required for each cluster should be as similar as possible. This allows for the standardization of building elements, making it easier to produce, transport, and install prefabricated components at scale.
3. **Economic Viability through Scale**: Renovation projects must be economically viable by establishing a minimum cluster size. Larger clusters allow for economies of scale, reducing costs by enabling mass production and streamlined processes for both materials and labor.

The follow-up research by Mohan (2022) emphasizes the thermal and building characteristics that significantly influence energy use, drawing insights from qualitative interviews with renovation industry experts and data analysis from housing associations. The results from the research show a classification table:

Table 5 Classification characteristics for standardization (Mohan, 2022)

Housing characteristics that govern the design of clustering methods	Number of categories	Categories
Roof shape	3	Pitched roof Flat roof Others
Construction type of roof	2	Wooden roof Other
Construction type of wall	2	Brick masonry Other
Existing insulation level - façade	2	Level 1 Level 2
Existing insulation level - roof	2	Level 1 Level 2
Existing insulation level - windows	2	Level 1 Level 2
Ownership type	3	Housing association Individual homeowner Others
Typology	2	Apartment Row houses & other
Presence of existing cavity	2	Yes cavity No cavity

According to Mohan (2022), the goal was to decrease the number of clusters to create larger samples and scale up the renovation. The table currently shows 110592 different clusters. Mohan has three recommendations that could decrease this cluster size to 48 categories. Innovation of renovation products, the use of common financial models, and optimization of the insulation levels can remove some characteristics of the clustering system.

These criteria are crucial to achieving scalability in renovating the Dutch housing stock. By focusing on standardization and aligning renovation projects with these criteria, the overall efficiency and impact of the renovation process can be significantly enhanced, helping to accelerate the transition to a zero-carbon built environment by 2050.

6.3 Mass production vs mass customization

In the construction industry, mass production and industrialization are taking over. Products and materials are manufactured faster and on a larger scale in factories to decrease costs, speed up production, and minimize error.

In the context of façade renovation, mass production has advantages and challenges. Mass production excels in delivering standardized façade solutions at scale and cost-efficiency. This approach is highly effective when dealing with homogeneous building stocks or large renovation projects. The primary strength of mass production is its ability to rapidly produce and install prefabricated façade elements, significantly reducing renovation time and costs. However, it becomes more challenging with non-uniform buildings, and the approach might need to shift towards mass customization.

Mass customization integrates the flexibility of personalized products with the near efficiency of mass production. Differentiation is pursued through personalizing components and their combination with mass-produced components. Van Groesen (2022) describes customized standardization as the most preferred strategy. This strategy allows the configuration of various products from a limited set of standardized components.

This approach is particularly relevant in façade renovations where variations in building design, material preferences, and performance requirements are standard. A key advantage is the ability to offer a degree of personalization while maintaining cost and time efficiency.

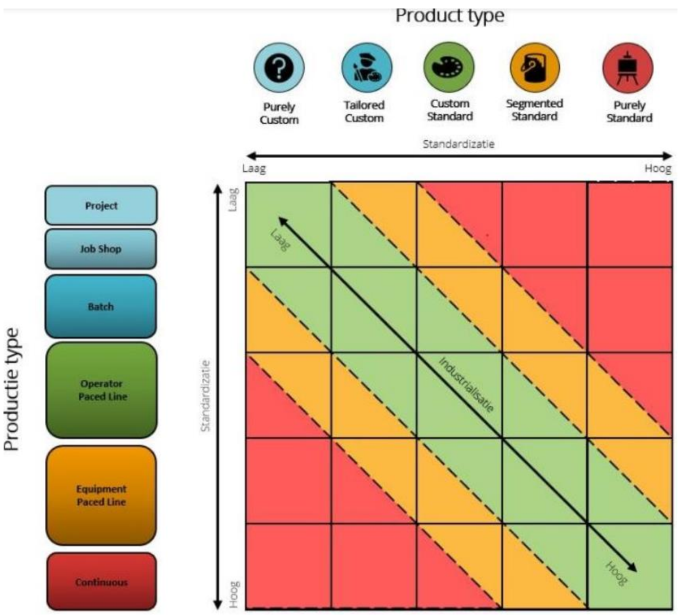


Figure 23 Alignment between the production system and the product type (van Groesen, 2022)

Figure 23 shows "production type" on the Y-axis and "product type" on the X-axis in Van Groesen's research, illustrating the relationship between the degree of product customization and the type of production system. It shows how standardized products best suit highly automated production systems, while highly customized products require more flexible systems. The graph emphasizes the importance of aligning the production system with the product's level of customization to achieve efficiency in mass customization.

Chapter 7 explores the system-built houses. By analyzing the system-built houses and using Van Groesen’s research on mass customization, design criteria can be set for the scalability and mass production of the façade system.

According to van Groesen (2022), the elements that limit the standardization of the production line are often related to the desired renovation solution and the degree of customization required by the client. Specifically, the variability in renovation demands and customization options offered to customers can hinder the full standardization of the production process. This includes offering too many product variations or customization choices, making streamlining production difficult.

Groesen's (2022) research mentions that companies like Weinmann and VolkerWessels are advancing in mass customization. Weinmann uses innovative technologies such as nailing bridges that automate the positioning, fixing, and nailing of components based on CAD files. These nailing bridges can be fed by either operators or robotic arms, reducing manual labor and ensuring accurate nailing of roof elements. Additionally, Weinmann employs an insulation blower machine, which automatically fills cavities with insulation material, further automating the production process. Figure 24 shows an example of this industrialized production line.

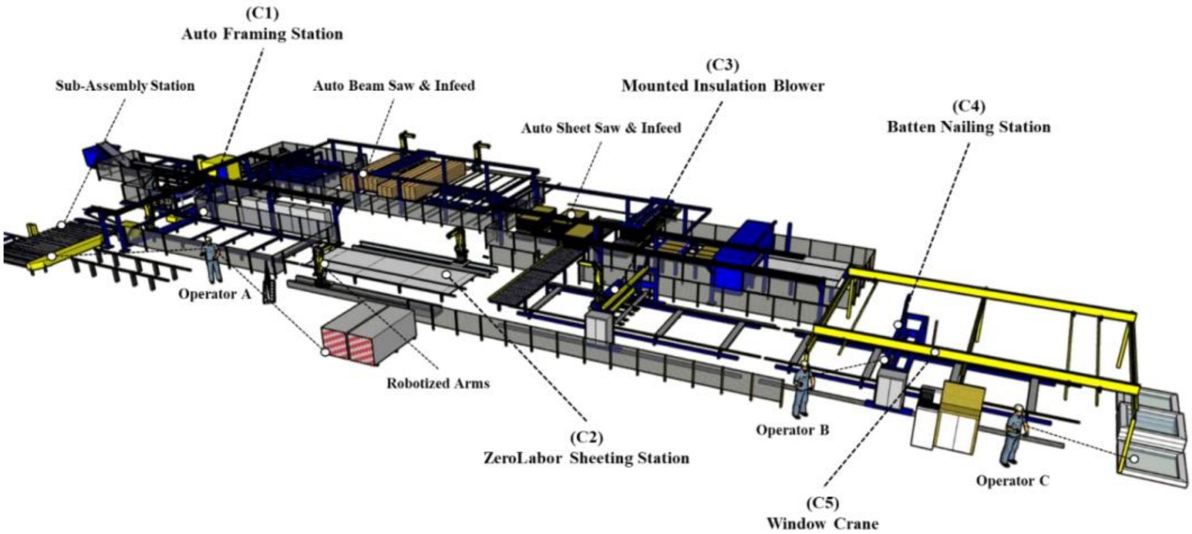


Figure 24 Shows an industrialized production line (van Groesen, 2022a)

6.4 Conclusion

Scalability in façade renovation systems is crucial in addressing the large-scale renovation needs of the Dutch housing stock. Achieving this requires a balance between mass production and customization. Standardization of components enables cost-effective, large-scale renovations while maintaining flexibility to adapt to different building types and renovation needs.

A critical factor in scaling up is creating large-scale demand. Mohan's research highlights the importance of clustering buildings with similar characteristics to enable economies of scale. Reducing the number of clusters streamlines production and allows manufacturers to produce standardized components, driving down costs and increasing efficiency.

Technologies like Weinmann's nailing bridges and insulation blowers further enhance the automation and precision of the renovation process, improving both speed and quality. The renovation industry can be scaled up by aligning production systems with product customization needs and generating large-scale demand.

7 ANALYSIS OF DUTCH SYSTEM-BUILT HOUSES

The analysis of Dutch system-built houses focuses on understanding their characteristics and construction methods to tackle their problems and use their advantages. For this analysis, key sources such as the “Documentatie systeemwoningen 50-75” by Platform31 (2013) and the book “Niet-traditionele woningbouwmethoden in Nederland” by Priemus & Elk (1971) are used. Additionally, reference projects from the Bachelor of Architecture and the Built Environment from TUDelft are reviewed to better understand the details and building styles. This chapter aims to compare and organize the different building systems so that a façade renovation system can be applied.

7.1 Most common building systems

In Chapter 2.4, it was mentioned that Dutch system-built houses hold considerable renovation potential due to their uniform construction methods and durable prefabricated elements. However, not all building systems from this period share the same renovation prospects. While many system-built houses were designed to be efficient and adaptable, particularly those utilizing concrete prefabrication, others are more rigid in design and present significant challenges for modernization.

Some systems, for instance, were built with limited architectural flexibility, making it difficult to implement energy upgrades or reconfigure layouts to meet contemporary living standards. Additionally, other systems face structural issues or material degradation that reduce their suitability for renovation. Although the uniformity of construction supports large-scale interventions in some cases, other systems exhibit complexities that make renovation either economically unviable or technically challenging.

In this chapter, we will explore the various system-built housing types, focusing on their characteristics, strengths, and limitations for renovation. Platform31 (2013) has identified 21 of the most common building systems (shown in Table 6), representing more than half of the system-built houses in the Netherlands.

Table 6 The 21 most common building systems for system-built houses (Platform31, 2013)

	System name	Amount of cases	Construction method
1	Muwi	37.831	stapelbouw
2	RBM	32.292	gietbouw
3	Coignet	31.378	montagebouw
4	BMB (o.a. HeBoMa)	29.369	montagebouw
5	Pronto	17.836	stapelbouw
6	Rottinghuis/IBC	17.000	montagebouw
7	Korrelbeton	15.394	gietbouw
8	VAM	14.000	montagebouw
9	BBB: Bredero eп Bredero '55	13.118	stapelbouw
10	Pege	11.000	stapelbouw
11	Wilma	12.579	gietbouw
12	Smit	10.000	montagebouw
13	Airey	9.975	montagebouw
14	ERA	9.810	gietbouw
15	EBA	19.291	gietbouw
16	Elementum, later PLN	8.574	montagebouw
17	Vaneg	7.000	montagebouw
18	Bakker	5.643	stapelbouw

19	Welschen	5.602	gietbouw
20	B-G	5.581	montagebouw
21	Tramonta	4.845	montagebouw

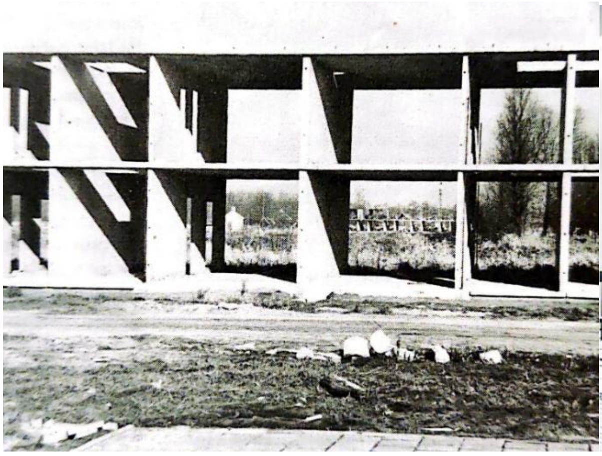
These represent 318 thousand system-built houses in total. Their main construction methods can be categorized into three types: stapelbouw, gietbouw, and montagebouw.

