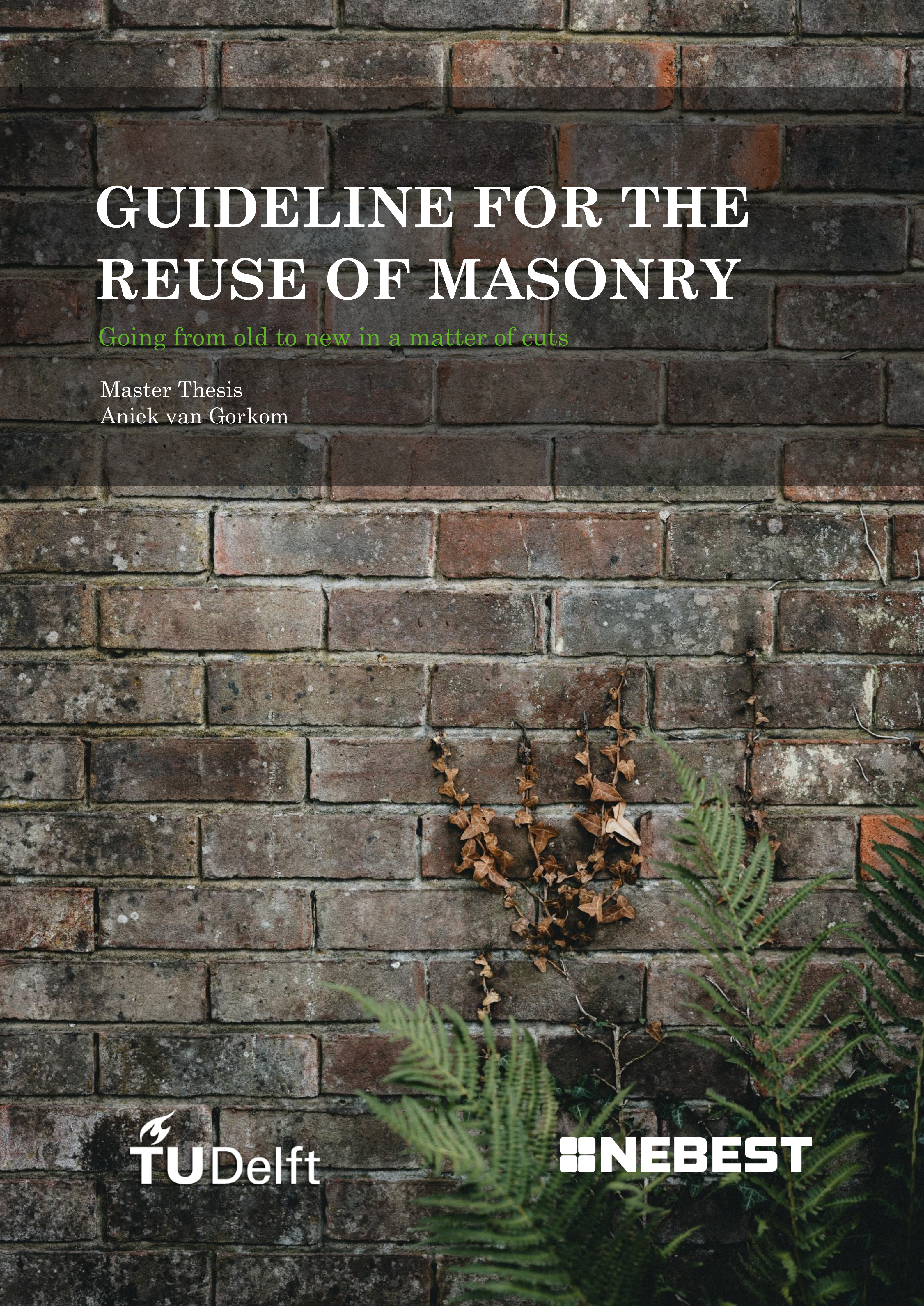
GUIDELINE FOR THE REUSE OF MASONRY

Going from old to new in a matter of cuts

Master Thesis

Aniek van Gorkom



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As this chapter of my academic journey closes, I am filled with anticipation and gratitude as I prepare to embark on my career. I look forward to applying the knowledge and skills I have gained, and I am deeply thankful to all who have supported me along the way. To everyone who contributed to this thesis, I extend my sincere thanks. I hope you find joy in reading my thesis as much as I have enjoyed working on it.

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Abstract

Reusing construction materials has become increasingly significant in the context of the Netherlands's goal to achieve a fully circular economy by 2050. This thesis provides a guideline for the reuse of masonry, emphasising the transition from traditional demolition methods into techniques that facilitate the reuse of masonry elements. The research explores the development of masonry, current practices, and future perspectives, highlighting the environmental gain and durability proceedings.

Masonry, a cornerstone of Dutch residential construction, offers significant potential for reuse due to its durability and historical prevalence. Despite innovations like drystacking and prefabrication, traditional masonry remains dominant. This study underlines the urgency of enhancing masonry reuse in light of the projected increase in new housing construction and subsequent demolitions. The research identifies a gap in the reuse methods of masonry, proposing an approach of cutting out panels from exiting walls for incorporation into new projects.

The thesis begins with a historical overview of masonry and its separate elements, mortar and brick. It traces its development from Roman times to the present. Early masonry in the Netherlands saw the use of tuff stone and brick, evolving through various phases influenced by technological advancements and changes in construction methods. The introduction of cavity walls, the development of different brick bonds, and the use of various mortars are detailed, highlighting the transition from masonry as a structural element to its current role as a (decorative) façade.

Innovations in masonry construction are examined, focussing on drystacking, robotics, and prefabrication. Drystacking allows erecting masonry facades without mortar, facilitating easy disassembly and reuse. While promising, Robotics in masonry construction face challenges in widespread adoption due to the complexity and precision required. Prefabrication, though historically significant, remains underutilised in modern construction.

The thesis analyses the current stock of buildings in the Netherlands, emphasising the potential of masonry reuse. It discusses the materials flow, highlighting the substantial use of bricks and concrete in new construction. The research outlines the demolition trends, noting that older buildings, particularly those from the post-war period, are prime candidates for material recovery.

A significant portion of the thesis is dedicated to the practical aspects of masonry reuse. It describes the process of removing masonry elements, including desk research, visual inspection, and destructive tests. Techniques for sawing, hoisting and transporting masonry panels are discussed, providing a step-by-step guide for practitioners. The study also addresses storage and implementation, emphasising the need for proper handling to maintain the integrity of the reused material.

Durability is a critical concern in masonry reuse. The thesis evaluates structural and climate durability, assessing the properties of masonry elements under various conditions. It explores the impact of frost/thaw cycles, improper joint application, and strategies on the longevity of reused masonry. The research employs DIANA modelling to simulate the structural behaviour of masonry panels, providing insight into their performance during non-conventional boundary conditions of lifting the element from the existing structure.

The environmental impact of masonry reuse is quantified through a life cycle assessment (LCA). The study compares the environmental burdens of reused masonry elements with traditional buildings and reusing masonry bricks. It highlights significant reductions in CO2 emissions and total MKI value in both comparisons.

The thesis concludes with practical recommendations in the form of a guideline, encouraging a shift towards more sustainable building practices. The research emphasises the importance of

quality control and standardisation in reusing, ensuring that reused material meets current regulations and performance standards.

By addressing the technical, environmental, and practical aspects of masonry reuse, this thesis contributes to the broader discourse on sustainable construction. It provides a valuable framework to enhance masonry reuse, aligning with the Netherlands' ambition for a circular economy. The guideline presented in this thesis research aims to facilitate the adoption of masonry reuse practices, promoting environmental conservation and resource efficiency in the construction sector.

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Chapter 1
INTRODUCTION

This introductory chapter sets the stage by elucidating the context, presenting the existing challenges, establishing a problem definition, and laying the groundwork for the comprehensive research described in the subsequent chapters.

1.1 RESEARCH CONTEXT

Pursuing a fully circular economy in the Netherlands by 2050 has catalysed ambitious governmental measures, ranging from reducing raw material use to extending product lifespan (Rijksoverheid, 2024). As part of this initiative, attention has been directed towards understanding and optimising the reuse potential of various building materials. While substantial strides have been made in assessing the reuse of materials such as steel, concrete, and timber, the focus on other construction materials, such as masonry, has been notably limited.

Masonry, a cornerstone of residential construction in the Netherlands, poses a unique challenge and opportunity for circularity. Despite innovations like drystacking, the predominant construction method remains rooted in traditional masonry. The impending surge in new housing construction until 2026, followed by a significant increase in demolitions (EIB, Metabolic and SGS Search, 2022), underscores the urgency to address the reuse potential of existing masonry structures. Bricks, renowned for their durability, theoretically offer a lifespan exceeding 500 years. (Bown, 2007). However, the premature demolition of structures often prevents realising this potential.

1.2 STATE OF THE ART

This chapter will describe the current innovations in masonry. These include new applications of masonry in the form of drystacking, prefabrication, and the options robotics offers. Also, the current forms that support the circular economy are discussed, such as reused brick by brick and recycling.

1.2.1 Recycling Masonry

The recycling process of masonry undergoes several steps. The first step happens at the demolition location, which is the collection. The collecting means also the division of clean masonry from polluted masonry. Once the sorted masonry is collected, it undergoes crushing and grinding to reduce the size of the material. Heavy machinery such as crushers and shredders are commonly used for this purpose. The crushed material is often referred to as recycled aggregate. The recycled aggregate is screened to separate different sizes of particles. This ensures that the material meets specific size requirements for the intended application. A quality control test is performed to assess the properties such as gradation and durability. This ensures that recycled material meets the industry standards and specifications. Clay brick particles possess desirable characteristics such as colour variety, open porosity, and frost resistance, making them suitable for diverse applications, including sports field construction, road construction and aggregate materials. In sport field construction, recycled brick is utilised in layers to meet wear, frost resistance and permeability requirements. In road foundations, the recycled materials are incorporated into base courses and frost protection layers, contributing to the reduction of natural aggregates. The recycled materials for road construction undergo tests to ensure they meet certain standards for strength and durability. The aggregates can also be applied in concrete production, although the masonry aggregates' low particle density can affect the concrete's strength. The same is the case for new clay brick production. However, challenges such as impurities and moisture content must be addressed to ensure the quality of the final product (Anette Müller, 2018). Of all the aggregate in the Dutch material stock, 77% goes as stabilisation material under asphalt roads, and the other 23% is foundation material for cobblestone roads. In 2019, a total of 7610kton was needed in the GWW sector, while in the demolition of roads, a total of 3870kton was collected. Therefore, the GWW sector needs more recycling aggregate. This recycling aggregate is the product of demolished masonry and materials such as concrete and calcium-silicate (EIB, Metabolic and SGS Search, 2022).

1.2.2 Reuse Masonry Bricks

Reclaimed bricks are sought after for their unique character, often developed through years of maturation and weathering. The appeal lies not only in the aesthetic qualities but also in the potential sustainability. Although reclaimed bricks are less readily available, their reuse can offer environmental benefits, especially considering the energy required for reclamation. In infrastructure projects, such as street construction, the reuse of clay bricks is a common practice. Clay pavers, when reclaimed, must exhibit full frost resistance to ensure durability in outdoor settings. This was the case when the clay pavers were already applied in an environment exposed to the same weather conditions. This is different for façade bricks. Bricks from the early 20th century are typically joined with lime mortar, which is easier to remove than the modern Portland cement mortar (Koen van Balen, [et al], 2003). When applied correctly and with patience, even lime mortar can have a strong bond strength with the bricks. Therefore, some caution must be exercised during the removal of the mortar to avoid damaging the brick's surface. Power tools are not recommended due to the risk of surface disfiguration. Often, a heavy hammer and a broad cold chisel for large lumps of mortar are used. A brick hammer with a replaceable hardened claw steel tip is useful for smaller pieces. A further cleaning method is proprietary, often based on diluted hydrochloric acid, and can effectively remove stubborn mortar or lime stains from brick faces. However, the proper precautions must be taken to prevent acid penetration to the brick, such as wetting the surface to reduce the surface absorption rate.

Klinker Historika is a significant player in the Netherlands and Germany, mainly known for its commitment to circularity in reusing clay bricks. They oversee the entire process of reusing brick faces and conduct testing and reporting for each harvested brick batch. The Institute of Ziegelsorschung Essen analysed the CO_2 reduction. They found a 95% reduction in CO_2 emissions for recycled-faced bricks, positioning it as an eco-friendly alternative to new brick production (Nelissen, 2023). Klinker Historika provides several steps in the process of reusing bricks, such as harvesting, sorting, resulting, stacking, processing, and appearance or new construction (Klinker Historika GmbH, 2024). Before harvesting, a visual inspection is performed to ensure the existing masonry is suitable for the reuse process, such as cracking in the wall or freeze-thaw damage on the brick face. Furthermore, a test can be performed to determine how strong the mortar and brick are bonded. This is done to decide whether or not it would be possible to remove all mortar from the brick. The harvesting or demolition marks the beginning of the brick reuse process. In most cases, the reuse of bricks is most used with total demolition, where the walls are dismantled as in a traditional demolition case, and bricks are salvaged afterwards. While this method minimises time for the demolition crew, there is a risk of brick breakage during the process. However, meticulous handling can partly mitigate this risk, ensuring a higher yield of intact bricks for reuse. Following the harvest, the salvaged bricks undergo a sorting process. The bricks are inspected for quality, size, shape and remaining mortar. Bricks with excessive damage or mortar residue that compromises their integrity are discarded. The bricks that can be cleaned are included in the sorting. This phase ensures that the best bricks proceed to the next stage of the reuse process. Additionally, not all bricks may be suitable for external use. For example, when the inner leaf of the cavity wall is also a clay wall, these bricks are not suitable to be applied as an outer leaf in the next project. Thus, some distinction needs to be made. When the sorting is completed, the selected bricks are ready for further processing. This results in a collection of salvaged bricks that meet the necessary criteria for reuse. Each batch of bricks is carefully inspected, and additional cleaning or repairs can be performed as needed to prepare the bricks for stacking and storage. When the salvaged bricks are clear, they are stacked on pallets in preparation for storage. Proper stacking ensures that the bricks remain stable and secure, minimising the risk of damage during storage and transportation. The bricks are stored so that they are ready to be used in a new project. They can be used as an exterior façade, pathways, or interior features; the salvaged bricks bring a unique character and charm to the built environment. Their weathered appearance adds a sense of history and authenticity to architectural design.