- **Stapelbouw** uses lightweight, hollow concrete blocks stacked to form the building's structure. Once in place, the hollow blocks are filled with concrete to increase rigidity and strength. This method allows for relatively quick construction compared to traditional bricklaying while providing a robust building structure. (image: de Vree (n.d.))

- **Gietbouw** refers to cast-in-place concrete construction, which involves pouring concrete into molds or formwork on-site. After the concrete sets, the following section can be cast, typically on the following day. This method was widely used for its strength and durability, making it a popular choice for more robust structures in system-built housing. (image: de Vree (n.d.))

- **Montagebouw** takes a more industrial approach, involving prefabricated building elements assembled on-site. Though some handwork is still required, this method significantly speeds up the construction process compared to ‘stapelbouw’ and ‘gietbouw’. It was a key innovation during the post-war housing boom, allowing for faster and more standardized construction. (image: de Vree (n.d.))

All of these construction methods use concrete. The advantage of this from a renovation perspective is the long life span of the material. Starting in the post-war period after 1945, concrete was used to construct most new residential buildings. Even though three different construction methods were used across the system-built houses, there was much uniformity between the construction frames. Figure 25 shows an image of the Breda system, and Figure 26 shows the Vaneg system. Breda uses the 'Gietbouw' method, while Vaneg uses the 'Montagebouw' method. However, the construction is almost the same, and both use a box-frame method (primarily used in the Netherlands). This means that the load-bearing walls of the building are the inside walls, which leaves the façade not as a part of the building's main construction. This allows for flexible changes to the façade during the renovation process. Even though the box-frame method does not allow the most flexibility in the plan changes, it allows for flexibility in the façade changes.



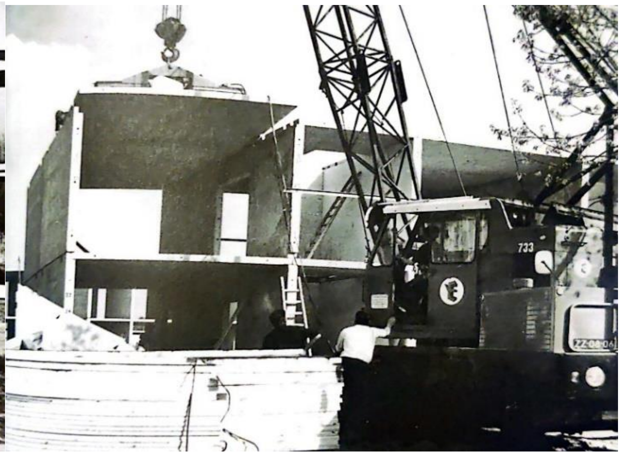


Figure 25 Left: Construction frame of the Breda system (foto: archief Bouwmij, Priemus & Elk (1971)**)**

Figure 26 Right: Construction frame of the Vaneg system (foto: archief van Egteren, Priemus & Elk (1971)**)**

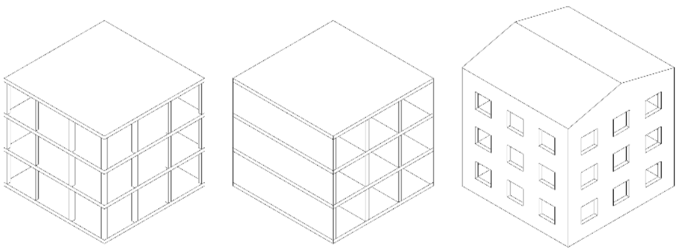


Figure 27 Different construction frames from left to right: skeletal, box-frame and loadbearing façade, modified from (Konstantinou, 2014)

The following sub-chapters explore the most common system for each construction method. The reason why BMB substitutes Coignet is that many of the Coignet buildings have been demolished over the years.

7.1.1 Muwi

The most common system from the post-war period is the Muwi system. There has already been some research into the renovation potential of this system by BouwhulpGroep (2016).

According to the report by BouwhulpGroep (2016), the Muwi system's flexibility and ability to quickly adapt to technical developments were key reasons for its widespread adoption. The system utilized the *Stapelbouw* method for the wall construction, and floors were constructed using pre-stressed concrete beams with infill blocks (shown in the figure 28).

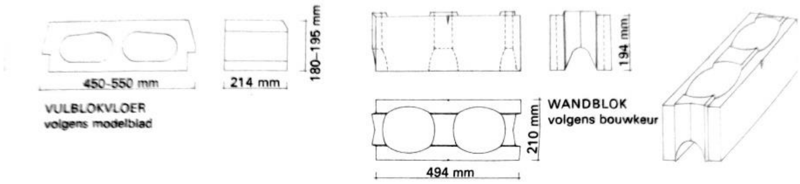


Figure 28 Concrete blocks used for load-bearing walls and floors (Priemus & Elk, 1971)

When evaluating the renovation potential of Muwi system-built houses, not all buildings constructed with this method are equally suitable. Earlier generations of Muwi homes used poured concrete for the balconies, which made them part of the structure. Later generations saw improvements, such as introducing cavity walls and separating balconies from the main structure. The system also implemented some prefabricated methods for the cavity walls.

Despite these challenges, the report (2016) highlights that most Muwi houses have significant renovation potential. Many of these homes have had some maintenance or renovation, and some renovations are not entirely documented, which caused unknown changes in the building details. The plan of the buildings is quite flexible, as most internal walls are non-load-bearing, allowing for functional changes. Additionally, the construction was primarily internal, which meant that the Muwi system allowed for more accessible façade renovations, making it possible to upgrade the building's energy performance by changing the façade.

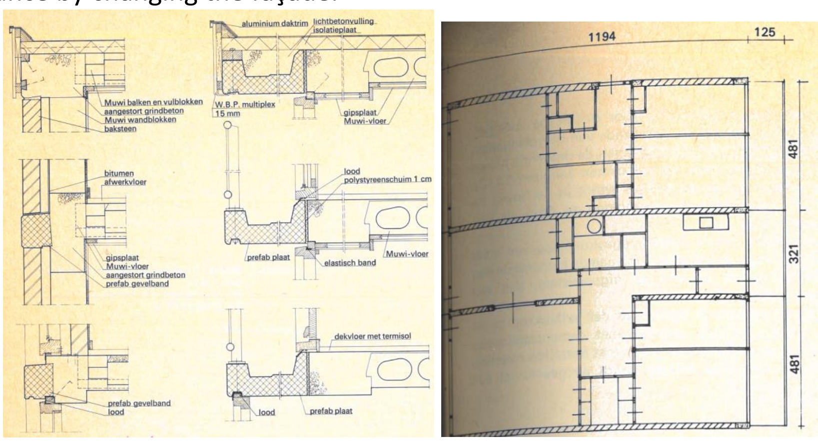


Figure 29 Facade section and plan of the Muwi system (Priemus & Elk, 1971)

7.1.2 R.B.M. (Rijnlandsche Betonbouw Maatschappij)

The R.B.M. system is a system that used both *Stapelbouw* and *Gietbouw* for its construction. According to (Platform31, 2013) it can be said that it is not a system but a way of building. It can be divided into two different categories: RBM-I and RBM-II.

RBM-I:

This version is a combination of *Stapelbouw* and *Gietbouw.* The first buildings were constructed mainly through the *Stapelbouw* method, but because of economic reasons, it failed. It was then switched to mostly *Gietbouw*. The structural and house dividing walls and floors were poured concrete. The façade was made as a standard brick cavity wall, and because there were no constraints with the façade measurements, there was much variability between the system. Moreover, the system could be applied to row houses, *portiekflats*, and *gallerijflats*, being the reason for many differences within the system.

RBM-II:

After 1965, the company switched to a complete *Gietbouw* system. Cranes and materials were much more readily available, making this other construction method possible. The system allowed for the efficient construction of high-rise buildings. The balconies and galleries were made of prefabricated concrete, which again allowed for the removal of the balconies during a renovation (Priemus & Elk, 1971).

According to the research by Platform31 (2013) it is difficult to assess the system's renovation potential as there is so much variability within it. As the galleries were supported on consoles, insulating the external walls of the buildings could prove quite challenging because thermal bridging could occur through the consoles (balcony/gallery support integrated with the load-bearing wall).

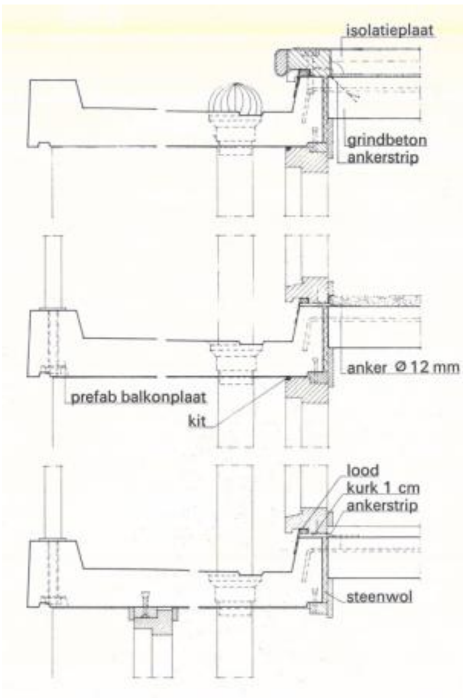


Figure 30 Facade section of the RBM system (Priemus & Elk, 1971)

7.1.3 B.M.B. (Baksteen Montage Bouw)

The BMB system used *Montagebouw* as its primary construction method. The concrete load-bearing walls were made in factories and consisted of half-story or full-story high prefab walls. The floors and even the masonry façade walls were made in a prefab manner. Due to this complete prefab construction, the system saved over 65-70% of man labor on the construction site (Platform31, 2013).

The system can also be divided into two sub-systems:
BMB-I, which used smaller prefab walls due to limited mold sizes, uses half-story prefab walls stacked on top of each other. The BMB-II used complete story high load-bearing walls from 2.7m high and 4.5m wide (Priemus & Elk, 1971). The system also used traditional prefab masonry cavity walls, which had been prefabricated in a factory. Due to the high prefabrication rate and similar mold sizes, the system is relatively uniform, allowing for the potential for large-scale renovation. The system also had a minimal target size for the number of houses, ranging between 200 and 2000 units, to make the investment viable (Priemus & Elk, 1971). The plans are also spacious and allow for various renovation strategies.