1.2.3 Drystacking

Circular building has become more important. One way of implementing this in masonry could be dry stacking. Drystacking is a method that allows the erection of a traditional masonry façade without using mortar or adhesives. This method allows for easy demountability at any time and would afterwards be reused in the same function, preventing materials from going to waste. To ensure the strength of the façade, separate components are applied to hold the bricks together. Some systems use stainless steel plates with recycled plastics, and others do not. This façade technology is more sustainable than conventional construction methods. It requires fewer nitrogen and greenhouse gas emissions because joint material is not applied. (KNB (vereniging Koninklijke Nederlandse Bouwkeramiek), 2023) Even though his method has been on the market for some years, and most brick manufacturers have their own dry stacking system, the amount of application compared with traditional masonry is still small. Partly, this concerns the concept architects want to apply and the craftsman's attitude. Van der Sanden B.V. has an academy that teaches its façade systems and educates new craftsmen. They often hear that dry stacking is more like carpentry than bricklaying since it is about measuring and precision. When the younger generation of bricklayers is reluctant to embrace dry stacking, veterans will often have an even stronger opinion. The change will slow down if the craftsman is reluctant to work with the system.

Figure 1: Drystacking Principle (Wienerberger, 2024)

Figure 2: Final Look Drystacking (Wienerberger, 2024)

1.2.4 Robots

In 1904, the first patent for a "mechanical bricklayer" was granted to John Thomas. The idea is to speed up and make the construction process more effective. In the 1960s, another invention was made: the "motor mason". However, there could not be much difference found with the patent from 1904 in constructing masonry. It was said that the machine would be ten times faster than a bricklayer. But from what is known, it has not been used often; therefore, you could not speak of a big success. In the last decade, SAM (Semi Automated Mason) has been created by an Amerikan company called Construction Robotics. This machine is used as support for the bricklayer, but it cannot independently erect a brick façade wall. However, because the machine only assists the bricklayer, the actual profit in time could be questioned. At the same time, Christian Keller from Keller Ziegeleinen te Pfungen (CH) got inspiration from Fabio Gramazio and Matthias Kohler (ETH Zurich) and created the masonry robot ROB. This was also the start of a new way to create prefab masonry elements that bricklayers often cannot make. Ropax from the Netherlands has produced a bricklaying robot that can create the traditional masonry façade on the construction site. This bricklaying robot improves SAM and fits the digital design process well. Though the question is whether the innovation of bricklaying can be found in Robots, as the past project has shown, it is at least a difficult path. (Vekemans, 2023)

Figure 3: Robot Applying Mortar (Ballast Nedam, 2022)

Figure 4: Robot Applying Brick (Ballast Nedam, 2022)

1.2.5 Prefab

In 1932, English mechanical engineer Henry Dyke received a patent to produce clean masonry on an assembly line. This changed the principles of the industry, and a factory was established for only this purpose. (patent title: Improvements in or relating to the manufacture of pre-formed building units (Great Britain Patent No. GB382723A, 1932)) After the Second World War, this principle was applied in The Netherlands. It was called BMB (Baksteen Montage Bouw). Because of the high demand for housing, the system grew into one of the Netherlands' most highly regarded systems. However, prefabricated construction elements were not further developed after this. The majority of our buildings are still primarily made from traditional construction methods. Some prefab masonry systems products are on the market, but this is only a small part of the total masonry construction share. Prefab masonry can often be combined with prefab concrete as a prefab façade. (Vekemans, 2023)

Figure 5: Prefab Masonry Lifted (Vekemans, 2023)

Figure 6: Prefab Masonry on Location (Vekemans, 2023)

1.3 PROBLEM STATEMENT

In pursuing a circular economy in the Netherlands, masonry has been partly left aside. Despite innovations, traditional masonry prevails in residential construction, presenting challenges with a surge in new housing construction and demolitions. New types of more sustainable building options are available, such as dry stacking, prefabrication and robotics. There is no comprehensive way to reuse masonry. Recycling of masonry is mainly applied in the Netherlands to build our roads, and in the last few years, reusing masonry bricks is also an option. But not so much for masonry as a whole.

This research addresses these constraints by exploring the innovative approach of cutting out panels from existing masonry walls and incorporating them into new construction projects. The study seeks to provide practical insights and recommendations by scrutinising feasibility and environmental impact, contributing to the broader discourse on sustainable construction practices within the evolving circular economy landscape. This will result in a guideline for the recycling process.

Part I
Research Framework

Chapter **2**

RESEARCH APPROACH

This chapter explains the aspects of the research. It begins with a research objective (the main goal), research questions, and the definition of the scope, research strategy, and research outline.

2.1 RESEARCH OBJECTIVE

This research aims to contribute to a more sustainable and circular future by addressing the need for environmental conservation on Earth. In alignment with this broader aim, the specific focus is on masonry elements due to their widespread use in Dutch construction and the potential for substantial environmental impact. To achieve the government's target for a circular economy, the effort to increase materials reuse emerges as a crucial strategy. This research zeroes in on masonry, recognising its significance in the construction industry and its potential to contribute to a more sustainable and circular economy. The primary objective of this study is to assess and enhance the practical reuse potential of masonry elements. This evaluation will be conducted through an analysis of durability and environmental impact. The research aims to lower the overall environmental burden by promoting the practical reuse of masonry materials. This is done by a guideline for the reuse of masonry.

Within the broader goal, this report will specifically:

1. Evaluate the durability of the masonry: investigate the structural integrity and viability of reusing masonry elements in various construction scenarios. His will involve an examination of the technical aspects associated with the reuse of masonry materials
2. Assess environmental impact: analyse the Life Cycle Assessment of masonry elements. The goal is to provide insight into how reusing these materials can contribute to a more sustainable and environmentally friendly construction industry.

It is anticipated that fulfilling these specific objectives will lead to an increase in the reuse of masonry elements. By providing an understanding of both the structural and environmental aspects, this thesis aims to offer actionable insights and recommendations for industry stakeholders. Ultimately, the research endeavours to play a role in advancing the broader goal of fostering a sustainable and circular future through responsible material reuse practices.

2.2 RESEARCH QUESTION

The escalating environmental challenges facing the construction industry demand innovative and sustainable solutions to curtail the ecological footprint associated with building materials. In this context, reusing existing masonry walls, particularly those with half-brick bonds, emerges as a promising avenue for advancing sustainability in construction practices. This research addresses the question:

How can existing clay masonry walls of houses with half-brick bonds be reused as panel elements in a sustainable and durable way?

To unravel the complexities and intricacies surrounding this central inquiry, the study will delve into four main sub-questions. These four sub-questions are further defined to provide insights into various facets of the reuse process.

1. **How does the historical, present, and future evolution of masonry impact the viability of its reuse?**
   - How did masonry develop over the years?
   - What kind of masonry is applied in the Netherlands?
   - What is the material flow in the Netherlands now and in the future?
   - What does the reuse process of masonry look like?
2. **How can masonry panel elements be removed from existing houses and applied in new construction?**
   - What are the steps to remove an element from the existing wall and later apply it in new construction?
   - How can the panel be safely removed from the existing structure?
   - In what way can the element be applied in new construction?
3. **How can the durability of masonry panel elements be ensured?**
   - What are the current standards and regulations regarding masonry?
   - What test must be performed to ensure the masonry elements correlate with the current standards and regulations?
   - What is the minimum flexural bond strength needed during reuse to ensure the structural durability of the masonry panel?
   - What is needed of the masonry to ensure climate durability of the masonry?
4. **How can the environmental impact of the reuse of masonry for this concept be quantified?**
   - What is the environmental impact of reusing masonry in element form?
   - What is the difference between the environmental impact of reusing masonry in element form and brick reusing?
   - What is the difference between the environmental impact of reusing masonry in element form and traditional building

2.3 SCOPE

This thesis focuses on Reuse, which includes reclaimed building materials that is applied in its original form in a similar situation. Repurposed masonry is also a form of Reuse, but this is not discussed in this thesis. Recycling, the process of taking waste materials and converting them back into raw materials to create new products, is not focused on in this thesis. The document focuses on the Dutch building sector. Therefor everything in this rapport is focussed on Dutch material, Dutch regulations and building designs. The masonry that eligible by means of this thesis comes from residential housing. Though a strong connection with non residential housing can be found. To limit the scope of this thesis the choice is made to focus on residential housing. Furthermore infrastructural is not covered in the process of reuse, except when a comparison is made between the end of life phase in life cycle analysis. An other point of limitation is that this thesis is primarily focused on the most common masonry bond. Furthermore this thesis focuses on residential building with demolition and new construction application. Therefore renovation is not covered in this thesis.

2.4 RESEARCH STRATEGY

Before the actual research starts, a prior literature study is conducted. This is used to derive the scope of this thesis. The research starts with the area defining the Netherlands. Defining material flows in the Netherlands. Based on material flows, an indication can be made of how much material will become accessible in the following years. Next, the different types of masonry applied in the Netherlands are researched. This includes different bonds and materials. With all the information gathered, a guideline will be created to inform about the reuse of masonry in newly designed construction, instil more confidence regarding quality assurance in reusing masonry elements, and provide practical added value.

2.5 RESEARCH OUTLINE

The research is divided into three parts: research framework, research methods and results, and final remarks. Each part of the thesis plays a role in contributing to the overall research. The research framework primarily involves an in-depth literature study, addressing various sub-questions that collectively shape the research trajectory. The findings in their initial phase prompt subtle adjustments to the scope and research questions. The second section focuses on research methods, housing most investigative work. It serves as the nexus where novel knowledge is actively constructed. The insights gathered here lay the groundwork for the subsequent validation in the third and concluding part of the research. This concluding phase mirrors a traditional conclusion, encompassing the culmination of results derived from the research methods. Within this section, a synthesis of the research findings takes place, leading to conclusive statements and actionable recommendations. The meticulous progress from literature study to knowledge construction and validation ensures a comprehensive and well-structured exploration of the thesis subject.

The part below is an overview of the research questions in each phase.

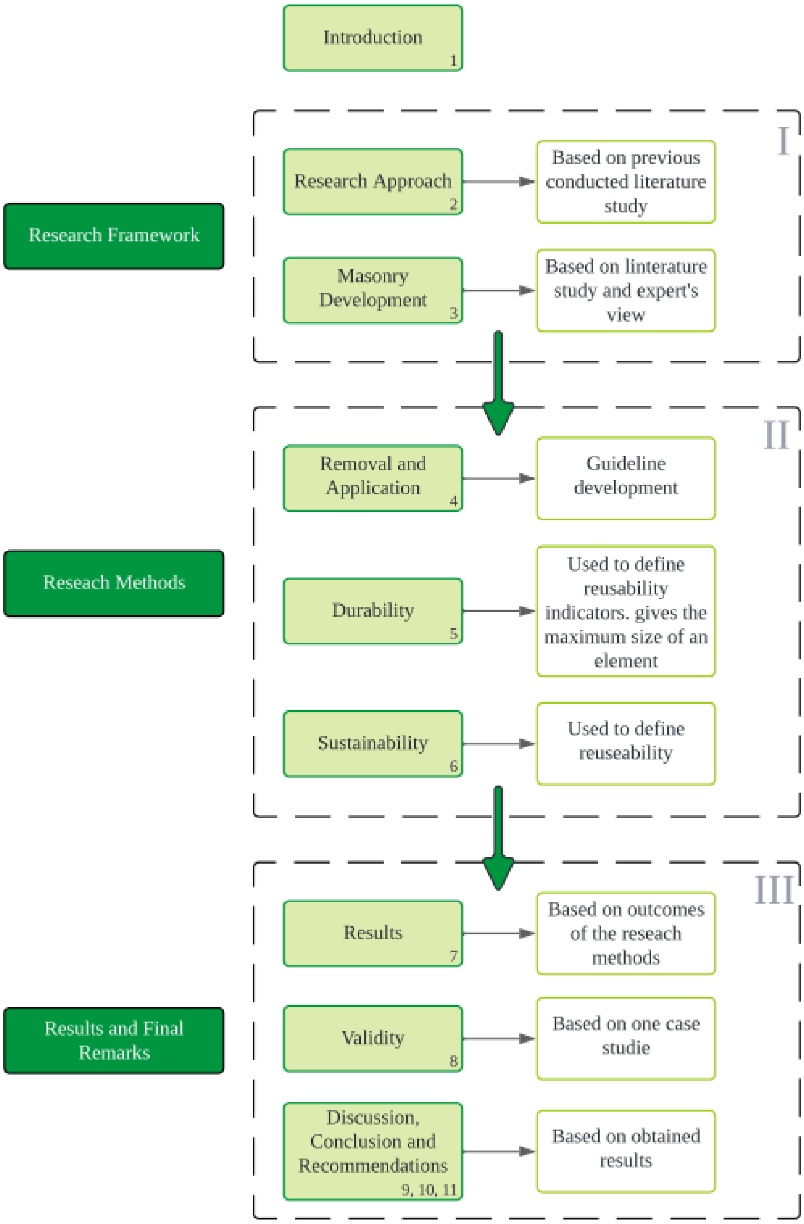


Figure 7: Thesis Outline

Chapter **3**

MASONRY DEVELOPMENT

3.1 MASONRY OF THE 20TH CENTURY

3.1.1 How Masonry Started

Masonry traces its origins to the Roman Empire, but knowledge of stone baking declined in the Netherlands after the empire's fall in the 5th century. It reemerged in Europe during the 8th and 9th centuries, particularly in Lombardy and Germany. By the mid-12th century, monks in northern Germany and Denmark began constructing brick monastery churches, and this knowledge eventually spread to the Netherlands. the first bricks in the Netherlands, dating to the late 12th century, were sized similarly to the tuff stone previously used (8-9cm thick and 37cm long), with tuff and brick often alternating in construction (Monumentenwacht Gelderland, 2010). Although the fundamental elements of masonry have remained consistent, its role has shifted form a primary structural material to a decorative outer layer, significantly impacting building practices. Modern construction now incorporate insulated cavity walls, diverging from historical method (Rijksdienst voor het cultureel erfgoed, 2023).