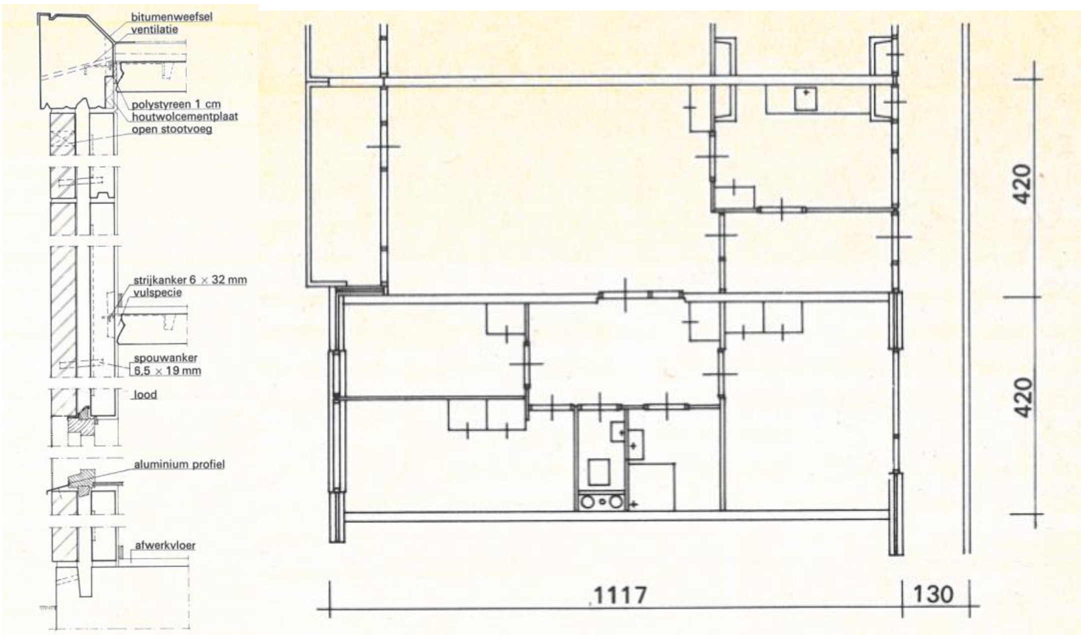


Figure 31 Facade section and plan for the BMB system (Priemus & Elk, 1971)

7.2 Similarities and differences between the different systems

When dividing the building system into just the façade types, there can be a main division between the 'Kopgevel' and 'Langsgevel'. There can also be a division between the building types: 'Rijtjeswoning, Portiekwoning and Gallerijwoning'. While these building types can have the same construction system, the connections and details can still differ because of the different typologies. There were only a few building systems that focused on one building type. The building system was just a system and could be used to create different building types, the image below illustrates the main building typologies per method. Next to residential buildings, some of the systems were also used for non-residential buildings with other functions.

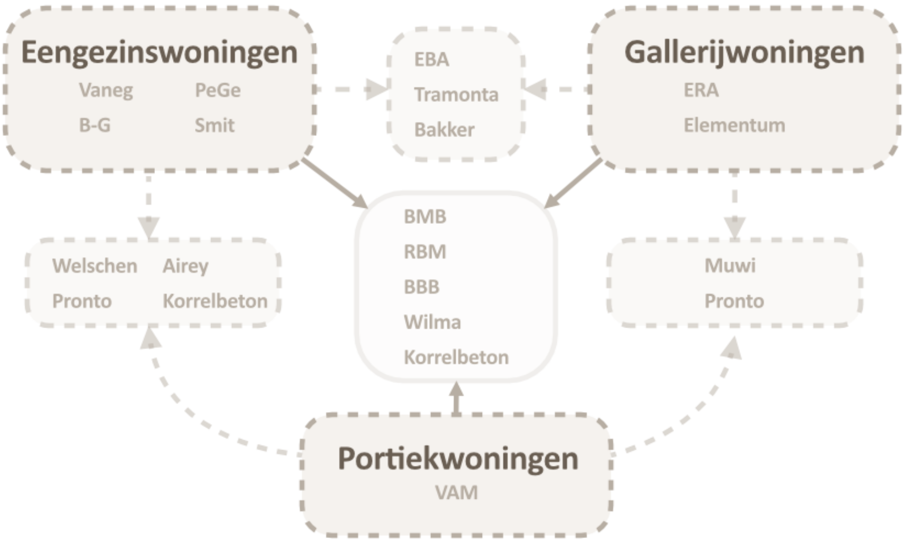


Figure 32 Division of building typology per construction system (own work)

There is a relation between the construction method and the building height or in this case the number of floors which is shown in Figure 33. For each of the construction methods, there are peaks at two, six, and ten floors. This is likely because most of the single-family homes or row houses had just two floors, which makes sense as this was a very common building type from that period. The peaks at six and above represent the *Portiek-* and *Gallerijwoningen*, the stapelbouw method did not support many buildings above seven floors. The number of floors will also be an important variable for the renovation solution.

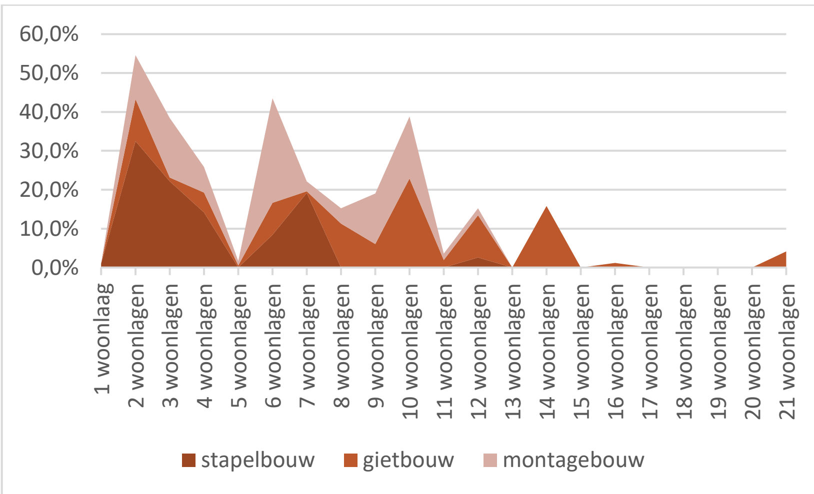


Figure 33 Relation of building n of floor to construction method (modified from (Priemus & Elk, 1971))

The research from Priemus & Elk (1971) has also reviewed the most common plan layouts for the system-built houses. Plans are very relevant for the renovation strategy, but because this research focuses on the façade, this will be less influenced. It is interesting to see the most common plans for each building type: eengezins-, portiek-, and gallerijwoning. Figure 34 shows the most common plans for *portiekwoningen*. Plans E3 and E5 represent more than half of the post-war *portiekwoningen*. When comparing this with the cases from the Architecture course from TUDelft, three of the seven projects have the E3 plan configuration (Appendix A). However, although over 20 different plan configurations were given, one of the seven projects could not be combined with a common plan layout. This indicates that there is less uniformity in the system-built houses than expected.

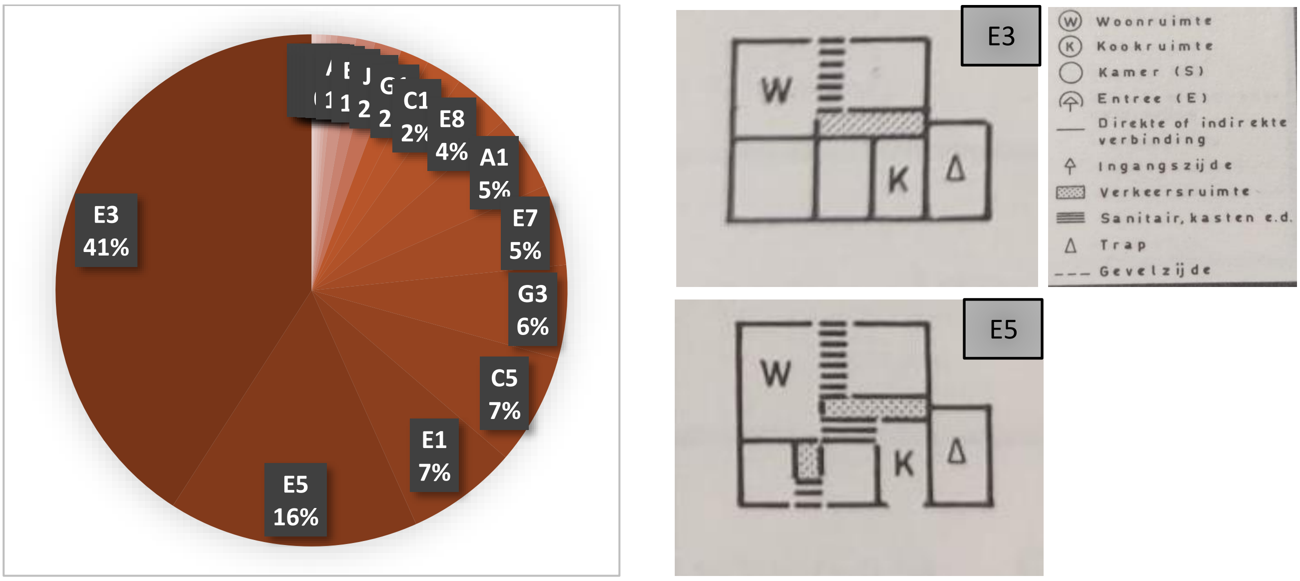


Figure 34 Common plans for *portiekwoningen* (modified from (Priemus & Elk, 1971))

Figure 35 shows the most common plans for *gallerijwoningen*. Plans E1, C7, and C1 represent almost ¾ of the used plans in the system-built *gallerijwoningen*. These common plan layouts could be used to create a standardized renovation approach for the internal renovation of these buildings.

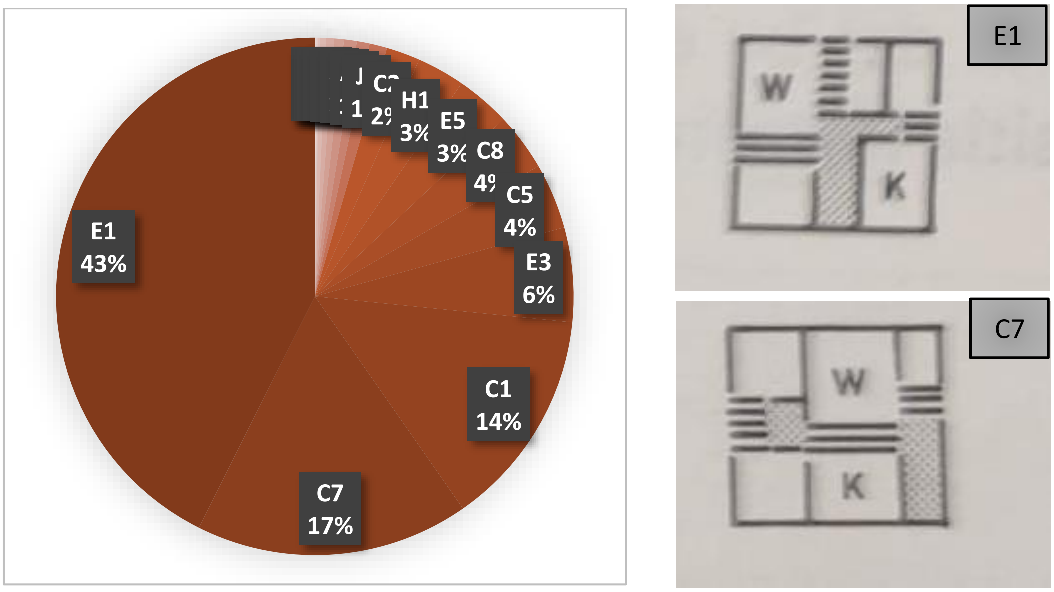


Figure 35 Common plans for *gallerijwoningen* (modified from (Priemus & Elk, 1971))

For the façade renovation of these buildings, the measurements are significant, particularly concerning production. The determination of minimum and maximum panel sizes for the facade is necessary for the required panel dimensions, which is useful to the manufacturer. Priemus & Elk (1971) has made an overview of the ´traveematen' for the multi-family homes, which are the measurements between the loadbearing columns.

Table 7 Traveematen voor meergezinswoningen

maat (cm)	stapelbouw	gietbouw	montagebouw	total
270	854	673	2015	3542
270- 299	641	5409	228	6278
300- 329	1938	3174	7891	13003
330- 359	624	0	1015	1639
360- 389	1307	6328	7337	14972
390- 419	3289	6200	3804	13293
420- 449	204	8270	6901	15375
450- 479	1536	1188	7901	10625
480- 509	318	2912	2195	5425
510- 539	0	282	0	282
540- 569	0	0	0	0
570- 599	0	0	0	0
> 600	8	4080	0	4088

From Table 7 the conclusion can be drawn that most measurements were not larger than five meters. The most common range for the measurements is between 360 cm and 480 cm. This data can be analyzed in more detail in order to have a great overview of the measurements within the façade. These standard measurements could stimulate a more industrialized approach to the renovation of these buildings.

7.3 Classification of Dutch system-built houses

It is difficult to classify Dutch system-built houses, not just because of the variations within a single system, but also due to the differences between the building characteristics. This variety in building characteristics makes it challenging to classify them using a more general approach. For example, a single building system can be used for the construction of two or three different building types, this means that within a single system, there can be multiple façade combinations, balconies or galleries, and different attachment methods for the elements. Figure 36 shows the *kopgevel* and *langsgevel* of the E.B.A. system, both have a different façade, which would require a different approach.

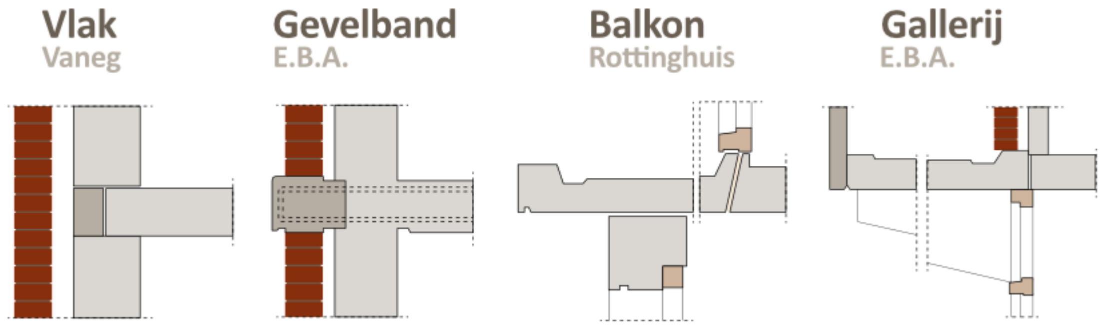


Figure 36 Different facade implications illustrated with the *systeemwoningen* (own work)

Figure 37 displays the possible combinations of a balcony or gallery and the construction on top. These have been divided into four different classes which would require a different approach. The concrete cast balconies are less common as they were difficult to cast perfectly, the industry quickly moved to prefabricated balconies and galleries. The difference between prefab consoles and cast-in-place consoles is that cast-in-place consoles are difficult to remove and could be a problem for cold bridges.

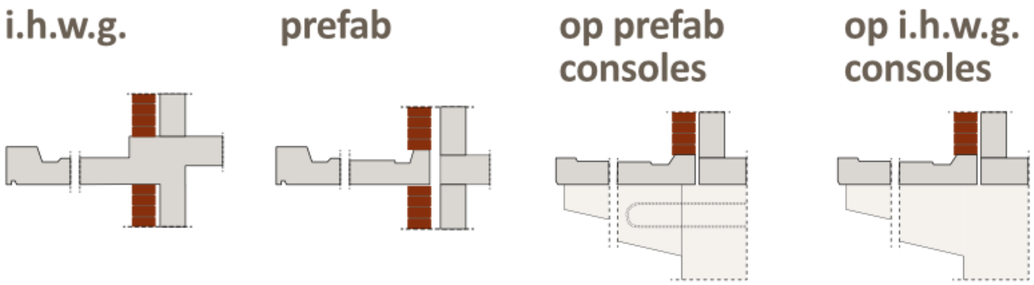


Figure 37 Different connections for balconies and galleries for the *systeemwoningen* (own work)

Figure 38 shows a classification of the different façade combinations available for the system-built houses based on façade type. It is difficult to classify the systems into specific façade combinations, however some are more common than others. The traditional cavity wall is especially common, mainly for the *kopgevels*, but also used in the *penanten* and *borstweringen* in the *langsgevel*. A few systems stand out: Coignet, Airey, Wilma and VAM. These systems use concrete panels for the outside façade. Airey uses a different construction than the other systems based on concrete pillars, this system could require a different approach.

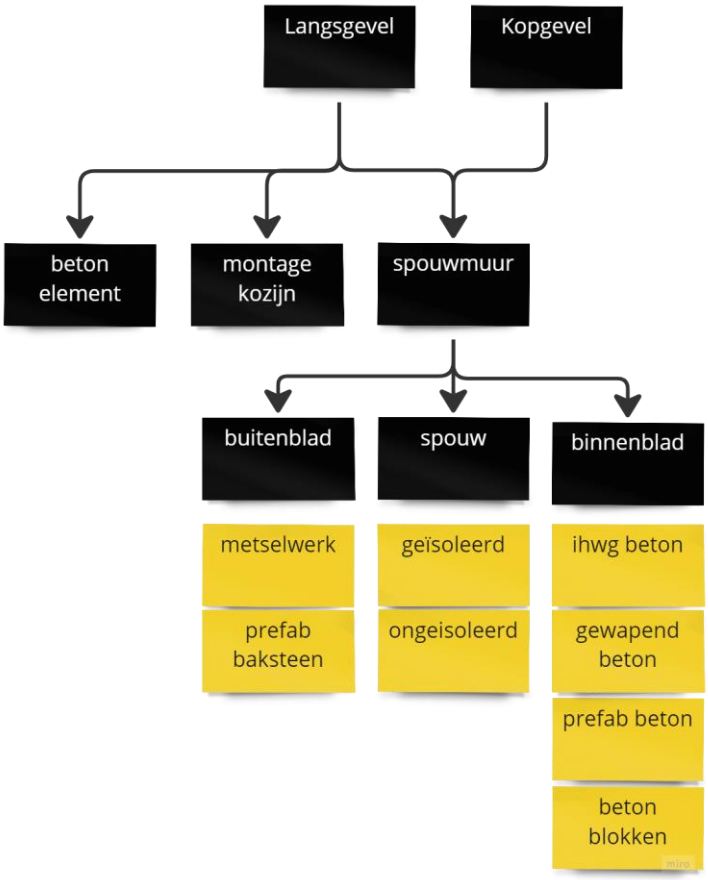


Figure 38 Facade combinations for the 21 different *systeemwoningen* (own work)

7.4 Conclusion

The analysis reveals that while system-built houses may share construction methodologies, their specific typologies (such as *rijtjeswoningen, portiekwoningen*, and *galerijwoningen*) exhibit variations in details and connections, significantly influencing renovation strategies. The text also underlines the impact of *traveematen* on façade renovation, noting that standardizing these measurements could facilitate an industrialized renovation process.

Moreover, the number of floors emerges as a crucial factor in determining renovation solutions. Different building heights, with notable peaks at two, six, and ten floors, affect both structural and functional renovation requirements. Within the same building system, façade types (*kopgevels* and *langsgevels*) differ, further complicating the classification and the approach to renovation. Additionally, balconies and galleries present unique challenges, particularly when dealing with cast-in-place elements that may introduce thermal bridges that are challenging to remove.

8 DESIGN CRITERIA

The design criteria for this research project focus on balancing energy efficiency, scalability, comfort, and circularity to ensure practical and sustainable solutions. This chapter explores the key aspects that must be addressed to achieve successful renovations. Each section provides a detailed look at the essential factors driving renovation strategies.

8.1 Energy

This project will focus on achieving the target Rc-value of 4.7 m²K/W, the current standard for new buildings. This standard is attainable with careful design and material choices. An advantage in this case is that the renovation mainly focuses on exterior insulation. This allows for fewer space constraints inside the building, making applying insulation easier without reducing interior space. Additionally, as most system-built houses are not considered monumental, there are fewer restrictions on preserving historical elements, allowing for more flexibility in the design and materials used.

A key design challenge lies in the high percentage of glass present in many system-built houses. Large windows can significantly reduce the overall façade Rc-value, as glass typically has a much lower thermal resistance than insulated walls. While reducing the window-to-wall ratio could improve energy performance, this may affect the aesthetics and functionality of the building. High-performance glazing, such as triple glazing, can mitigate heat loss, but it is expensive and heavy. Therefore, careful consideration must be given to the balance between improving thermal performance and maintaining the architectural integrity of the façade.

Proper ventilation is required to maintain air quality and ensure the health and comfort of occupants. According to the NTA 8800 and the *Besluit Leefomgeving Bouwwerken* (2024), ventilation requirements are based on the room's size and the number of people occupying it.

The area-based ventilation requirement specifies that living spaces should have a ventilation rate of 0.7 liters per second per square meter (l/s·m²) of floor area. This ensures that larger rooms receive sufficient airflow to maintain air quality. For most spaces, the minimum required air flow rate is 25 m³/h to ensure basic ventilation is always provided, even in smaller rooms.

In addition to area-based criteria, the person-based ventilation requirement adds another layer to the standard. It dictates that rooms should provide 25 m³/h per person, ensuring that spaces with more occupants maintain appropriate levels of air exchange, particularly to manage CO_2 levels.

In Chapter 3.5, comfortable indoor temperatures for residential buildings are discussed. The design criteria for indoor temperatures are based on the adaptive comfort model, which allows for flexibility in indoor temperatures depending on outside conditions. This approach minimizes energy consumption by minimizing the temperature difference between outdoor and indoor environments. The minimum acceptable indoor temperature in winter is set at 20°C to ensure adequate warmth. During summer, it should not exceed 25°C to prevent overheating. This temperature range should allow for comfortable temperatures throughout the year.

Another criterion explored in Chapter 3.3 is the Paris Proof standard, being a maximum operational energy of 35 kWh/m2 for ground-bound houses and 45 kWh/m2 for apartments. This will be used as a guideline for the energy simulation as the maximum operational energy after the renovation. The reason why it will be used as a guideline is because it is difficult to find the distinct difference between operational energy and energy lost through the façade. Furthermore, the Paris Proof standard accounts for total renovation, including heat pumps, solar panels, and other building services.

8.2 Cost-effectiveness

Cost-effectiveness in energy renovations can be defined as the comparison between an investment's costs and benefits. The goal is to select projects that offer the highest energy savings and additional benefits for each euro invested, aligning with the broader principles of economy, efficiency, and effectiveness (European Court of Auditors, 2020). To quantify cost-effective energy savings, accurate simulations and monitoring of actual energy savings post-renovation are needed. The easiest way to quantify this is through economic payback time, which is the time it takes for the energy costs saved post-renovation and the investment costs of the renovation.

Cost-effectiveness is important for designing a façade renovation as it defines the economic viability of the research project. However, due to its complexity and the difficulty of figuring out material, labor, and other costs, it will not be assessed in this research. Considerations will be made on material usage and its advantages and disadvantages in terms of costs, sustainability, and potential for disassembly. Furthermore, the goal is to decrease the costs of the total renovation. According to RVO (2023) a plan-based approach can decrease renovation costs by around 15% compared to a project-based approach.

There are also other possibilities for decreasing renovation costs in such projects. As mentioned in Chapter 2.4, the construction of system-built houses is often very rigid. In some projects, there is the potential for topping up the building with an extra floor; this added value can cover part of the costs. Another reason for targeting these buildings is their poor energy performance. The buildings that perform worst can have the best increase in performance. The energy saved will increase in comparison to the initial investment, increasing the project's cost-effectiveness.

8.3 Circularity

To ensure that specific materials or components reach the end of their functional lifespan, they should be efficiently disassembled for recycling or reuse, thereby extending the façade system's overall lifecycle. Reversible joints and connections can facilitate straightforward disassembly while preserving the integrity of other components. Design for Disassembly by Durmisevic (2005) is an important supporting tool to consider the flexibility of the joints and connection used. It will be used to assess whether the system has enough disassembly potential.

Material selection plays a pivotal role in achieving circularity goals. Priority should be given to recyclable or biodegradable materials to ensure that components can be processed with minimal environmental impact at the end of their functional life. This can drastically improve the environmental payback time of the renovation.