3.1.2 Development of Bricks

Around 1200, brick became a significant building material in the Netherlands. Production methods saw little change until the new-19th century. Clay was extracted through open-pit mining in the fall, allowed to ripen over winter, then transported and dried before firing. This process involves slow heating and cooling, resulting in variable brick quality (Rijksdienst voor het cultureel erfgoed, 2023). Post-1850, brick production accelerated with new baking and moulding techniques. The use of iron and reinforced concrete enabled thinner walls and introduced decorative masonry. Despite war damage, production levels were restored by 1949, with innovations such as machine-made handmade bricks, vacuum-extruded bricks, and lighter stones for better insulation.. By the late 1980, the industry modernized with tunnel kilns for precise baking and customizable colors and textures. (Rijksdienst voor het cultureel erfgoed, 2023)

3.1.2.1 Brick Size

Brick size evolved over time and can indicate the age of masonry. Older bricks, often based on foot measurements, were approximately 300x150x100mm. By the 13th century, mass production led to smaller, more uniform bricks, improving drying, firing and handling. It was also easier to handle the bricks during bricklaying and was more suitable for thinner walls in simple structures (Rijksdienst voor het cultureel erfgoed, 2023). Common sizes in the Netherlands include "The Vects format" (210x100x40mm), "The Waals format" (210x100x50mm), and "the F5 format" (230x110x57mm). Bricks can vary in colour, surface texture and profiling, and perforations – whether round, rectangular or slot-shaped- are used to reduce weight and enhance handling, bonding and drying efficiency. (ing. Ch. Rentier, 2005).

3.1.2.2 Shape Method

There are different shape methods developed. Traditional hand moulded bricks are created by throwing clay into a sand-coated mold, which is ten partially filled with clay. Excess clay is cut off with a wire, resulting in a brick with rough, sand-coated surface on five sides. This method creates bricks with an irregular grain pattern. Machine-made simulated hand-moulded bricks involve pushing clay into molds with a mechanical pressing block, which smooths off excess clay. These bricks have four sand-coated sides and one smooth, flat side.

Machine made extruded wire-cut bricks are produced by extruding clay into long strands, which are then cut into brick shapes. This method allow for various shapes, size and perforations, which help reduce weight, improve drying and firing processes, and enhance bonding strength. The surface of these brick can be smooth, sand-coated, grained, or rough.

Machine-made pressed bricks are formed by pressing clay into precise steel molds. These bricks have a distinct, regular shape and often feature factory marks or stamps. The bricks are dried before firing to prevent issues during baking. The final structure and colour are developed during the firing process.

3.1.3 Development of Stone Bonds

When bricks were first applied, a structured bond was not yet developed. In the northern part of the Netherlands, a variation of the Norse bond was used, and later, in the 13th century, in the southern and western parts of the Netherlands, the Flemish bond became popular. In the 14th century, the Flemish bond made a place for the English bond. Brick bonds serve a structural function. The connection between mortar and brick was not particularly strong; therefore, the brick bond had to ensure stability. (Monumentenwacht Gelderland, 2010)

As steel and concrete dominated structural frameworks, masonry became more of a filler than a structural wall. This made that the emphasis on strong masonry bonds was less necessary. Thin is commonly adopted a half-bond pattern, also called a stretcher bond. (Rijksdienst voor het cultureel erfgoed, 2023)

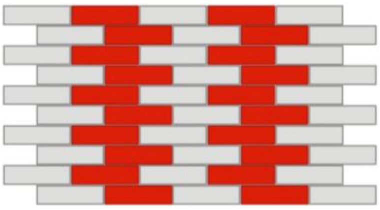


Figure 8: Stretcher Bond **(Röben, 2024)**

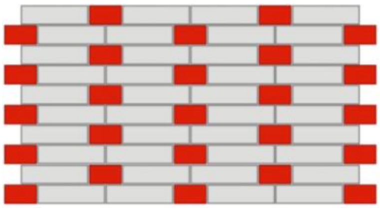


Figure 9: Nors Bond **(Röben, 2024)**

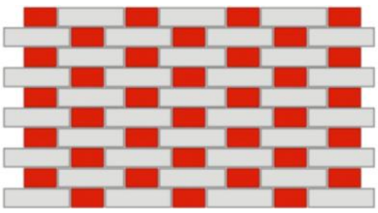


Figure 10: English Bond **(Röben, 2024)**

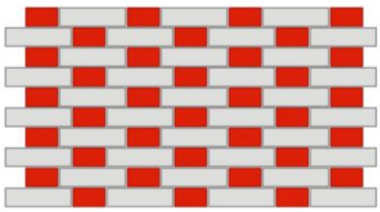


Figure 11: Flemish Bond **(Röben, 2024)**

3.1.4 Development of Mortar

Mortar, a blend of inorganic binders, aggregates, water and additives, has been essential in masonry, plasterwork, and floor finishes. Traditionally, it was made from shell slime and sand, with ground tuff stone enhancing waterproofing to create trass mortar. Mortar was applied generously, benefiting form lime's slow harding process (Rijksdienst voor het cultureel erfgoed, 2023). Between 1837 and 1914, natural cements like roman cement emerged, offering quicker setting times and increased strength, which accelerate construction. The introduction of Portland cement around 1850 revolutionized building techniques, particularly for concrete foundations, through it only became the dominant binder in mortar later in the century. (Lynch, 1994)

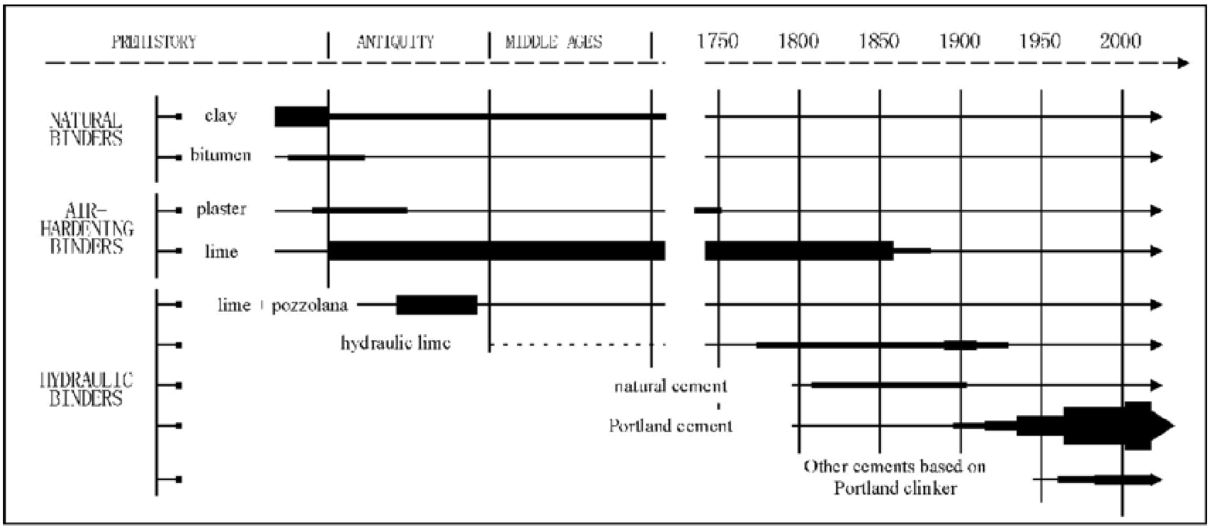


Figure 12: Overview of the Use of Binders in Construction (Modified form Furlan & Bissegger, 1975) **(Jan Elsen, 2011)**

The introduction of cement as a binder around 1850 led to the development of various modern mortars. Cement and lime are commonly used in mortar. Cement hardens though hydration, and incorrect water ratio can weaken it. Lime, including powdered, shell, and carbide lime paste hardens with CO2 from the air and improves workability, density and moisture regulations but slow the hardening process. Combining lime with Portland cement allows for a balance of workability and rapid setting. By the mid-20th century, prefab mortars became popular, including wet, semi-dry and dry types. Wet and semi-dry mortars are often used for masonry cement. It is a bled of Portland cement, limestone powder, and air-entraining agents, while dry mortar primarily relies on Portland cement with additives for enhanced performance. The compressive strength of mortar for exposed masonry must be a t least 7.5N/mm^2 (Rijksdienst voor het cultureel erfgoed, 2023). The choice of binder and mortar composition depends on factors like brick hardness, season of construction, desired workability, joint colour and mixing methods (ing. Ch. Rentier, 2005).

3.1.4.1 Aggregates and Water

Sand is used as an aggregate in mortar. The grain composition and size of the sand play a crucial role as they determine the density and load-bearing capacity of the mortar. The ideal particle size for masonry sand is between 0.1 and 3mm. Very fine particles in the sand may not exceed 2% of the total. However, some fine sand is always necessary to adequately fill the spaces between coarse grains.

The amount of water needed in mortar for masonry depends on the brick type, the nature of the binder and the type of sand used. Different bricks have different absorption rates. Some bricks extract too much water from the mortar, and this can disrupt the hardening process. (ing. Ch. Rentier, 2005). This also influences the mortar's adhesion to the brick. Good adhesion is achieved by adjusting the water retention capacity of the mortar to the suction capacity of the brick. (ing. Ch. Rentier, 2005).

3.1.4.2 Additives

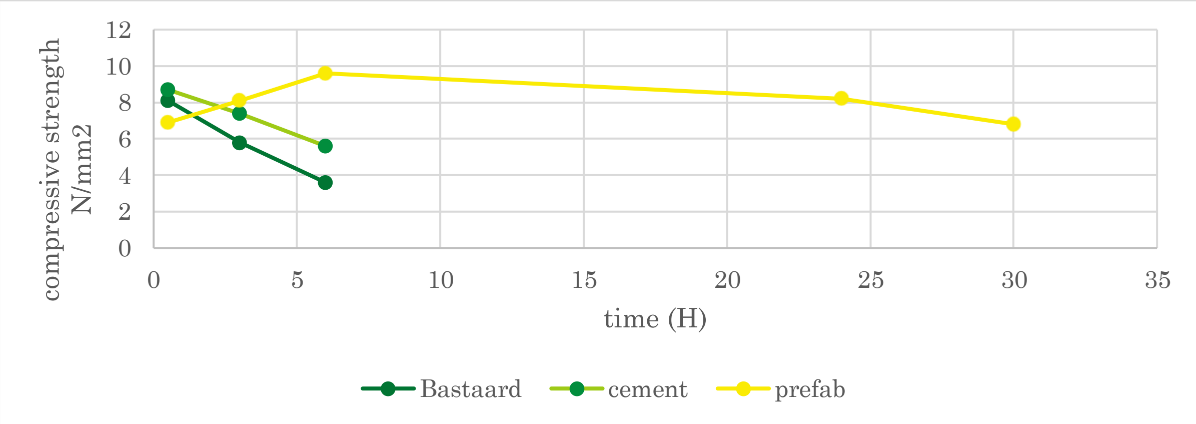
Additives such as air-entraining agents, plasticisers, and retarders can be used. Air-entraining agents improve workability by creating air bubbles but can increase water permeability and frost susceptibility. Plasticisers enhance workability but may also compromise mortar strength. Retarders extend the usability of prefab mortar. Prefab mortars offer consistent quality and performance. They are pre-mixed for reliability, whereas traditional on-site mixing often results in inconsistent quality (ing. Ch. Rentier, 2005).