8.4 Scalability

In the context of façade renovation, ensuring scalability necessitates a design approach that balances standardization with flexibility to accommodate diverse building characteristics. An essential aspect of scalability is the system's adaptability to structural variations, including wall types and roof configurations. An effective façade system should seamlessly integrate with existing structures constructed from brick masonry or other materials. Manufacturers can significantly reduce installation complexity and time by developing components that can be applied to multiple structural conditions with minimal modifications.

Mohan's research underlines the importance of clustering buildings with similar physical attributes. By standardizing solutions for groups of buildings that share comparable roof shapes, insulation levels, and construction types, the façade system can be implemented on a large scale with fewer variations. This clustering approach enhances scalability and facilitates economies of scale in production and logistics, ultimately improving cost-effectiveness.

Furthermore, the design process should incorporate considerations for future technological advancements and changing environmental regulations. This ensures that the façade system remains relevant and adaptable, contributing to its long-term scalability and sustainability.

9 DESIGN

With the design criteria in place, this chapter will discuss the recommendations for a concept design. This will be done with the help of a 3D model and a steady-state energy demand calculation with an Excel sheet that includes an hourly energy balance for a full year including transmission, ventilation, infiltration, solar radiation, and internal heat sources. This model is used in education at TU Delft.

9.1 Layer composition

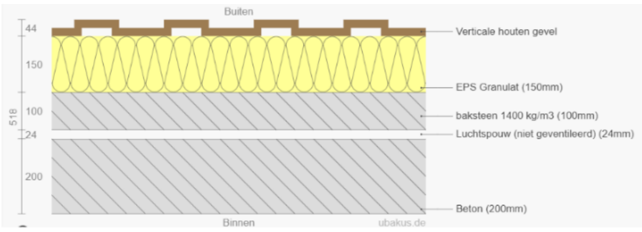
In the build-up of the layers, it is important to keep in mind the moisture and temperature transport in the façade. As described in chapter 4.4 the layers should be built with moisture transport in mind. Building with low mu value from the inside to the outside can prevent condensation and allow the building materials to dry. Ubakus (www.ubakus.de/u-wert-rechner) has been used to analyze the traditional cavity wall and what different materials would mean for the Rc-value and moisture problems. The walls are built up from bottom to top because Ubakus makes a **horizontal section**.

The first two images compare the influence of a different material for the inside loadbearing wall as this varies for the system-built houses. The difference is between lightweight concrete and regular concrete. The only change is in Rc-value and there are no moisture problems with external insulation.

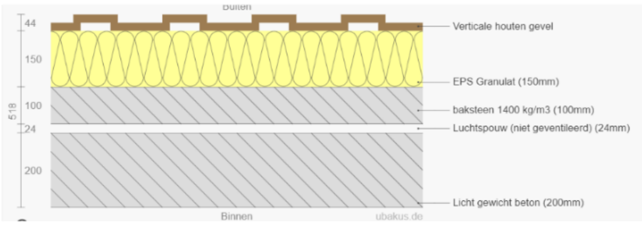
The third and fourth images test the difference in insulation material. For wood fiber insulation a much thicker layer is required to meet the criteria, compared to EPS or mineral wool.

The last image shows the use of a different cladding, the tests above use a vertical wooden façade with low permeability, which allows moisture to get out of the insulation. The bottom image uses a slating with low permeability, which causes moisture to build up within the insulation material. This can be prevented by the use of an water vapor retention layer on the inside.

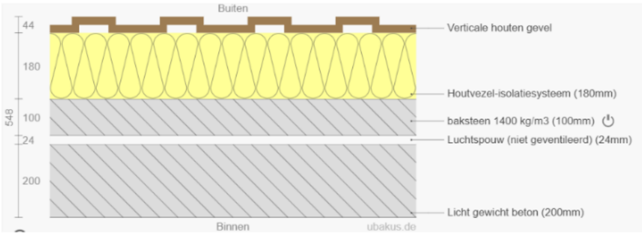
Rc = 4,91



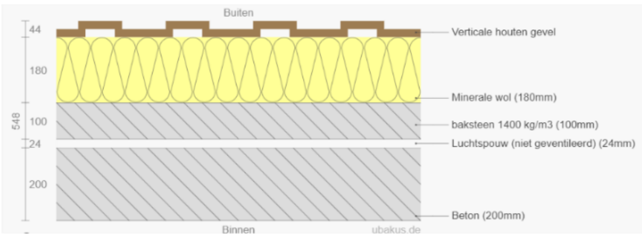
Rc = 4,96



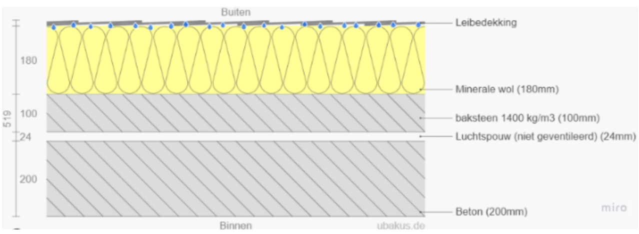
Rc = 4,17



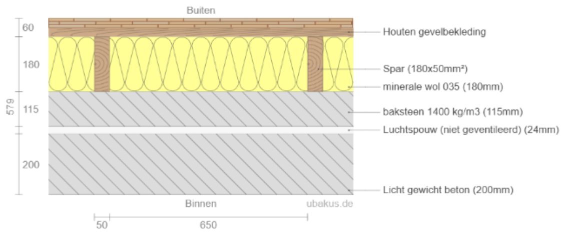
Rc = 5,12

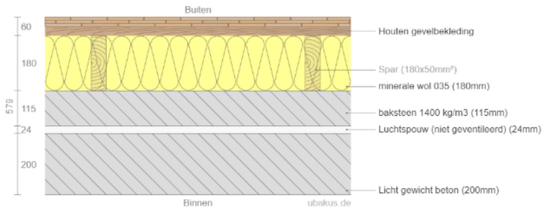


Rc = 4,97



A similar thickness in different insulation materials does have different Rc-values. In this case, for most materials, 180mm is enough to reach the required Rc of 4.7 m2K/W. When using a wooden frame this needs to be taken into account in the insulation value. The layer composition with a wooden frame has an Rc of 4.9 m2K/W and without 5.4 m2K/W. This accounts for a 0.5 m2K/W difference which is quite significant and needs to be accounted for when choosing the insulation material.





For the basic layer buildup, the recommendation would be to use a vapor-proof layer between old construction and insulation, although this might not even be necessary if materials are used that are vapor-permeable and water-resistant. The company Baumit (https://baumit.co.uk/guide/external-wall-insulation/ewi-baumit-opensystem) uses this concept in their open external façade insulation. The materials used are highly water- and vapor-resistant and breathable. The insulation material is a highly breathable expanded polystyrene. While it is an interesting solution, this system does not allow for flexibility in layer build-up or material choice and uses chemical connections between the layers.

In the Netherlands, brick remains a popular choice for renovations, especially when it comes to post-war and heritage buildings. This preference is to maintain the traditional look that is characteristic of Dutch architecture.

Vandersanden has introduced brick strips as a resource-efficient alternative to full bricks (shown in Figure 39 left). These strips offer the same visual appeal as traditional brickwork but use considerably less material. However, Vandersanden's strips are typically applied with mortar, which does not align with Durmisevic's principles of Design for Disassembly.

The Mechslip system by Ash & Lacy offers a more flexible approach and an interesting solution (shown in Figure 39 right). This system uses mechanical fixings to secure real brick slips, eliminating the need for mortar. As a result, the façade can be easily dismantled. This demountability allows the bricks to be reused or recycled after the building's lifespan. Additionally, the bricks have an extruded shape, which means that they could be produced through extrusion—a method that has higher efficiency than molding the bricks.

Figure 39 Vandersanden brick slip system (left) Mechslip system (right)

For the layer buildup, several options are already available on the market:

Frame:
A wooden frame can be used for the structure of the system because there are production methods available that can mass-produce wooden frames such as the auto-framing station from Weinnman.

Insulation:
As mentioned before, there are lots of materials available and with a frame in place, there are no requirements for rigidity of the material. Due to the insulation being inside the frame, it might be required to add an extra layer of rigid insulation in front of the frame.

Frame closing:
OSB (Oriented Strand Board) panels can be used for the enclosure of the frame.

Cladding:
The cladding can be any material. The main thing to consider is that it is vapor-permeable and water-resistant. There is even the possibility of introducing a cavity with a metal frame on which brick strips or other façade material can be mounted.

9.2 Concept

The challenging parts of the connections are the galleries and balconies that complicate the application of a certain renovation strategy. Figure 40 shows that the galleries show quite some complications, they would either have to be removed or the construction would have to be mounted against the gallery. The curtain wall on the left is a more common solution for this building type, then the second illustration shows a new façade against the gallery, and the third illustration shows the renovation system against the façade. The challenge with the last one is that the galleries would have to be removed and the *consoles* on which the galleries stand would have to be either removed if possible or could cause cold bridging problems.

For *portiekwoningen* the balconies are often placed inwards, with the façade falling back. The easiest solution is to insulate around the balcony increasing indoor space, however, this will remove the availability of outdoor space. According to the Dutch building decree (2024), there are no direct articles on the preservation of outdoor space during a renovation but article 4.1 ensures that renovation should not degrade any comfort standards of the building, including private outdoor space.

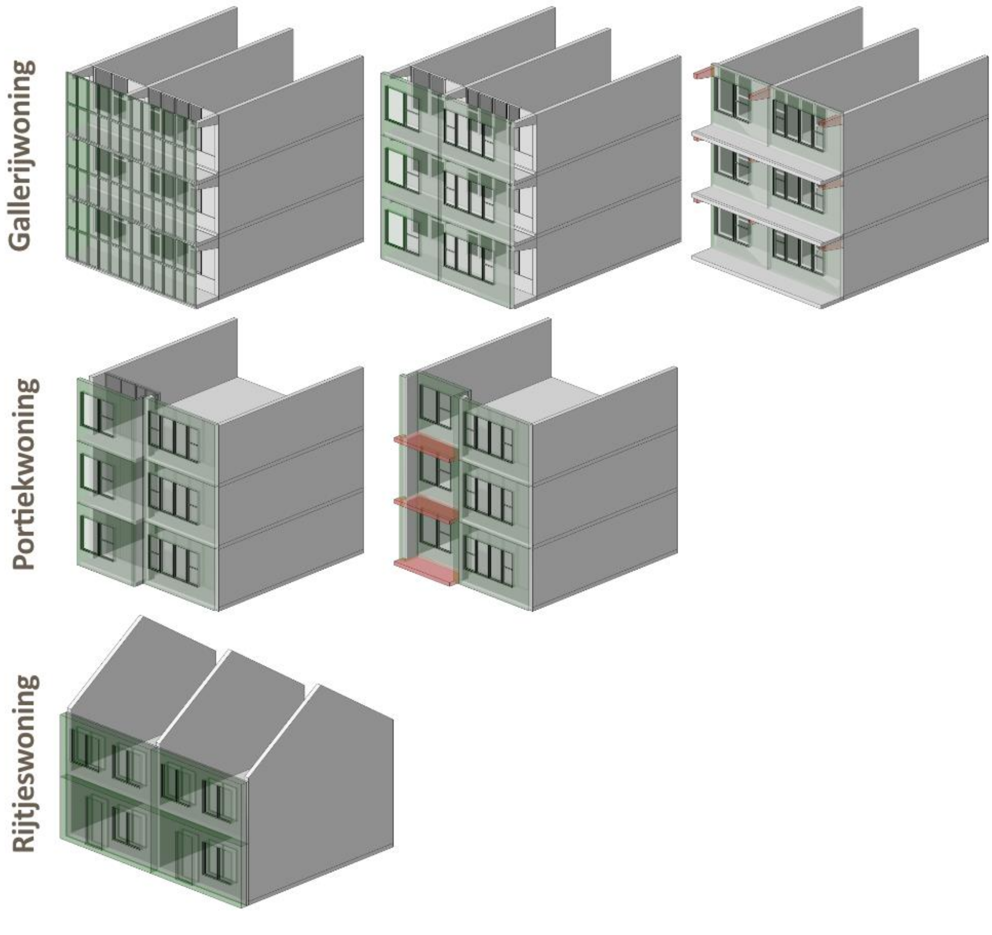


Figure 40 Possible design solutions depending on the building type (own work)

Figure 41 shows a 3D model of a more detailed design solution. The system would be divided into straight panels and two corner panels (inside and outside corners). These could be produced separately from the straight panels. The system would be mounted on a metal frame.

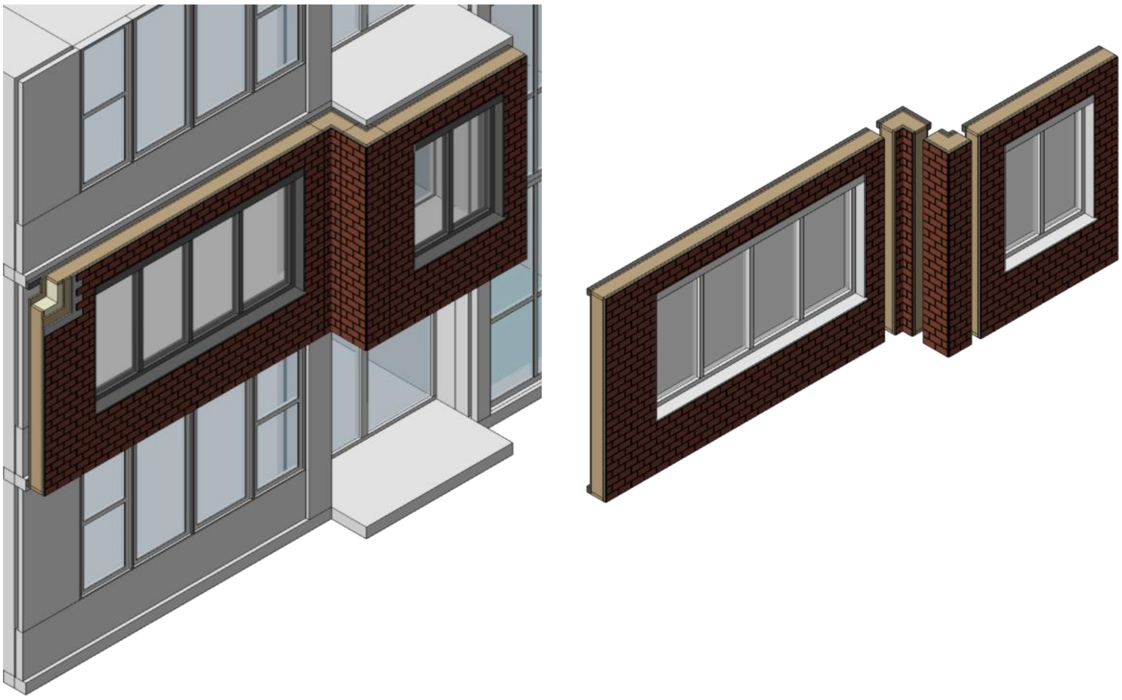


Figure 41 3D model of a possible design solution for *portiekwoning* (own work)

9.3 Window frame

For the windows, the following information provided by Martin Tenpierik is used in the calculation. For the U-value of the windows 1.4 W/m2K is recommended, assuming HR++ glass with a 1.2 W/m2K value with the 0.2 W/m2K extra being accounted for the connection and window frame. The g-value for the glass will be set at 0.65 and the g-value for the blinds will be set to 0.15. The threshold for the activation of the solar blinds will be set to a solar radiation of 150 W/m2. Figure 42 shows a visualization of the window frame for the design.

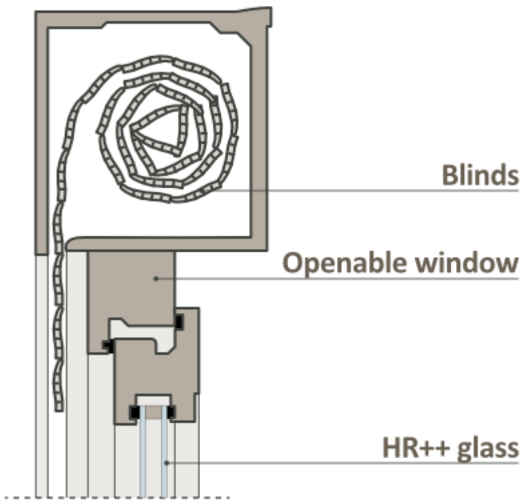


Figure 42 Visualization of window frame with external blinds (own work)

9.4 Steady state calculation

For the steady-state calculation, the following building has been chosen: Tingieterpad residential complex in Delft by Arch. A. Verschoor & Teun Bier. An in-between apartment has been chosen with only surface area for energy loss on the front and the back. A 3D model has been constructed (Figure 43) from which the surfaces for the input of the simulation have been extracted. According to the drawings the buildings are oriented in multiple ways; South-North and East-West. For the input of the calculations, both orientations will be tested. Appendix D shows the input sheet for the calculation.

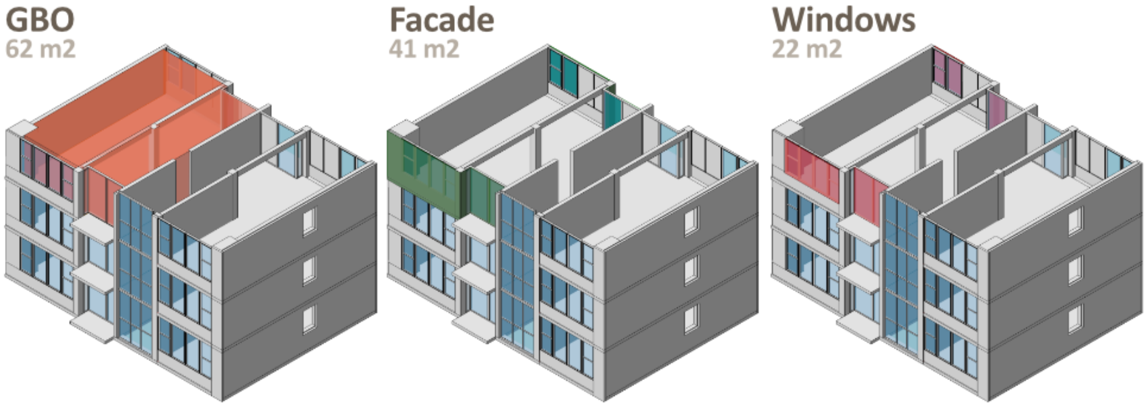


Figure 43 Model of the calculated apartment (own work)

Table 8 shows the results for the North-South orientation and Table 9 the results for the East-West orientation. Although there would be an expected increase in cooling demand for Nort-South, the differences are negligible. Assuming Paris Proof for an apartment, the operational energy should be 45 kWh/m2. The calculation just uses the input of the envelope changes, no systems are added or changed. This shows that just hot water energy demand is already higher than the requirements. The addition of a heat pump with high COP and solar panels would be required to account for these energy costs.

Table 8 Yearly operational energy demand for North-South orientation

	Total		/m2
Year space heating energy demand	2254	kWh	37,6
Year space cooling energy demand	780	kWh	13,0
Year hot water energy demand	5094	kWh	84,9
Year electricity demand	1094	kWh	18,2

Table 9 Yearly operational energy demand for East-West orientation

	Total		/m2
Year space heating energy demand	2293	kWh	38,2
Year space cooling energy demand	733	kWh	12,2
Year hot water energy demand	5094	kWh	84,9
Year electricity demand	1085	kWh	18,2

Initially, the input for the indoor temperature of the calculation was 25 degrees Celsius. This showed results of around 13 kWh/m2 for the yearly cooling demand. Assuming the adaptive comfort model together with the use of natural ventilation this could be neglected from the energy demand because it is such a small contribution. However, if the calculation is for the top-floor apartment, overheating could be something that needs to be considered.

9.5 Conclusion

This chapter examined various design options for a scalable and circular façade renovation system. While time constraints prevented the development of a full concept design, the analysis reveals that many existing market products align well with Design for Disassembly principles. Systems like Mechslip offer flexible, demountable solutions for cladding, while Baumit's open façade system, addresses moisture concerns.

Mass-production methods for insulation, OSB panels, and wooden frames, exemplified by Weinmann's auto-framing station, provide a solid foundation for a modular approach adaptable to various building typologies. These existing solutions offer a promising starting point for developing a renovation system that balances scalability and circularity. Future work should focus on refining these concepts to create an adaptable façade renovation solution.

10 CONCLUSION AND FUTURE RESEARCH

This chapter provides the conclusion, future research, limitations, and the reflection of this paper.

10.1 Conclusion

This research set out to answer the central question: "How can a scalable and circular façade renovation system be designed for Dutch system-built houses from the post-war period?" Through an extensive literature review, analysis of the system-built houses, and exploration of design criteria, several insights have emerged that address both the main research question and the supporting questions.

The study of the Dutch building stock distribution revealed that post-war system-built houses, particularly those constructed between 1945 and 1975, represent a significant portion of the current housing inventory. These dwellings, designed for mass production using prefabricated systems, often prioritized speed over energy efficiency. However, the research uncovered substantial diversity within this stock, encompassing multiple typologies such as *rijtjeswoningen, portiekwoningen*, and *gallerijwoningen*. This variation introduces complexity to the scalability of renovation systems, as each building type presents unique structural and functional requirements. Furthermore, differences in ownership patterns (private versus social housing) add another layer of intricacy to renovation possibilities.

Regarding current façade renovation systems and technologies, the study found that while several systems in the market are well-suited for application to post-war system-built houses, they face limitations in terms of flexibility and adaptability. Technologies such as prefabrication and modular façade panels show promise, but the diverse characteristics of Dutch system-built houses—including varying *traveematen* (grid measurements), façade types, and attachment methods—challenge the universal application of any single solution.

Circularity emerged as a critical factor in the design of future renovation systems. The research highlighted the increasing importance of circular design principles, such as design for disassembly, material reuse, and reducing embodied energy, in meeting long-term sustainability goals. While some existing systems incorporate these principles, the market currently offers limited fully circular solutions, presenting an area for further research and development.

The investigation into scalability requirements underlined the necessity of addressing the large number of homes needing upgrades to meet 2050 climate targets. However, achieving this scalability proves challenging due to the aforementioned variations in building types, materials, and structural systems. The findings indicate that no single solution can be scaled across the entire stock; instead, a flexible system allowing for both standardization and customization based on specific building characteristics is needed.

Analysis of similarities and differences between Dutch system-built houses revealed that while they share commonalities in their use of prefabricated systems, significant differences exist in façade types, structural elements, and building heights. These differences profoundly influence both the choice of renovation approach and the performance of façade systems, particularly in terms of energy efficiency and thermal bridging.

In conclusion, while it is possible to develop scalable and circular façade renovation systems for Dutch post-war system-built houses, the diversity within this housing stock still poses significant challenges. There is no single, universally applicable solution. Instead, a range of adaptable systems must be employed, each tailored to specific building types, structural details, and renovation goals. Existing façade systems provide a good foundation, but there remains substantial potential for further development, particularly in terms of circularity and scalability.

Through this flexible approach, it becomes possible to address the urgent need for sustainable renovation across the Dutch housing stock. By balancing scalability with adaptability, and standardization with customization, future façade renovation systems can more effectively renovate the existing building stock.