3.1.4.3 Mortar Composition

The composition of mortar varies depending on factors like season and type. For composite mortars, typical formulations are Portland cement-lime sand in a 1:1:5 ratio for summer and 1:0.5:4.5 or 2:1:9 ratios for winter. Cement-sand mortar, in a 1:3 ratio, is less resistant to deformation, less workable, and retains less water during curing compared to composite mortars. Mortars can be prepared traditionally on-site or as prefabricated products. Traditional mortar is mixed on-site, often imprecisely using shovels, leading to variable quality. Prefabricated mortar, including wet, semi-dry, and dry types, offer more consistency. Wet prefab mortar is ready to use with a usable time of 12-30 hours and often includes additives like air-entraining agents, retarders, and plasticisers. Traditional mixed mortar is only workable for a maximum of 2 hours (ing. Ch. Rentier, 2005). Semi-dry mortar is delivered in a sile with sand an binders separated, with only water added on site. The sand has a maximum moisture content of 4% which helps prevent segregation. Dry mortar, which is pre-mixed with binder, sand and additives, only requires the addition of water on-site, ensuring consistent quality.

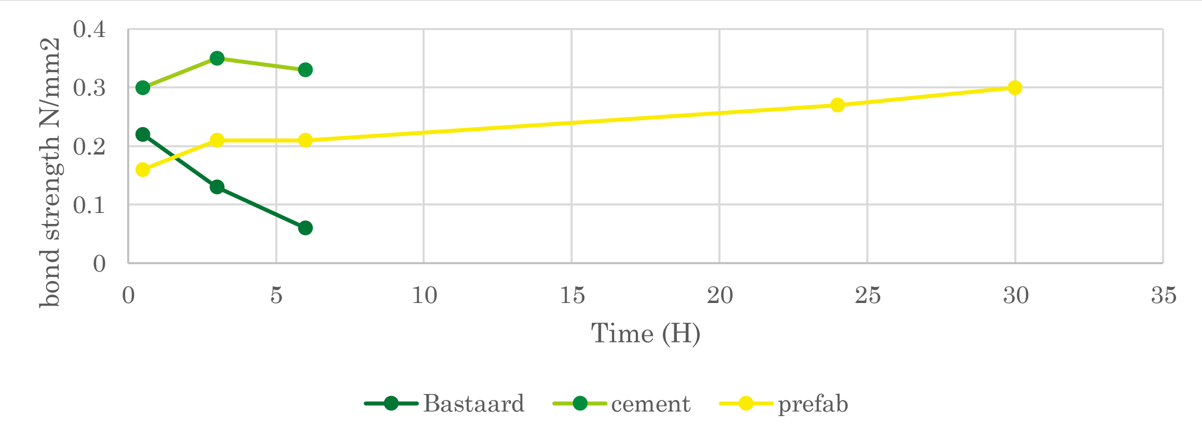
Research by SBR in 1979 showed that prefabricated mortars are more reliable then traditional site-mixed mortars. Prefab mortar demonstrated increased compressive strength over the first 6 hours, reaching put to 9.6N/mm², before decreasing (Table 1: Influence of Processing Time on Compressive StrengthTable 1).

Table 1: Influence of Processing Time on Compressive Strength **(Dreu, 1979)**



In contrast, traditional mortars, particularly bastard and cement mortars, showed a decrease in strength immediately after application. Prefabricated mortars also exhibited improved bond strength over time compared to bastard mortars. Although cement mortar had the highest bond strength (Table 2), it was less workable than prefab options. Overall, prefabricated mortar offer better consistency, workability, and reliability than traditionally mixed mortars. This also implies that building where prefab mortars has been applied correctly are best suitable for reuses due to the consistency in quality and strength of the masonry.

Table 2: Influence of Processing Time on Bond Strength **(Dreu, 1979)**



3.1.4.4 Mortar Durability

The durability of mortar joints in masonry lifespan is closely tied to their surface hardness, predominantly influenced by cement content. Insufficient hardness can result in gradual erosion of the joint surface due to physical damage, wind exposure, insect infestation, and salt crystallisation effects. Mortars are classified into grades MX1 t/m MX5, determining both durability requirements and strength properties (Nederlands Normalisatie-instituut, 2011).

Table 3: Requirements for Material Selection in Relation to Environmental Class **(Nederlands Normalisatie-instituut, 2011)**

Environmental class	Brick Unit	Mortel	Masonry $f_{xk,1}$
MX1	Every	Every	≥ 0.2 N/mm²
MX2.1	F0, F1 or F2 and S2	≥ M5	≥ 0.3 N/mm²
MX2.2	F0, F1 or F2 and S2	≥ M5	≥ 0.3 N/mm²
MX3.1	F2 and S2	≥ M5	≥ 0.3 N/mm²
MX3.2	F2 and S2	≥ M5	≥ 0.3 N/mm²
MX4	F2 and S2	≥ M5	≥ 0.3 N/mm²
MX5	The effect of exposure needs to be assessed.		

To manufacture masonry that meets the specific criteria and withstand the environmental conditions, consideration should be given to climate factors, moisture exposure, freeze and thaw cycles, and the presence of chemicals causing damaging reactions. Consideration should be given to the effect of macro-conditions on the micro behaviour when determining the extent of exposure. Macro-environmental factors include rain, snow, wind and rain combinations, temperature, fluctuations, relative humidity variants, and coastal exposure to airborne chlorides and seawater. Potential sources of sulphates can include natural soil, groundwater, landfills, construction materials, and air pollution. In cases where aggressive chemicals other than airborne chloride and seawater may corrode the masonry, a class MX5 environment should be assumed. For areas within 10km of saltwater, the environmental class will generally be MX4. (Nederlands Normalisatie-instituut, 2011)

Table 4: Connection between Environmental Classes and Corrosion Classes according to NEN-EN-ISO 12944 **(Nederlands Normalisatie-instituut, 2011)**

Environmental class	Corrosion class	
MX1	C1	Within dry, heated buildings

MX2.1	C2	Unheated buildings, condensation possible
MX2.2	C2	Environment with low pollution levels, often rural areas
MX3.1	C2	Environment with low pollution levels, often rural areas
MX3.2	C2	Environment with low pollution levels, often rural areas
	C3	Urban and industrial environments with moderate sulfate and sulfur dioxide pollution
MX4	C3	Coastal areas with low salt content in the atmosphere
	C4	Industrial and coastal areas with moderate salt content in the atmosphere
MX5	C4	Industrial and coastal areas with moderate salt content in the atmosphere
	C5M	Coastal and offshore areas – high salt content

3.1.5 Development of Cavity Walls

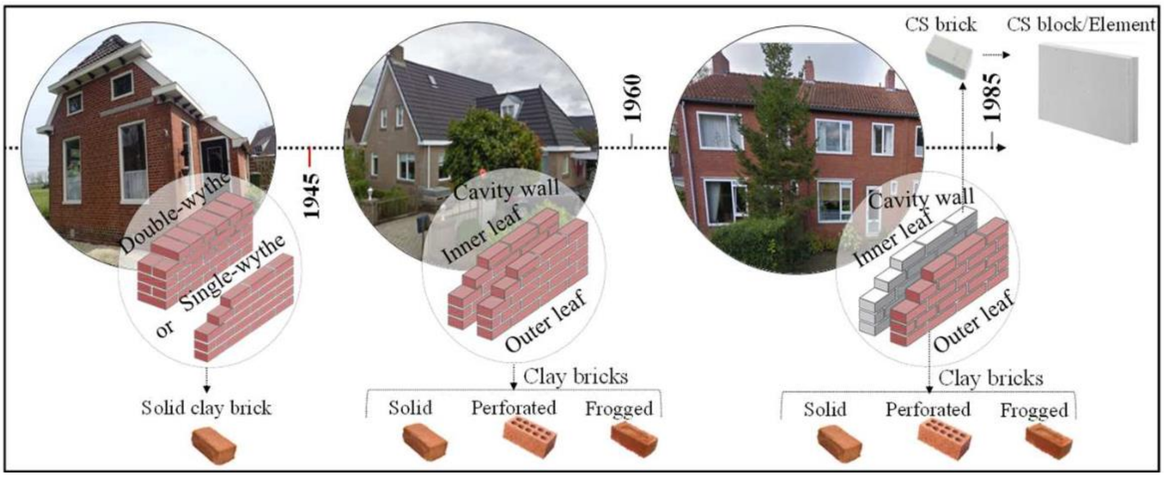


Figure 13: Types of Masonry Cavity Wall in the Netherlands. **(Jafari, 2021)**

In the twenties, cavity walls were developed to prevent water penetration into solid walls. The thickness of the cavity walls depends on the applied insulation. Normally, a 40mm air gap is applied between the outer leaf and the insulation. The air gap is necessary for ventilation. Ventilation facilitates the drying of the outer leaf. Cavity ties are used to connect the inner and outer leaves. It contributes to the stability of the external façade; therefore, a cavity tie must withstand various forces such as wind loads, deformations and corrosion. (ing. Ch. Rentier, 2005). The outer leaf of the cavity wall can be schematised in three different ways. On the left side of **Error! Reference source not found.** masonry supports are visible; therefore, the masonry is a pplied to elements. In the middle of the figure, concealed masonry supports are applied. Therefore, the masonry looks like continuous masonry, though it is not. On the right side, continuous masonry is applied. (SBR, 2012)

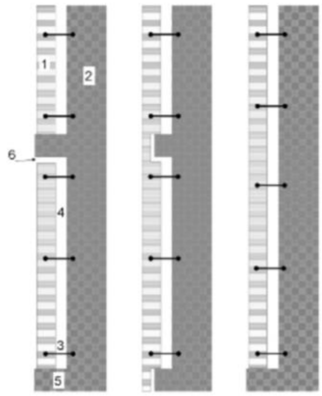


Figure 14: Schematized View of Cavity Wall

Samira Jafari researched the building stock in the Groningen region. Here, she found out that most pre-war buildings were constructed of a double wythe brick masonry wall ("steensmuren") with timber floors. At the beginning of 1945 cavity walls were applied with a non-load-bearing outer leaf of a sing-wythe clay brick masonry and a load-bearing inner leaf of single-wythe clay masonry. Later, around 1960, the inner clay masonry leaf was replaced with calcium-silicate masonry. (Jafari, 2021).

3.2 APPLICATION IN THE NETHERLANDS

The Netherlands, with its rich cultural heritage and strong commitment to sustainability, stands out for its dynamic urban landscapes, characterised by diverse buildings that shape the physical environment. Residential buildings are categorised into single-family and multifamily houses, each further delineated into specific types. Single-family houses include detached, semi-detached, and serial houses, while multifamily houses comprise apartments and other multifamily configurations. See Table 5 for the overview. Other buildings that fit the non-residential are discussed in Appendix B.

Table 5: Type and Functions of Residential Housing

Residential
Single-family houses
• Detached houses
• Semi-detached houses
• Serial houses
Apartments/multifamily houses

By examining the current stock of buildings, demolition rates, and future perspectives, we can show the potential available material for reuse.

3.2.1 Current Stock

Understanding the current housing stock in the Netherlands is crucial for understanding the quantities available for various purposes, including potential material reuse. As of the latest data from the Central Bureau of Statistics (CBS) in 2023, the total stock of buildings in the country is divided into residential and non-residential categories, with residential structures dominating the landscape. Residential houses contribute significantly to the overall stock, with an impressive total of around eight million units. In contrast, non-residential buildings constitute less than one million of the total stock. It's worth noting that the stock quantity doesn't directly translate to the available masonry, but it provides a foundational understanding of the built environment's composition.

Table 6 Presents a breakdown of the current stock of residential houses in the Netherlands, numbers for non-residential houses can be found in Appendix B. Residential houses are often constructed using traditional methods, including masonry.

Table 6: Current Stock of Houses in the Netherlands **(CBS, 2023);**

	2023
Detached houses	1042700
Semi-detached houses	704100
Serial houses	3380100
Apartment	2945900

However, it's not just the total quantity of residential houses that is important; the temporal aspect of their production also holds significance. Analysing data from the CBS allows us to map out the stock of houses per building period, revealing insights into construction trends over time.

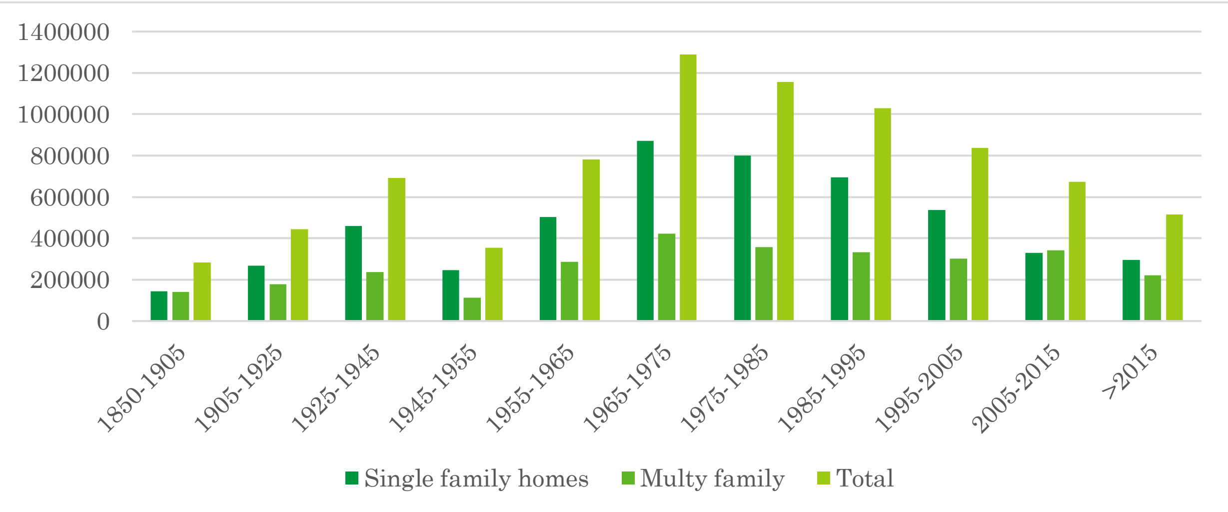


Figure 15: Current Stock per Building ear **(CBS, 2023)**

Figure 15 Illustrates that single-family homes have consistently been constructed in significant numbers across different periods of the last century, with a notable exception in 2005-2015. The most substantial increase in house construction occurred during the period 1965-1975, with a total of 1.29 million houses built. This provides a historical perspective on the evolution of residential construction in the Netherlands, offering valuable context for understanding the age, structural characteristics, and potential material availability of existing housing stock.

3.2.2 Demolition Numbers

The dynamics of construction and demolition in the Netherlands are intricately tied to various determinants that shape the housing landscape. Household growth is a primary driver for new home construction, while the age and quality of the housing stock significantly influence the demolition of existing homes. In addition, evolving quality standards play a crucial role in the decision-making process for demolition. These include the age distribution of the building stock, anticipated economic growth, ongoing sustainability policies, changing quality standards, and the overall development of the building stock. To provide a comprehensive overview, demolition numbers for residential housing have been meticulously documented, not only by type but also by construction year class. The materialisation of these buildings can vary significantly based on the era in which they were constructed. Notably, a substantial number of demolitions occurred in 2019, focusing on serially built single-family homes and apartments from 1945 to 1970. This trend is attributed to these early post-war homes' comparatively lower quality and the heightened standards expected of modern residences. See Table 7.

Table 7: Demolition Numbers Residential Housing **(EIB, Metabolic and SGS Search, 2022)**

	< 1945	1945 - 1970	1971-2000	>2000	Total
Single-family	**1300**	**3000**	**500**	**300**	**5100**
Detached	300	200	100	0	700
Semi-detached	200	300	100	0	600
Serial	800	2500	300	300	3800
Apartments	**700**	**3600**	**900**	**500**	**5700**
Total	**2000**	**6600**	**1400**	**800**	**10800**

Moreover, housing corporations play a pivotal role in this landscape, as their stocks predominantly consist of apartments and serially built single-family homes. Consequently, they contribute significantly to the higher demolition rates in these categories, in contrast to private landlords and homeowners. The demolition numbers provides insights into the trends and preferences shaping the evolution of residential structures in the Netherlands.

3.2.3 Future Perspectives

It is expected that new residential construction will continue to increase in the coming years, reaching approximately 90,000 homes per year until 2026 to meet the demand for housing. From 2026 onwards, new construction will gradually decrease to around 700,000 homes in 2030 and decline to nearly 50,000 in 2050. This decline over time is the anticipated decrease in household growth. As fewer households are expected to be added over time, there will be progressively less demand for expansion. However, the demand for replacements is likely to increase over time. The demolition of homes is expected to increase over time, reaching around 17,000 houses in 2030 and 24,000 in 2050. This represents more than a doubling compared to 2019. The associated gradually increasing demolition rates are influenced by factors such as the growing emphasis on sustainability and comfort standards, leading to more demolitions over time. While in 2019, new construction far exceeded demolitions, in the future, these two aspects will come closer together. Despite the increase in demolitions relative to new construction, it is projected that in 2050, more than twice as many new homes will be built compared to the number demolished.

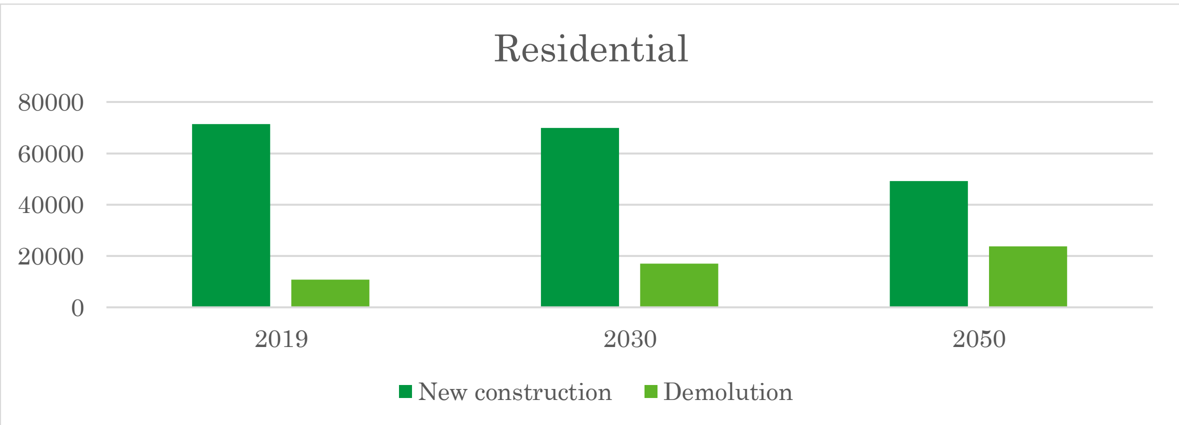


Figure 16: Residential Comparison of New Construction vs Demolition **(EIB, Metabolic and SGS Search, 2022)**

In Table 8, the figures mentioned above are more comprehensively described. What stands out is that, compared to the scenario in 2019, the construction and demolition of homes will come closer together. In 2019, the number of new buildings was nearly seven times higher than that of demolitions; however, by 2030, this ratio will be reduced to four times, and by 2050, it will decrease to only twice as large. The situation is slightly different for non-residential construction. Here, demolitions increase somewhat, but the overall pattern remains the same: new constructions will be approximately twice as many as demolitions.

Table 8: Future Perspective of New Construction and Demolition (EIB, Metabolic and SGS Search, 2022)

	New Construction			demolition		
	2019	2030	2050	2019	2030	2050
Residential	**71500**	**70000**	**49300**	**10800**	**17000**	**23800**
Single-family	43600	33300	23500	5100	8500	13700
Multiple family	27900	36700	25800	5700	8500	10100

3.2.4 Conclusion

The analysis of the current stock reveals a predominant presence of residential housing, with a significant concentration in houses constructed between 1965 and 1975. This period marked a surge in residential construction, which aligned with post-war housing needs. The temporal correlation is further emphasised by the peak in residential housing demolitions in 2019, predominantly affecting structures built from 1945 to 1970, totalling 6,600 houses. This demolition trend encompasses 3,000 single-family homes and 3,600 multifamily dwellings. Post-war housing demands necessitated rapid construction, resulting in a substantial number of houses that, while meeting immediate needs, are often perceived as of lower quality. It's essential to clarify that the term "lower quality" does not necessarily refer to the structural integrity of the houses but instead reflects their alignment with contemporary standards. Many of these structures, especially those built from 1945 to 1970, may not meet modern expectations regarding amenities, energy efficiency, and design aesthetics.

3.3 MATERIAL FLOW

3.3.1 Bricks

Figure 17 shows that most building types have an average of 75% concrete. It is also evident that a relatively large number of bricks are used except in distribution centres, commercial buildings, and large offices. On the other hand, schools and residential care centres contain a relatively significant amount of sand-lime bricks. Aligned with the production and demolition landscape, the inflow of materials exceeds the outflow. Even with the direct, high-quality application of all materials released from demolition, restoration, and renovation, less than a quarter of the total demand for construction materials within the chain could be achieved. In practice, many materials are not immediately suitable for high-quality reuse, resulting in a much lower potential. The potential for reuse is highly product- and context-specific, influenced by factors such as quality differences, technical specifications, logistics, and financial-economic aspects. The mass balance, therefore, only reflects the theoretical potential in which the supply of secondary material could meet the demand. In 2019, the supply of sand-lime bricks was 1.4 times greater than the demand. Sand-lime bricks are more abundantly generated during the demolition of older buildings than used in new construction. Row houses accounted for the largest share of the total demand for construction materials within the housing sector in 2019. 35% of the total material demand stemmed from row houses, 25% of the material was used to construct detached homes, and 16% went towards multi-family dwellings and apartments. It appears that approximately 87% of the materials still have a primary origin, while about 8% of the materials have a secondary origin.

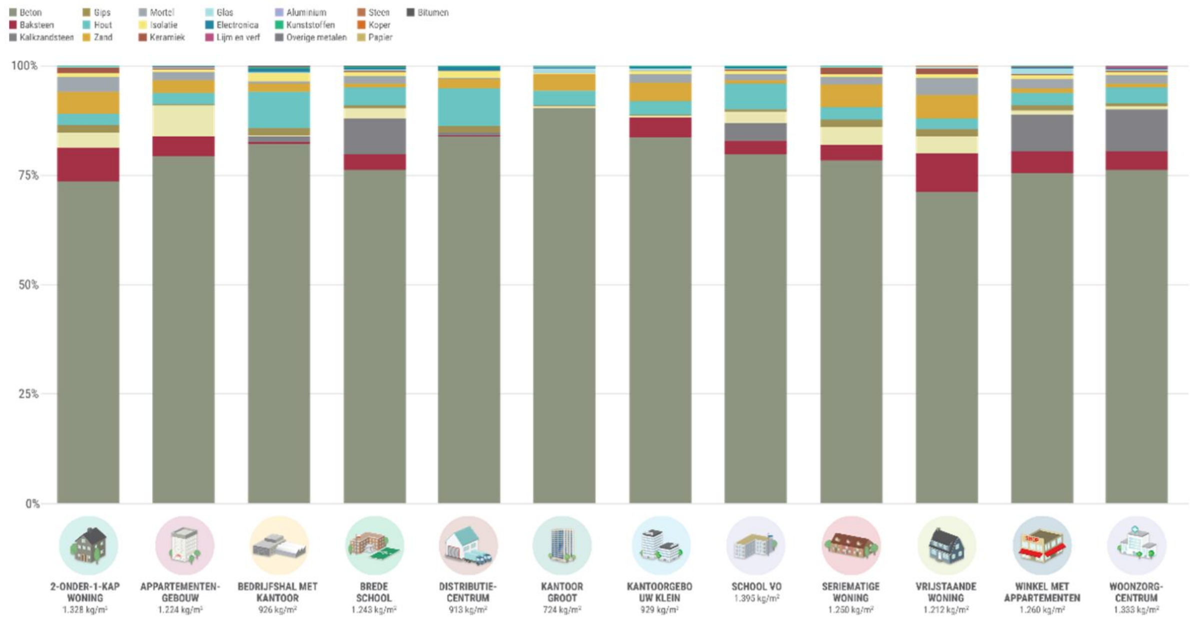


Figure 17: Materials Needed for New Construction per Building Type (EIB, Metabolic and SGS Search, 2022)

Looking ahead to the future perspective in 2030 and 2050, it can be observed that the inflow and outflow of clay masonry materials are converging. In contrast, the trend for sand-lime bricks has remained relatively consistent over the years.

3.4 REUSE PROCESS

The CB23 (circular building 2023) has published a guideline for the quality assessment and assurance of building products (Platform CB'23, 2023). This document will also be the guideline for the guidelines produced in this thesis. According to CB23, a product is suitable for reuse if it meets all functional requirements of the new application, complies with current legislation and regulations, and can be dismantled and installed in the new structure for any desired period. This involves both technical and human factors during the quality assessment. For reusing masonry, not only must the masonry quality be assured, but design-specific requirements must also fit into the donor project.

In Figure 18 The division of the guideline is given. Here, the divergent types of routes of the reuse process, in terms of financial flow, information flow, physical flow and process steps, are given. They divided this scheme into four parts. A: Preliminary Phase, B: Matchmaking Phase, C: Quality Research Phase, and D: Implementation Phase.

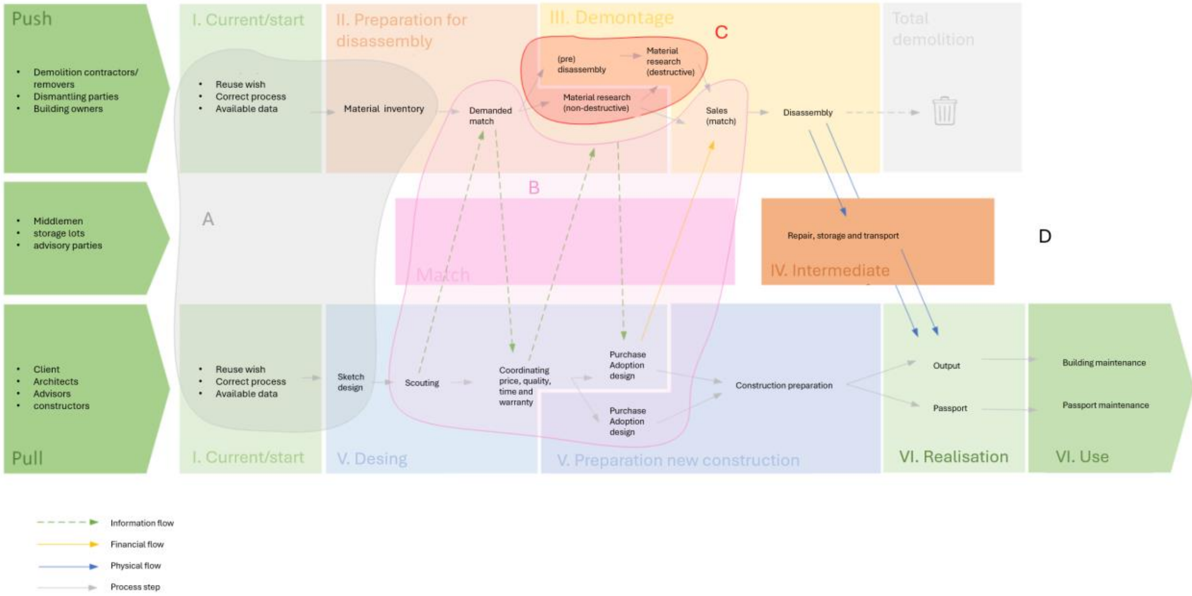


Figure 18: Division Guideline (Platform CB'23, 2023)

3.4.1 Preliminary Phase

In the preliminary phase, it is possible to look at it with different functions, for example, the client or a (demolition) contractor. When a client takes the initiative to reuse during the demolition (Push), they are responsible for mapping the buildings. This can be done by reusing scans. This involves identifying which products are suitable for reuse and gathering relevant information for potential buyers. Information collection includes data on the building and its products, such as mandatory hazardous materials inspections, types of material used, connection in the original construction, and usage and renovation history. Other relevant information can be an LCA that has been performed at the delivery of the original construction, original product sheets from the manufacturer, technical drawings of the structure, inspection reports, damage reports, and photos of the building. This will give a general view of the building as a whole, as well as how all the parts are connected. When the client is on the pull side and is looking for a product, it is essential to create a broad plan and identify reuse needs as early as possible. Finding a match and conducting quality research takes time, and reuse projects are more likely to encounter unexpected issues and setbacks. If no suitable reuse match is found, the design may need to be adjusted.