10.2 Future research

The research also identified several key areas for future exploration:

- Circularity and disassembly of existing systems: A more detailed analysis of how current façade renovation systems align with circular economy principles could provide valuable insights for improving their sustainability.
- Flexible Paris Proof requirements: Building upon Nieman's work, future research could focus on developing more flexible, building-specific energy performance requirements based on factors such as building compactness. A possible challenge is that this will make it more difficult for homeowners to identify this compactness.
- Automated frame generation: Developing a script that can automatically generate a frame based on connection points and windows obtained from a 3D scan could significantly enhance the efficiency and scalability of façade renovation processes.
- Hygrothermal performance: It would be interesting to look at the hygrothermal performance of demountable joints, but due to time constraints, this was not possible. This could be interesting for future research.
- Simulation: It would be interesting to research the energy demand of multiple types of buildings, compare results, and do a more detailed energy simulation. The Steady-State calculation uses the reference climate year; 64-65. With climate change in mind, yearly data from the expected temperatures in future years would be interesting to test for cooling demand.

10.3 Limitations

This research finds several limitations within its scope:

- Diversity of Building Stock: A significant constraint is the high variability within Dutch system-built houses from the post-war period. Although the study categorizes common typologies such as rijtjeswoningen, portiekwoningen, and gallerijwoningen, the differences in construction methods, dimensions, and façade types pose challenges to developing a universally scalable solution. The absence of a one-size-fits-all system limits the broad applicability of systems, necessitating a more flexible approach to façade renovation.

- Behavioral Factors and Occupant Impact: The research does not extensively address the behavioral impact of renovations on occupants. Occupants' comfort, both during and after renovations, is crucial for the success of scalable renovation systems. By not fully exploring how these systems affect day-to-day living and energy consumption behavior, the study may underestimate the practical challenges involved in implementing large-scale renovation projects.
- Theoretical Focus: This study primarily relies on theoretical research and literature-based analyses. While it provides valuable insights into the potential of scalable and circular façade renovation systems, the lack of field testing limits the research's ability to fully assess the effectiveness of the proposed solutions in real-world scenarios.

10.4 Reflection

The main objective of this research was to create a housing classification system that will help stimulate the growth of large-scale renovation approaches in the industry. The secondary objective was to find renovation solutions that are scalable and applicable to a greater number of buildings, therefore increasing the volume and lowering the renovation costs. Multiple research studies have classified the Dutch building stock based on architectural properties. However, not much research has been done to classify buildings based on building properties that influence the standardization of renovation approaches. During the research process the research had been narrowed down to the design of a façade renovation system specific to system-built houses.

Methodology and Approach

This research aims to identify essential building characteristics that influence renovation solutions. During the research process, interesting research was found as part of the IEBB (Integrale Energietransitie Bestaande Bouw). This follow-up research from Mohan (2022) focuses on classifying the Dutch housing stock based on standardizing renovation solutions and developing a tendering mechanism for large-scale renovation. The research approach is based on interviews and workshops with renovation industry experts to conclude which building characteristics are most important for standardizing renovation solutions. Mohan’s research explores this topic well. To further build on this, the research will look at the criteria for scalability mentioned in her work, and together with a detailed look into system-built houses, a design will be formed.

This changed the research approach halfway, as the most essential building characteristics for standardization have already been identified. With the support of my mentors and additional research, I noticed that a significant factor influencing building renovation solutions was not considered in the P2. This factor is the desired solution for the building owner, tenants, and other stakeholders. According to the industry stakeholders interviewed during Mohan's research (2022), the quality of the renovation solution is the most important factor, not the cost or scalability of the project.

Throughout the research process, various cases have been examined. While many buildings may share comparable features, the Dutch post-war housing stock has the most similarities. However, upon closer inspection of building details and plans, it becomes clear that each building has unique characteristics. Even within the same building blocks, variations in orientations and design account for more differences. This has proven to be a significant challenge in the context of this graduation project, which is why the research focus has been narrowed down to just the system-built houses of this period. Another reason for focusing on this building group is that there is a significant amount of data and technical drawings available about these buildings.

While much information about the Dutch housing stock is publicly available, it is spread out and hard to evaluate. Different books and websites were necessary to gather the data. The WOon 2018 dataset is helpful, but it is complex and contains numerous variables, making it difficult to filter for the most relevant ones. Nieman (2020) used the same dataset to research Rc values for different housing classes, which has then been used in this research.

Relation to graduation

The graduation topic addresses issues in renovating the building envelope for the Dutch housing stock. It addresses the energy performance of existing buildings and how specific renovation measures could improve this performance. This is in line with the climate design chair from Building Technology. On the other hand, it focuses on investigating the existing building stock and classifying it to create a demand for large-scale renovation. Adaptability, materialization, and manufacturing play a great part in this research. This fits the chair of façade and product design.

The Building Technology track focuses on research, technological design, and innovation. It deals with the newest technology and interacts with the current market of the building renovation industry. It balances research and design, which is also important in this graduation project. The graduation topic covers multiple disciplines and relates to the master’s program where architecture and engineering come together.

Relevance

The existing building stock has a significant impact on today’s energy usage. The new highly sustainable buildings are not considered a problem which we add to this building stock. However, this is merely a small percentage of the total building stock.

Energy poverty is becoming a worldwide issue, especially with the current energy prices. Large-scale renovations should tackle these problems and provide affordable, quality living conditions. Gentrification often occurs when buildings are renovated, the rent is increased, and lower-income classes cannot afford to live there anymore. Tenant disruption is also important and should be considered with renovations. Furthermore, the renovation market has a massive labor shortage, and the industrialization of this process has the potential to fill this gap.

Transferability

The transferability of this research lies in its potential to inform and influence large-scale renovation approaches within the Dutch housing industry and in similar contexts worldwide. By identifying important building characteristics that impact the standardization of renovation solutions, this research provides valuable insights that can be adapted and applied in diverse settings facing similar challenges related to energy efficiency, building renovation, and affordable housing. The methodology that involves analyzing building data and different case studies offers a replicable framework for conducting similar studies in different regions or countries.

Questions

- How might incorporating stakeholders' desired solutions impact the effectiveness and feasibility of standardized renovation approaches within the Dutch housing stock, particularly in achieving scalability?
- Considering the complexities and variations within building characteristics, how can a classification system based on simple building characteristics lead to the most optimal renovation solution?

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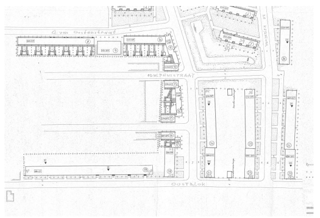
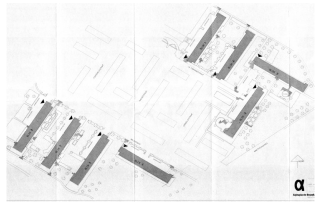
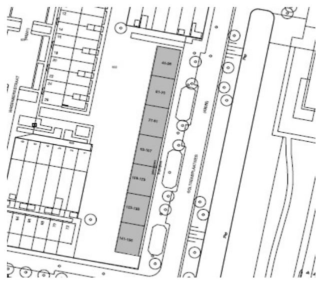
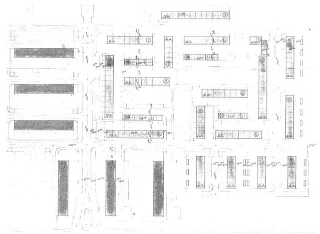
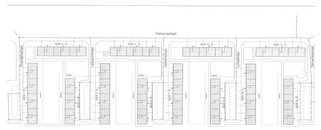
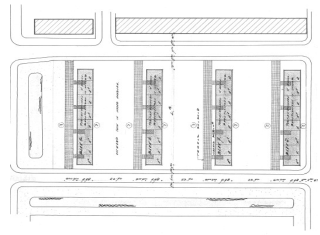
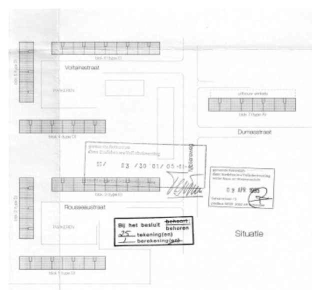
APPENDIX A – BK2TE5 CASES ANALYSIS

	Project 1 Lodensteynstraat	Project 2 Moliereweg	Project 3 Ooltgensplaatweg	Project 4 Philip Vingboonsstraat	Project 5 Pirandellostraat	Project 6 Tingieterpad	Project 7 Voltairestraat
General dwelling characteristics							
Dwelling type	Portiekwoningen	Galerijwoningen	Portiekwoningen	Portiekwoningen	Portiekwoningen	Portiekwoningen	Portiekwoningen
Number of units per typology	36	48	56	18	32	32	32
Location of the house	Vrijenban, Delft	Lombardijen, Rotterdam	Pendrecht, Rotterdam	Alexanderpolder, Rotterdam	Lombardijen, Rotterdam	Hof van Delft, Delft	Lombardijen, Rotterdam
Built year	1955	1959	1956	1964	1960	1958	1959
Number of layers	4-5	5	5	4	5	5	4
Roof type	Pitched roof	Flat roof	Flat roof	Flat roof	Flat roof	Flat roof	Flat roof
Construction type floor	Cusveller	Cusveller	Concrete	Concrete	Cusveller	MUWI	Concrete
Construction type façade	Masonry	Masonry	Masonry	Masonry, cavity, masonry	Masonry	Concrete, cavity, masonry	Masonry
Construction type				Stapelbouw	Stapelbouw	Stapelbouw	
Elevation (first apartment)	1m NAP	2.5m NAP	1m NAP	2.5 NAP	2.5 NAP	1.5m NAP	2.5 NAP
Number of rooms	5	3	4	4	4	4	5
Additional structures to the house	Balconies	Balconies & Galleries	Balconies	Balconies	Balconies	Balconies	Balconies
Plan type	E3	C3	G2	E3	E3		C7
					3,50		
	4,02		3,72	3,72	2,97	4,15	4,80
Grid (m)	1,97	6,38	1,92	2,70	2,20	2,50	3,85
	3x NW - ZO	6x NO - ZW	1x N - Z	3x N - Z	4x O - W		
Kopgevel	1x NO - ZW	2x NW - ZO		3x O - W	8x N - Z	4x N - Z	
				3x N - Z	8x O - W		
Langsgevel	6x NO - ZW		1x O - W	3x O - W	4x N - Z	4x O - W	