In terms of the demolition contractor on the push side, since this method of demolition involves more dismantling, it is necessary to gain experience and specialise in the dismantling process to create more possibilities for reusing products. The same goes for the contractor on the pull side; expertise is needed to handle reuse products, and adaptation to the way of construction may be a given.

3.4.2 Matchmaking Phase

The matchmaking phase brings the supply (push) and demand (pull) together. Matchmaking involves both human and technical aspects. The matchmaking phase has a more dominant human aspect to it. Since it involves collaboration between parties, as well as timing of execution and negotiation conversation. To be able to have these conversations, it is also important to determine the quality of the reused product. Masonry is a design-specific product, which means that additional information to determine the quality is often needed to ensure the quality. It is important to check the planning on both the push and pull sides and start with early accessible information before moving to harder-to-find details. Sometimes, readily available information can show that a product doesn’t meet the requirements, preventing unnecessary research costs.

3.4.3 Quality Research Phase

During or shortly after the matchmaking phase, quality investigations are needed to determine if the masonry is suitable for reuse in a new construction. This includes determining the suitability for reuse by assessing if the masonry meets the requirements of the new structure. In Table 9 Part of the assessment list for reuse is given; this table only includes topics that are suitable for the reuse of masonry.

Table 9: Assessment List (Platform CB'23, 2023)

Intended objective	Assessment of masonry is suitable for reuse in an adopted structure.	
	Quality studies to be carried out	Explanation
Obstacles to reuse	Assessment of the condition of the product to make a statement about conservation for reuse in relation to building regulations	Visual inspection is performed for abrasion, deformation, damages, thaws-freeze damage, etc.
Feasibility of intended reuse	Investigate the method of disassembly	Technically and financially
	Assessing the feasibility of transport	Technically and financially
	Assess temporary storage	Where it can or cannot be placed
	Investigate methods for reassembly	Technically and financially
Suitability of product due to age	Research year of construction of the doner building	Municipal archives are at the building owner
	Determining the residual life of the product	The assessment of the condition.
Mechanical and material properties	Research into the mechanical and other material properties	Which research is required to be performed based on what is found in existing calculations and technical drawings
	Applicable standards during installation, during construction and renovation	Needs to be checked with existing calculations.
	Determining material strength	Test performed in lubritorium of in-practice
Making it plausible that with the application of the product, the adopted structure can meet the requirements of structural safety	Testing against the public law structural requirements for application in the adopted structure	New construction (Eurocode) and renovation (NEN8700)

When testing structural products, three important aspects are composition and mechanical material properties, load-bearing capacity, deformation capability, and remaining lifespan. For all structural products, generic quality parameters affecting reuse are divided into five categories: general data, load-bearing capacity, remaining lifespan, dismantlability and environmental data. For masonry, the following information is a possible reuse parameter.

- **General data:** Availability of original documentation and calculations, maintenance history, age, environmental conditions, load history, quantities and availability, owner, current product function, dimensions and location.

- **Load-Bearing Capacity:** compressive strength, flexural tensile strength, flexural bond strength, type and quality of bricks and mortar composition
- **Remaining Lifespan:** Condition and state of masonry, modifications, defects, impregnation of material, permeability, frost-thaw resistance, and mortar joint hardness
- **Dismantlability:** Application method, form closure, connection accessibility, location in the environment and the location in the building
- **Environmental** Data: building physic properties, coating/impregnation and cement type.

The easiest and most cost-effective way to obtain the first information is through desk research. This involves checking the original calculations, tender specifications or product sheets. However, in practice, these documents are often missing. If the desk research yields no results, visual inspections and non-destructive measurements can provide valuable information. The first findings of the desk study, together with a visual inspection, can give an indicative understanding of the properties, which is often sufficient at the beginning g of the process to decide between reuse and high-quality recycling.

The following tests can give an overview of the masonry facade properties and their potential for reuse.

- **Joint hardness measurement with a pendulum hammer:** this helps determine the environmental resistance of the masonry;
- **Bond-wrench tests:** these assess the cohesion of the masonry;
- **Compression tests:** these tests determine the compressive strength of the bricks;
- **Core drilling and laboratory analysis:** These tests examine the physical properties of the masonry;
- **Mortar sample analysis combined with chemical laboratory analyses:** These analyses provide detailed information about the mortar composition;
- **Building physics test:** these tests assess the permeability and frost-thaw resistance of the masonry;

3.4.4 Implementation Phase

The matchmaking phase results in the purchase or sale of a product, followed by the implementation phase, where dismantling, transportation, potential repairs, and storage occur before the final application in the new structure.

Before the demolition/dismantling starts, a project work plan should be made. This includes information about what parts of the wall will be dismantled and which parts will be demolished in the traditional way, a planning for the demolition activities and what techniques are used, any hindrances that can be expected, the ways to comply with demolition regulations and additional municipal conditions, and a dismantling plan. This dismantling plan consists of work instruction, an overview of all recovered materials elements, including possible contaminations, dismantling tasks for harvesting reusable elements, including packaging, transport and storage methods, product quality aspects, including internal rejection criteria, external acceptance criteria, and control methods, product control methods and responsible personnel, a destination for reusable products (storage, new structure, etc), control of proper disposal of reusable products, materials not reuse, separation methods, and recycling destination, an overview of waste streams with expected qualities, and registration requirements. ,

The dismantling client must verify substance accountability from dismantling to storage or application in the new structure. Substance accountability documentation should record the old location, new location (if known) or storage location, manufacturer (if known), quality, dismantling date, dismantling contractor, mass (kg), dimensions, product type, material family, material type, and functional test results. After delivery, document the new location, installation contractor, connected products, remaining lifespan, application, additional test results, product material, mass (kg), and dimensions, preferably in a building passport

Part II
Development Guideline

Chapter 4
REMOVAL AND APPLICATION

To get a full understanding of the possible process for the removal and application of masonry panels, different steps have been looked into. To make the concept work, it is assumed that there are six steps that nee to be performed. These also correlate to part of the steps in the reuse process (Chapter 3.4). the first step, which is about the current state of the masonry, can be split in an archive research an a visual inspection. The second step would be the physical inspection of the wall. In this case, that would entail testing if the wall has enough strength to be lifted and transported without failing. When the test is performed and the results are above the threshold, the next step would be removing the panel for the existing situation. The steps afterwards are within expectations, such as hoisting, transport, storage and the implementation of new construction. In this chapter, these seven steps will be thoroughly discussed.

The information in this chapter is based on a project of Vink B.V. called office full of trash (kantoor vol afval). This is a renovation project for the government real estate company where everything that is applied is either second-hand (reused) or product with production errors. Other knowledge can be pulled from a test performed by Nebest in Augustus 2023 on a demolition project in Zaandam for Marcus B.V.

4.1 DESK RESEARCH AND VISUAL INSPECTION

For the desk research and visual inspection the SBR publication 'Structural safety of existing masonry cavity walls' from 2012 can be applied. It indicates that in order to make a statement about the structural safety of a cavity wall, an inspection must be carried out. For a structural assessment, it is necessary to have information regarding the actual construction and state of the cavity wall. That information can only be obtained through an inspection. The necessary scope of an inspection is largely determined by the desired levels of reliability and the variations in the aspects to be investigated. The SBR provides a minimal 'basis inspection' requirements. It can be split into desk research and visual inspection.

4.1.1 Desk Research

The Desk research should be performed before the visual inspection. Desk research is often a less time-consuming activity to perform. It also gives an early assessment whether masonry is applicable for reuse. The SBR publication also gives some point that should be known before performing the visual inspection. But also says that when the specific information cannot be collected during the desk research that it can be found during the visual inspection.

The SBR publication notes that the following information needs to be collected during the desk research:

- Location
- Construction year
- Desired reference period
- Orientation of façade
- Number of storeys
- Whether there is a presence of visible concrete masonry supports
- Whether there is a presence of concealed concrete masonry supports
- The number of storeys where masonry continues uninterrupted.

The SBR introduces very general desk research; most can be found by using platforms such as Google Maps and Kadaster's BAG viewer. This is also a small-time consumer. An more including option could be to visit the archives of the concerned municipalities. This would be a bigger time consumer. Though not always the case, as some municipalities are digitizing the archive document. After the introduction of the Housing Act in 1901, municipalities were obliged to draw up building regulations. This contains the rules for the construction, renovation, use and demolition of the building. Since then, though not in all cases, files have been kept on building permits. This sometimes also includes construction drawings and calculations. This information can be used to collect additional knowledge about the concerned building. Not all information that is needed for this concept will always be available at the archive. But if the right information is available, the curtained conclusion can be drawn beforehand. The information that is needed would be the mortar type and brick type that is applied. This will most often be found in drawings or calculations. If the document says that the applied mortar is a lime mortar, the chances that the concept of this thesis will work are rather small. It could still be an option. However, the individual strength of bastard and cement mortar is stronger than that of lime mortar, which still says nothing directly about the bond strength. However, the chance that the needed bond strength is reached is higher. Masonry built with lime mortar is often better suited to the voor de reuse option 'brick by brick' due to the fact that the strength of the masonry and the bond strength of the brick and mortar are softer. Another important factor is the type of brick used in the masonry. In this case, the most important difference would be the non-perforated bricks and the perforated bricks. In the case of perforation in the bricks, there is a change that when cutting the element, some part of the brick will break off due to weaker location in the brick due to the perforations.

4.1.2 Visual Inspection

When the desk research is completed, a visual inspection can take place. The visual inspection takes place on-site. According to the SBR, a visual inspection should include the assessment of the entire façade form up close, if possible. Additional information must also be included about the structure of the façade, and it must be determined whether there are any imperfections or indications that may indicate the presence of imperfections.

The SBR publication says to check the following information during a visual inspection of masonry: SBR gives the following information to check during a visual inspection of masonry.

- Does the outer leaf, or part thereof, protrude?
- Do parts of the outer leaf remain damp for long periods?
- Is there any cracking in the masonry?
- Are there visible filling holes indicating retrofit insulation?

However, for this thesis, the standard inspection of the SBR is not enough to give an indication whether the masonry can be reused. More information can be collected that will provide a better understanding of the current state of the outer leaf. During the visual inspection, an assessment can be made of the nature and extent of visible defects in the masonry and mortar joints. Based on the visual inspection, priority can be made on what façade (section) should be investigated further. One thing to note before the inspection is that the southwest-oriented façade experiences a relatively high exposure to weather conditions. Therefore, it will often be the façade with the most imperfections. Therefore, I would also suggest collecting the following information:

- What type of brick is applied?
- What type of stone bond is applied?
- What type of joint is applied?
- Is there any damage to the mortar joints?
- Is there any corrosive material visible?
- Is there any loss masonry visible?
- Is there nay visible damage to the masonry?

- Is there any repaired masonry visible?

An example for the first three questions could be a hand-moulded brick in a stretcher bond with a flat joint. During the visual inspection, a few non-destructive tests can be performed as well. One of their tests is joint hardness. The joint hardness is measured using a rebound hammer in accordance with CUR recommendation 61:2013. Based on the median of the measured values, the mortar joints are classified into joint hardness. The result is verified against the criteria specified in CUR recommendation 61:2013 for each application class. Masonry with relatively low quality and/or shallow joints is susceptible to erosion and weathering. Therefore, the likelihood of moisture penetration is higher than with mortar joints in moderate conditions. This can eventually lead to a greater risk of corrosion of the cavity ties.

Figure 19: Determination of Joint Hardness Using Pendulum Hammer @nebest

The joint hardness found can be placed in different classes form <VH15, VH15, VH25, VH35, VH45, as found in Chapter 3, the joint hardness for the outer leaf of the cavity wall should be VH35 or above. The hardness of the joint indicates that it can be relatively susceptible to deterioration, such as weathering, erosion, and frost damage. Another test that can be performed is the water absorption test. This can be done by spraying water on the façade; the water absorption of the masonry is done indicatively. The water absorption can be further measured by testing with a Karsten tube. In this test, the water absorption rate of the masonry is measured. The instrument consists of a measuring tube with a scale in mm that opens into a bell at the bottom. This bell is placed waterproof on the surface to be tested. In this process, the masonry is subjected to a water column of approximately 10cm over an area of approximately 3cm2. The water absorption is measured for 10 minutes while trying to keep the water pressure as constant as possible. If the masonry does not absorb water quickly, it may have been treated in the past with a water-repellent substance. If water is absorbed, it has either not been applied or is outdated.

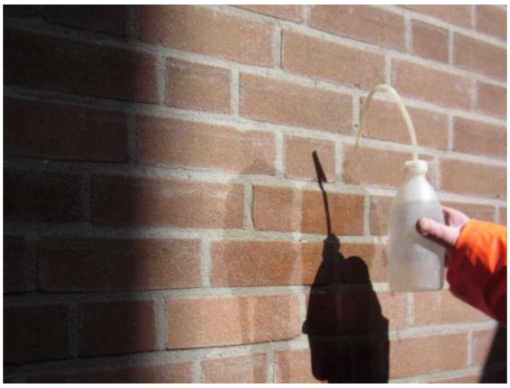


Figure 20: Indicative Determination of Water Intake @nebest

Figure 21: Testing Tube of Karsten @nebest

4.2 DESTRUCTIVE TESTS

When the desk research and visual inspection indicate that the masonry is in good condition to be reused, further testing is performed to ensure the structural durability of the masonry. Therefore, a test needs to be performed. These tests are destructive tests and will permanently change the brick façade, and parts of the wall won't be able to be used in the reuse process. Therefore, an overview needs to be compiled detailing all locations or sections of the masonry that will be reused. The destructive test can be applied to areas not designated for reuse. However, in case this is not possible, the quantity of the possible reuse elements will decrease to ensure the quality of the masonry. The primary focus of the destructive test is the bond strength. By removing masonry bricks through drilling and conducting lever tests, we can get an indication of the adhesion and cohesion of the mortar and the bricks. The flexural bond strength can be determined through tests such as EN 1052-5 and EN 2052-2. The test in EN 1052-5, the bond wrench method, is often used in practice on the location, while EN 1052-2 is tested in the laboratory with a testing machine. The bond wrench test described in Figure 22 to Figure 25 Can test 3-4 bricks on the flexural bond strength. To test these 3-4 bricks, about two layers of bricks above the to-be-tested bricks need to be removed to be able to place the lever head on the to-be-tested bricks. In the case of EN 1052-2, the laboratory test, the size of the masonry is important. It must allow for a distance between the inner and outer bearings equal to or greater than the specimen's thickness. It can be tested in the vertical and horizontal direction and is placed under a four-point loading. It is important that the base of the masonry specimen is free from frictional restraint. This can be done by setting it on roller bearings. The test can be seen in Figure 26 and Figure 27.

Figure 22: Removing Masonry Joints @nebest

Figure 23: Lever Test Determination of Bond Strength @nebest

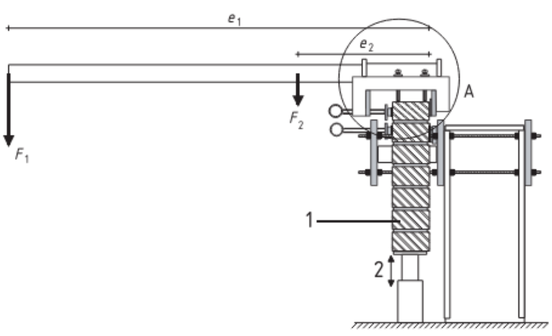


Figure 24: Overview Lever Test Principle EN 1052-5:2005

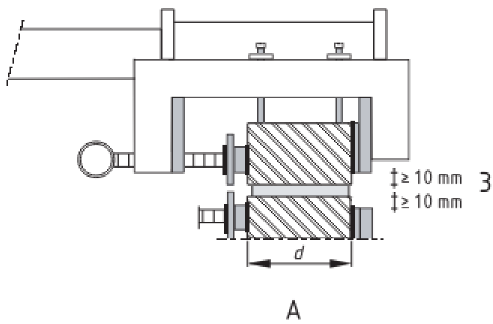


Figure 25: Detail Lever Test EN 1052-5:2005

Table 10: Specimens Sizes for Testing the Flexural Strength of Masonry Form NEN-EN 1502-2:2016

Direction	h_u [mm]	b [mm]	Additional conditions
Flexural strength for a plane of failure parallel to the bed joints	Any	≥ 400 and 1.5 l_u	Minimum two-bed joints within l_2
Flexural strength for a plane of failure perpendicular to the bed joints	≤ 250	≥ 240 and ≥3h_u	Minimum one head joint every course within l_2
	≥ 250	≥1000	Minimum one bed joint and minimum one head joint every course within l_2

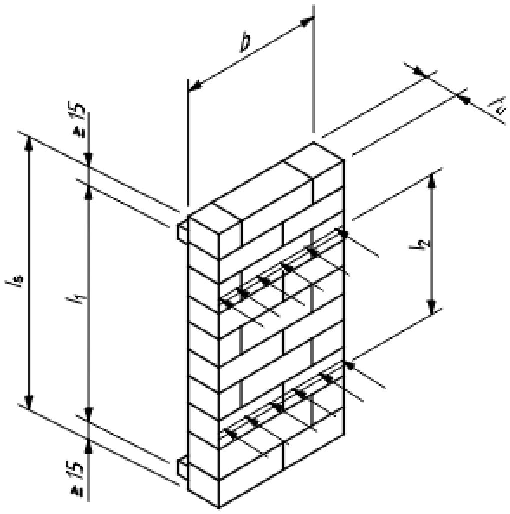


Figure 26: Flexural Strength for a Plane of Failure Parallel to the Bed Joints – NEN-EN 1052-2:2016

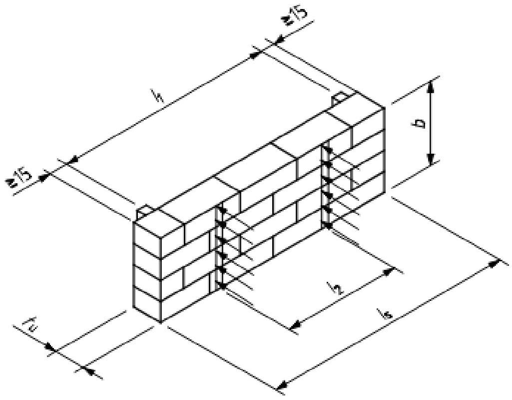


Figure 27: Flexural Strength for a Plane of Failure Perpendicular to the Bed Joints – NEN-EN 1052-2:2016

Both EN 1052-5 and EN 1052-2 specify the number of tests required. These regulations are more focused on testing in the laboratory, where specimens are produced and tested in controlled settings. The EN 1052-5 stipulates a minimum of 10 bed joints tested. However, interpreting this in a practical situation can become more complicated. For example, testing 10-bed joints on a brick façade of 40m² gives a very different conclusion than testing 10-bed joints in a 100m² brick façade. The size of the façade is important, as well as the results of the test and the testing locations. When the test locations are well distributed over the façade, and all results are well above the minimum value stated in the Eurocode, further destructive testing seems to be a waste of material that can be reused. However, in the case that the test results are on the border of the minimum stated value, more tests can be applied. In Table 11 It is an overview of possible scenarios and describes further actions. The ten bed joints that need to be tested can be more when the masonry wall is very long. For example, a number of terrace houses. There is a strong possibility for differences in flexural bond strength due to different circumstances when building, such as mortal mixture and weather. Therefore, more than ten-bed joint tests are required. EN 1052-2 stipulates that if fewer than five valid results are obtained, additional tests are necessary until five valid results are obtained. This test is not often applied in practice since the testing machine is needed to perform the test. With the offsite testing, additional transportation is a variable that makes it less appealing than the bond wrench test. The minimum flexural bond strength for traditional masonry, as discussed in this thesis, is given in NEN-EN 1996-1 as 0.3N/mm². However, for situations involving prefab or 'glued' brick strips, the required bond strength increases to 0.7N/mm². When the average results of the lever test are lower than 0.3N/mm², it is deemed unsuitable for reuse in the form of elements.

Table 11: An Overview of Possible Scenarios During Testing

Nr. of test	Distributed	Results (average)	Further steps
10	Well	> 0.3N/mm^2	No further steps are needed. Reuse is possible
10	Well	0.25N/mm^2 to 0.30N/mm^2	Test 6 more bed joints
10	Well	< 0.25N/mm^2	No further steps are needed. Reuse is not possible.
10	One-sided	Does not apply	Do more tests to make the test distribute well over the facade
16	Well	> 0.3N/mm^2	No further steps are needed. Reuse is possible
16	Well	0.25N/mm^2 to 0.30N/mm^2	It is possible to test more, but with the last six extra tests, the result has not gotten much better, so make a decision to test more only when it is useful.
16	Well	< 0.25N/mm^2	Do more tests to make the test distribute well over the facade

4.3 REMOVAL AND HOISTING

For the removal of the masonry, there can be a difference made between the two work methods. Outside in and inside out. Outside in means that the removal process starts by removing the outside to work your way to the inside. So removing the outer leaf to be reused, the inner leaf is still standing. In the case of inside out first the inner wall or load bearing wall will be removed. In both cases sawing is a big part of the process.

4.3.1 Sawing

Cutting masonry can be done in various ways. A distinction can be made between cutting with water or with a dust extraction. Cutting with water is often applied for hard types of stones and concrete, while dust extraction is applied to cutting red bricks or fast building blocks. The lever test discussed in paragraph 4.2, the cut is made in the mortar, not through the stone. For this purpose, a reciprocating saw can be used. This type of saw can also be seen in Figure 22. The saw machine can also be equipped with a special reciprocating saw blade for stones. This saw has a special tooth design that can cut through hard materials. Though in case of removing a big element, a more effective tool could be the hand-held wall saw shown in Figure 28. The figure below is a project carried out by Vink B.V. called Office Full of Trash (kantoor vol afval). The walls that separated the offices were cut into one-by-one masonry elements and used to build a new wall elsewhere in the office. Because the bonding of the masonry was quite bad (mortar was very easily removed from the brick), they took measures to keep the masonry together. They did this by placing wooden slats on both sides and attaching them with four bolts. Then, they cut the panel by moving the hand-held wall saw along the edges of the wooden slats.

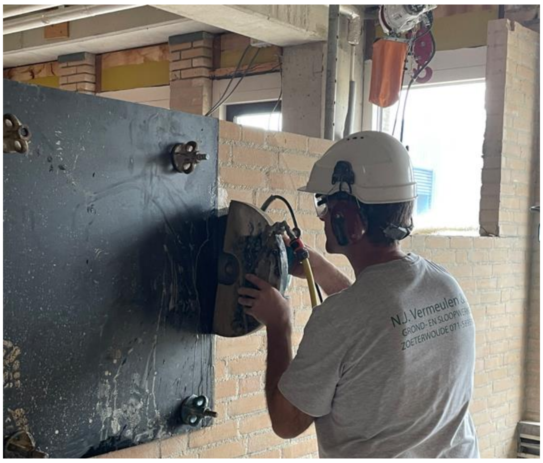


Figure 28: Hand-held Wall Saw by Vink B.V.


Figure 29: Transport by Forklift

4.3.2 Hoisting

Hoisting can be done in different ways. The three that are described in this thesis are transported by forklift, hoisting by a glass lifter and hoisting by lifting straps. Transported or hoisted by forklift is shown in Figure 29 and Figure 30. Figure 29 Shows how the masonry element was transported from the façade to the trailer for transport. Here, the masonry element was placed onto a steel frame and protected by wood pellets. In this case, it is possible to transport multiple units at once in between the pellets. In case of Figure 30 The wooden plates that are on the faces of the masonry hold the masonry together. In the case of direct reuse on location, this could be an option. Hoisting and transporting short distances with a forklift is convenient due to the straightforward way of working and the use of equipment that is most often already on site for demolition.


Figure 30: Transport by Forklift by Vink B.V.


Figure 31: Hoisting by Glass Lifter by Vink B.V.


Figure 32: Hoisting by Lifting Straps by Vink B.V.

The option to transport and hoist the masonry with a glass lifter is shown in Figure 31. The glass lifter cannot directly be used on the masonry. This does not have the sucking effect that glass has. An option is to apply a wooden plate on both sides to connect these with each other, and the glass lifter can be applied on the plate. Because it is connected to the plate on the back, it lifts the whole element. A downside of this is the size of the panel. A glass panel with a density of 2500kg/m^3 compared with a masonry panel with a density of 1900kg/m^3 is a big difference due to the thickness alone. The thickness of the masonry panel is an average of 50mm, while the glass is under 12mm. This gives the glass panel 30kg/m^2 and the masonry 95kg/m^2, which means that the masonry is 3.167 times heavier than a comparable glass panel. This means that the masonry panel will be three times smaller in area than the glass could be. This brings limitations to the process. Hoisting by lifting straps, illustrated in Figure 32, can be applied when removing the masonry on higher levels. A downside to this is the need for heavy machinery. But if this can be combined with the already applied machinery for the demolition, it can be combined. Another option would be a type of frame that can be lifted. One of these are in a research article of Zhiming Su (Zhiming Su, 2022) where the seismic vulnerability of masonry structures built with disassembled brick wall sections (DBWS) was tested. They developed a method for removal (Figure 35) and a method for lifting the wall elements by applying a clamping frame (Figure 36). The removal is done by a coring machine that forms holes at both sides; in later stadiums, these cores will be filled with concrete. Thus, the DBWS are used as infills. Because of the use of concrete, this is not specifically applied as an option in this thesis. The clamping frame they develop is an option that can be used for all masonry elements. This is a good option in case of the repetition of the same size masonry elements.