APPENDIX B – ANALYSIS SYSTEEMWONINGEN

										kopsgevel			langsgevel				
Column1	Column2	aantal	periode	periode2	eengezins	portiek	galerij	bouwsysteem	vloerdragende/woningscheidende wand	buitenblad	spouw	binnenblad	opbouw	vloer	balkon	% sloop	potentie
4	BMB (o.a. HeBoMa)	29.369	1949	1973	15%	40%	45%	montagebouw	prefab beton	baksteenelement	ja	prefab beton	prefab spouwwand	gemetselde vloerplaten		5%	redelijke maatvoering in woningen, veel oplossingen mogelijk, goede ruimtelijke plattegronden
13	Airey	9.975	1949	1968	55%	35%	10%	montagebouw	betonblokken gevuld met beton	betonplaatjes		betonnen stijlen	montagekozijnen	houten vloeren		25%	gevel dominant aspect van architectuur, lastig te wijzigen, eengezinswoningen bieden voldoende grootte, herinde
19	Welschen	5.602	1947	1955	50%	50%	0%	gietbouw	ihwg beton	enkelsteens		ihwg beton		houten vloeren		25%	meeste woningen zijn al gerenoveerd of gesloopt, zelden op agenda voor kwaliteitsaanpassing
14	ERA	9.810	1964	1972	0%	0%	100%	gietbouw	ihwg beton	metselwerk	ja	ihwg beton	montagekozijnen	ihwg beton			beukmaat van 7,80 biedt voldoende ruimte, slopen bij deze woningen brengt veel problemen met zich mee, eerde
1	Muwi	37.831	1951	1973	1%	53%	46%	stapelbouw	betonblokken gevuld met beton	metselwerk	ja	betonblokken gevuld met beton	montagekozijnen	betonbalken met vulblokken	prefab beton	5%	weinig gesloopt, toekomstige kwaliteit, ruimte voor renovatie, ingrepen duur
6	Rottinghuis/IBC	17.000	1949	1973	2%	48%	50%	montagebouw	betonnen element	metselwerk	ja	prefab beton	trad spouw	prefab beton			eenvoudige wijze slaapkamer toe te voegen, mate van aanpassing kan zeer divers zijn per woning, vraag bepaald c
2	RBM	32.292	1945	1975	20%	40%	40%	gietbouw	ihwg beton	metselwerk	ja	ihwg beton	montagekozijnen	ihwg beton	onderdeel van constructie		potentie afhankelijk van woningmarkt, manier van bouwen, geen systeem, veel variatie, veel hoogbouw
7	Korrelbeton	15.394	1949	1970	25%	75%	0%	gietbouw	ihwg beton	metselwerk	ja	ihwg beton	montagekozijnen	plaatvloeren		25%	woningen vergen grondige aanpak, aanpassing plattegronden, energetische kwaliteit en comfort, hoge kosten
5	Pronto	17.836	1948	1975	32%	62%	4%	stapelbouw	betonblokken gevuld met beton	metselwerk	ja	pronto blokken	montagekozijnen	betonbalken met vulblokken		5%	zeer goede woningen, beperkte buitenruimte, gebruikskwaliteit moet versterkt voor toekomstwaarde
11	Wilma	12.579	1960	1975	33%	33%	34%	gietbouw	ihwg beton	metselwerk	ja	ihwg beton	montagekozijnen	ihwg beton		20%	kosten sterk afhankelijk van te realiseren programma, vooral aanpassen schil, ruimte is aanwezig
9	BBB: Bredero en Bredero '55	13.118	1948	1973	33%	33%	34%	stapelbouw	betonblokken gevuld met beton	metselwerk	ja	betonblokken gevuld met beton		houten vloeren			ruime woningen, toekomstwaarde in maatvoering, kosten in energetische kwaliteit, uitrusting en comfort
15	EBA	19.291	1962	1967	50%	0%	50%	gietbouw	ihwg beton	metselwerk	ja	ihwg beton	montagekozijnen	prefab beton	prefab beton	20%	potentie op basis van de plattegronden is groot, ruime woningen met veel potentie
21	Tramonta	4.845	1951	1960	50%	0%	50%	montagebouw	betonnen kolommen	metselwerk		betonblokken gevuld met beton	montagekozijnen	prefab beton			vrije indeelbaarheid van plattegronden, kolomstructuur en breedte maat bieden veel potentie, genoeg diversiteit
18	Bakker	5.643	1950	1966	50%	0%	50%	stapelbouw	betonblokken gevuld met beton	metselwerk	ja	betonblokken gevuld met beton	montagekozijnen	holle bouwsteen			afhankelijk van eigenschappen en context, grootte van complexen belangrijk, beperkte omvang,
12	Smit	10.000	1959	1975	100%	0%	0%	montagebouw	prefab beton	metselwerk	ja	prefab beton	montagekozijnen	houten vloeren			douche/badkamer is nadeel, verplaatsen van badkamer voor slaapkamer, veel opties voor aanpassen van kwaliteit
20	B-G	5.581	1960	1975	100%	0%	0%	montagebouw	houten wanden	metselwerk	ja	betonblokken					woningen zijn voornamelijk eigenaarbewoner, niet veel potentie, voornamelijk interesse in de kavel
10	Pege	11.000	1956	1975	100%	0%	0%	stapelbouw	betonblokken gevuld met beton	metselwerk	ja	betonblokken gevuld met beton	montagekozijnen	houten vloeren		15%	afhankelijk van gewenste prestaties, aanpassing aan energetische kwaliteit, uitstraling en bruikbaarheid zolder, me
8	VAM	14.000	1959	1970	0%	100%	0%	montagebouw	prefab beton	prefab beton	ja	prefab beton	montagekozijnen	plaatvloeren			pui elementen punt van vervanging, krappe ontsluitingen, mogelijk verminderen aantal woningen nodig, ruime wo
16	Elementum, later PLN	8.574	1960	1967	0%	0%	100%	montagebouw	prefab beton	prefab beton	ja	prefab beton	montagekozijnen	kanaalplaat			potentie voor optoppen, zijn al veel renovaties gedaan, differentiatie van aanbod benodigd
17	Vaneg	7.000	1965	1974	100%	0%	0%	montagebouw	prefab beton	prefab beton	ja	prefab beton	montagekozijnen	prefab beton			bouwsysteem heeft alleen toekomstwaarde als structureel beeld gewijzigd wordt, gevels hebben flinke opfrisbeur
3	Coignet	31.378	1959	1975	14%	24%	55%	montagebouw	prefab beton	sandwich betonelement		sandwich betonelement		prefab beton	prefab beton	15%	veel sloop, veel beton, weinig afwerking, veel ingrepen nodig, hoge kosten

totaal	288.749
rest	121.000

balkons vanaf 1965 niet
meer aangestort, maar
losgekoppeld en op
consoles

APPENDIX C – STEADY-STATE CALCULATION

Building Input Parameters

Fill in the buildng data | Don't change these data | White Cell: calculated value, don't change it

Qbalance=Qtrans+Qinf+Qvent+Qsol+Qint [Wh]

Indoor temperature heating mode	20	oC	Ground temperature	9	oC
Indoor temperatuur cooling mode	25	0C			
Total façade area (incl. glass) North	20	m^2	Window percentage North	33	%
Total façade area (incl. glass) North-East	0	m^2	Window percentage North-East	0	%
Total façade area (incl. glass) East	0	m^2	Window percentage East	0	%
Total façade area (incl. glass) South-East	0	m^2	Window percentage South-East	0	%
Total façade area (incl. glass) South	21	m^2	Window percentage South	60	%
Total façade area (incl. glass) South-West	0	m^2	Window percentage South-West	0	%
Total façade area (incl. glass) West	0	m^2	Window percentage West	0	%
Total façade area (incl. glass) North-West	0	m^2	Window percentage North-West	0	%
Total roof area (incl. glass)	0	m^2	Window percentage roof	0	%
Total ground floor area	0	m^2			
Floor height	2,6	m			
Total floor surface area	62	m^2	(This is the sum of all floor areas, from every level)		

portiek woning Muwi Tingieterpad

oost		
gevel	20026000	20,026
glas	6804000	6,804
		0,339758
west		
gevel	20995500	20,9955
glas	12925500	12,9255
		0,615632
vloer	60302500	60,3025

Transmission

Ptrans=U.A(To-Ti) [W]

Rc façade walls	4,7	m^2K/W			
Rc roof	6	m^2K/W			
Rc floor	3,5	m^2K/W			
alfai (convection/radiation coefficient indoor)	7,5	W/m^2K			
alfao (convection/radiation coefficient indoor)	25	W/m^2K			
U window	1,4	W/m^2K	Total Window (glass + frame) area	19,2	m^2
U facade wall	0,21	W/m^2K	Total Facade wall area	21,8	m^2
U roof	0,16	W/m^2K	Total Roof area	0,0	m^2
U floor	0,27	W/m^2K	Total Ground floor area	0,0	m^2

Infiltration

Pinf=minf.Cp(To-Ti) [W]

ACH	0,2	/h
Building volume	161	m^3
Flow rate infiltration	32	m^3/h
Dry air heating capacity	1000	J/kgK
Density of air	1,2	kg/m^3

m=rho.v/3600 [kg/s]
V=ACH.Vbuilindg [m3/hour]

Ventilation

Heat recovery efficiency	0	
Ventilation flow rate per person	25	m^3/h per person
Flow rate ventilation	75	m^3/h
Additional natural ventilation in cooling mode	2	/h (in ACH)
Flow rate additional natural ventilation in cooling mode	322	m^3/h
Dry air heating capacity	1000	J/kgK
Density of air	1,2	kg/m^3

Pvent=(1- η).mvent.Cp(To-Ti) [W]
Take 0 for natural ventilation
In the calculation sheet, we also assume there is no ventilation when people
are not home/in the office (see sheet hourly data), columns AE/AF
In moderate climate people would often use additional ventilation with fresh outside air when there is cooling needed. For th

Solar factors

					Threeshold solar radiation for blind down	150	W/m2
Solar heat factor glass (N)	0,65	Window area (glass + frame) (N)	6,6	m^2	Solar heat factor blinds (N)	0,15	
Solar heat factor glass (N-E)	0,65	Window area (glass + frame) (N-E)	0,0	m^2	Solar heat factor blinds (N-E)	0,15	
Solar heat factor glass (E)	0,65	Window area (glass + frame) (E)	0	m^2	Solar heat factor blinds (E)	0,15	
Solar heat factor glass (S-E)	0,65	Window area (glass + frame) (S-E)	0,0	m^2	Solar heat factor blinds (S-E)	0,15	
Solar heat factor glass (S)	0,65	Window area (glass + frame)(S)	12,6	m^2	Solar heat factor blinds (S)	0,15	
Solar heat factor glass (S-W)	0,65	Window area (glass + frame) (S-W)	0,0	m^2	Solar heat factor blinds (S-W)	0,15	
Solar heat factort glass (W)	0,65	Window area (glass + frame)(W)	0	m^2	Solar heat factor blinds (W)	0,15	
Solar heat factor glass (N-W)	0,65	Window area (glass + frame) (N-W)	0,0	m^2	Solar heat factor blinds (N-W)	0,15	
Solar heat factor glass (roof)	0,65	Window area (glass + frame)(roof)	0	m^2	Solar heat factor blinds (roof)	0,15	
f factor for light and heavy buildigs	0,85						

In the calculation sheet, the blinds go down only if the solar radition is above this value W/m2
Psol= SUMi(gglass.Awindow.Gshade.Psol) [W]
gshade=1: no blind; gshade =0: windows are completely obstructed
Correction factor for heavy buildings: light building f=1; heavy building f =0.85

Internal heat gains

Pint=Pint,people + Pint,lighting+Pint,appliances (W)

Number of people	3	people
Heat gain per person	117	W/person
Fraction light power thermally released	1	
Lighten floor percentage	1	
Total Floor Area	62,00	m^2
Light power per square meter	2	W/m^2
Appliances power per square meter	2	W/m^2

Pint,people=npeople.Pm (W)
Pint,lighting= ςlight,vent.θfloor.Afloor.Plight (W)
Pint,appliances=Afloor.Pappliances (W)
See sheet hourly data, columns AE/AF for presence of people

Building warm tap water demand

Water density	1000	kg/m^3	
Daily average volume of warm tap water per person	0,1	m^3/day	
Daily average volume of warm tap water in building	0,3	m^3/day	
Maximum simulatenous flow rate	0,0001	m^3/s	*per apartment*
Specific heat of water	4187	J/kgK	
Temperature cold water	10	ºC	
Temperature hot water	50	ºC	

~ 0.1 m3 per day for residential. For office buildings 0.005 m3 per day
Qhottapwater=365. p.V.Cp(Thot-Tcold)/3600 (Wh)
Phottapwater=p.Vmax.Cp(Thot-Tcold) (W)
V in m3/day

Building electrical energy demand

Ventilation

Pressure drop	50	Pa
Efficiency ventilator	0,7	
Power ventilator	1	W

take 0 for natural ventilation, 400 for mechanical supply or exhaust, 800 in case of mechanical exhaust AND supply

$P_{vent} = V.dP/\eta$ *v in m3/s*

Lighting & Appliances

Light power per square meter	2	W/m^2
Floor area	62	m^2
Appliances power per square meter	2	W/m^2
Floor area	62	m^2

Qelectrical=SUM((Pelec,vent.hvent)+Plight.Afloor.hlighting + SUM(Pappliances.Afloor.happliances) (Wh)