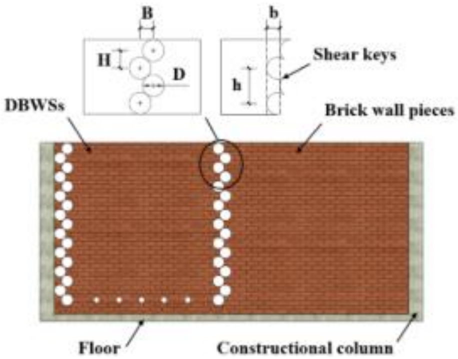


Figure 33: Removal DBWS (Zhiming Su, 2022)

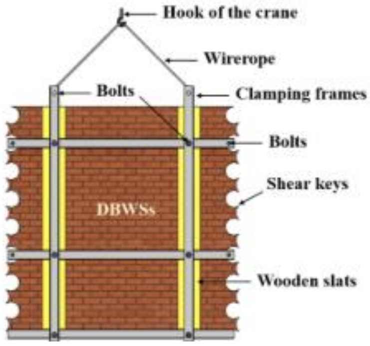


Figure 34: Clamping Frame Details (Zhiming Su, 2022)

Just as in Figure 34: Clamping Frame Details , where the masonry is supported on the bottom by a steel plate, it would be recommended to also apply the same principle in other hoisting methods. In this way the safety on the construction side can be guaranteed. Since no sudden lose bricks can fall down.

4.3.3 Outside In

With the outside in principle, the outside wall will first be dismantled. Therefore, the load-bearing structure of the building is still functioning. With the demolition of the complete building, the roof structures need to be removed first. Scaffolding is placed next to the façade, and gangways are made in locations that make it possible to cut in the masonry safely. Before cutting the masonry, the wall ties need to be disconnected from the load-bearing wall. If this is not done, there is a risk that the masonry will be damaged during the removal. In the case of corroded wall ties, the possibility exists that the wall ties will break during the removal before the masonry shows damage. However, this is not something that can be taken for granted. Masonry is weak in the out-of-plane direction. Thus, changes in damage are bigger. Removing the wall ties can be a bottleneck in the removal of the element. Not a lot of space is available between the inner and outer walls; also, there needs to be room to insert the tool to cut the wall ties. Therefore, if the corroded wall ties are already so far corroded that they do not physically connect the outer leaf to the inner leaf or the wall ties have been sparsely placed during construction, the outside-in method can be very easily applied. In the case that the to-be-cut element is large and normal cutting tools cannot reach the wall ties, a special tool can be made to reach and cut the wall ties. Since the roof is removed first, it is possible to insert the cutting tool from the top. After all the wall ties are removed, the vertical cuts and horizontal lower cuts can be made with a saw. The cut can be made at any location, though for the coherence of the masonry element, a cut that goes through the middle of the brick is advised. By lifting the element a few centimetres, small blocks can be placed underneath. This allows the lifting straps or forklift to be placed underneath to be transported to the ground level. This process can be repeated all the way until the masonry elements are located at ground level.

4.3.4 Inside Out

With the inside-out principle, the inside wall will first be dismantled. Just like the outside in method, the roof will be removed first. The scaffolding is placed in the same way as well. Because the proceedings for cutting the masonry element have not changed. To ensure the stability of the structure, smaller parts of the load-bearing walls will be removed. An advantage of using this method is that by removing the inner wall, the insulation material and the wall ties are easier to remove due to the fact that nothing is blocking the backside of the masonry element. When these are removed, the cutting process takes place using the same procedures as the outside method.

4.4 TRANSPORTATION

The transportation of the elements is a special case. Masonry is weak for out-of-plane loading; it can be compared to a reinforced concrete wall element. Transport for prefabricated elements goes hand in hand with careful planning and making the right adaptations to the elements. Transportation methods will vary depending on size, weight, quantity and the distance of transportation. The following transportation methods are common practices for prefabricated elements. Such as an indoor loader or, in the case of smaller elements, a trailer.

4.4.1 Indoor Loader

Loading and unloading with an indoor loader is quick and safe without the need for additional equipment. The loading pallet is lifted using hydraulic lifting. Prefabricated elements with a height of up to 3.7m can be transported without requiring special permits or exemptions. Loading and unloading without a crane. Especially when dealing with numerous large elements, this could be a viable choice. This is a method often used for big concrete elements. However, in this case, some form of reinforcement is always present to make sure that the element stays in one piece during transport. This is not the case for the unreinforced masonry elements that are discussed in this thesis. A form of proception is needed to protect the masonry and the cohesion between brick and mortar during transport. Such as is visible in Figure 29 The masonry element is surrounded by wood pellets and secured in an out-of-plane direction as well.

Figure 35: Back View Indoor Loader (Pacton, 2024)

Figure 36: Side View Indoor Loader (Pacton, 2024)

4.4.2 Trailer

In case of a low number of elements, small in-area elements or short-distance transport, a trailer would be the best option. The trailer is a more low-key option for smaller projects. With a simple trailer towed behind a car, small distances can be easily covered. Such is done with the project in Zaandam. Here, an element was loaded onto a trailer and transported 20km to a storage location. The element arrived without damage. This project was also tested with the lever test; the results were very positive. A flexural bond strength above 0.7N/mm² was found. The element was supported by wood pallets and secured with tie-down straps to minimise vibrations during transport.

Figure 37: Masonry Element Between Wood Pallets

Figure 38: Masonry Element on Transport

4.5 STORAGE

If the elements are not directly applied in another project but need to be stored at a separate location, it is important to consider the original situation of the masonry. For example, when inside walls are going to be reused, it is important that they are not stored outside, where weather influences can negatively alter the masonry. Such as excessive water in the bricks, frost damage and quicker deterioration. The environmental class of the masonry plays a big role in how weatherproof the masonry is. This is partly found in the porosity of the brick and the waterproofness of the mortar. A common rule should be to place the masonry element back in the environment it came from. Thus, inside masonry needs to be stored inside; outside masonry can be stored outside but is advised to be stored inside at all. In the case of storing the outside masonry in an outside storage, it is important to protect the backside of the masonry since this is not weatherproof, such as the front of the façade panel. Before storage, it is also important to remove the mortar from the sides of the masonry panel and clean it. At the time of implementation, the sides need to be clean to be able to be applied to the new construction.

4.6 IMPLEMENTATION

The elements can be implemented in two different ways. The first one is the same as normal masonry but with a lot bigger 'bricks'. In this case, the 'bricks' will be the masonry elements. This can be applied to low-rise buildings such as terraced houses. An important factor for this type of connection is that the sides need to be mortar-free, as well as mortar-free in the pores of the brick. This needs to be done to get a strong bond strength. If the pores of the bricks are full, there is no place for the new mortar to settle in, and it will ultimately not create a strong enough bond. Not only is clean masonry important, but so is the type of mortar that is used. The new mortar that is applied needs to be similar to the mortar applied in the masonry element. This is done to prevent cracks due to different deformations and to make sure the right type of mortar matches the brick. Another form of implementation is applying façade supports. These two methods can also be combined to get optimal results. Another important factor for masonry is the horizontal (high rise) and vertical dilatation. The location of the dilations should be more prominent during the design phase. Another crucial part of the cavity wall is the wall ties. With traditional masonry, wall ties are laid between the bricks during bricklaying. This is not possible enough anymore with the masonry elements. The ways to implement the wall ties differ depending on the method. The two methods can be described as outside in and inside out, just like in chapter 4.3. Though in this case, the inside-out method means building the load-bearing wall first and the outside wall afterwards, the outside-in method means that the outside wall is built first and the load-bearing wall is second. The inside-out method is comparable to traditional brick laying. The load-bearing wall is placed first, and afterwards, the masonry elements are placed. The wall ties can be placed on the edges of the masonry panel. Even if the masonry panel is 1m^2, wall ties are still needed in the element field. Because the load-bearing wall has already been constructed, the only possibility is to apply renovation wall ties. With the Outside In method, the existing wall of the masonry panel will be built op first. After this, wall ties can be applied on the edges of the masonry panels, and a plug can be used for the standard wall ties. When the load-bearing wall is constructed, the wall ties can be bricked in. therefore making a functional cavity wall again.

Figure 39: Masonry Elements are put in Place

Figure 40: Preparations before adding Mortar

Figure 41: Results of added Mortar (horizontal) and Joint Sealer (vertical).

Figure 42: Bricklaying the Inner Wall

Chapter **5**
DURABILITY

For the reuse of masonry durability is one of the most important factors for the appearance of masonry and also the structural safety. This chapter is divided into two parts: Structural Durability, which determines whether the masonry elements will remain intact during the reuse process and climate durability, which discusses the functional aspects of the masonry elements.

5.1 STRUCTURAL DURABILITY

Structural durability involves understanding how masonry responds to different load conditions, such as compressive, tensile and shear forces, both individually and in combination. This section discusses the relevant Eurocode rules and the methodology for numerical modelling using DIANA software.

5.1.1 Masonry Properties

5.1.1.1 Compressive Strength

Masonry behaves as an elastic material under compressive loads up to approximately 90% of its ultimate strength (Noortman, 2019). During this phase, the deformations are reversible, and the material returns to its unital state upon unloading. Despite this apparent elasticity, micro-cracks begin to develop even in this phase. Upon reaching the end of the elastic phase, the material enters an inelastic phase where deformations become irreversible. Initial crushing leads to a hardening effect where the stiffness of the material decreases, but it can still bear increasing loads. This hardening phase continues until the material reaches its peak strength, characterised by the formation of numerous micro-cracks, which eventually connect to form larger macro-cracks (Noort, 2012). After reaching its peak strength, the masonry enters a softening phase, where the load-bearing capacity starts to decrease. This phase follows a parabolic softening curve, indicative of the material progressive failure (Figure 43). The size and number of cracks increase, leading to a significant reduction in stiffness. However, a small amount of residual strength remains, forming a plateau in the stress-strain diagram.

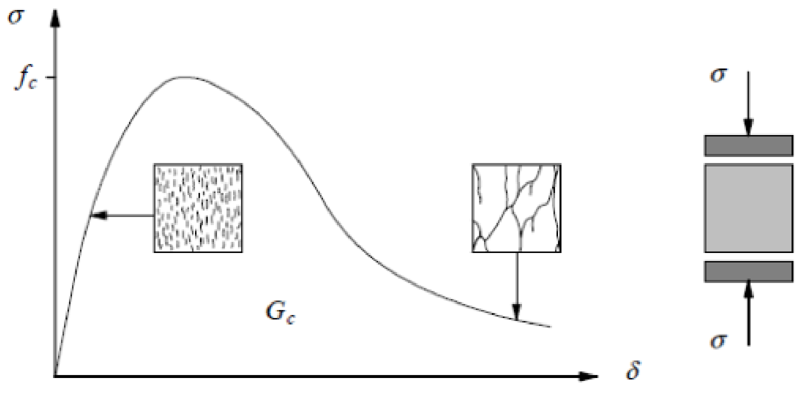


Figure 43: Compressive Behaviour of Stone-like Materials

The compressive strength of masonry is very directional. Compressive strength perpendicular to the bed joint is typically higher than the compressive strength parallel to the bed joint. Research, including tests by Hoffman and Schubert (Schubert, 1994), has shown that the ratio of compressive strength parallel to normal to the bed joints range form 0.2 to 0.8.

The normalised mean compressive strength, fb, is used to quantify the compressive strength of masonry bricks. This value can be declared by the manufacturer or determined using the procedures outlined in EN 772-1 Annex A. Research by S. Jafari on Dutch masonry in Groningen found that masonry built before 1945 has a mean compressive strength of approximately 19.40MPa, while post-1945 constructions have a strength of about 23.25MPa. These values will serve as the basis for general calculation in this thesis, though actual values may vary depending on specific construction details.

The compressive strength of masonry mortar, f_m, should be determined according to EN 1015-11. While it is a variable in this thesis's calculations, it is recognised that the compressive strength of mortar does not significantly influence the overall compressive strength of masonry. However, the mortar's compressive strength impacts the flexural bond strength of masonry. (Lissel, 2007).

5.1.1.2 Tensile Strength

Masonry, like many brittle materials, exhibits an initial linear elastic phase under tensile loading. This phase continues until the tensile strength (σ_t) is reached, at which point the first cracks appear. (Noort, 2012). This phase is characterised by reversible deformations, where the material will return to its original shape if the load is removed before cracking occurs. Once the tensile strength is surpassed, masonry enters a softening phase marked by a decrease in stiffness and load-bearing capacity. This phase starts with the initial cracking, followed by a progressive reduction in strength and stiffness until the material is fully failed. The total fracture energy, which is the energy required to completely fracture the material, can be derived from the stress-displacement curve by integrating the area under the curve (Figure 44). An experiment by van der Pluijm found tensile strength for bricks ranging from 1.5N/mm^2 to 3.5N/mm^2 and fracture energies from 0.06N/mm to 0.13N/mm. (Pluijm, 1992).

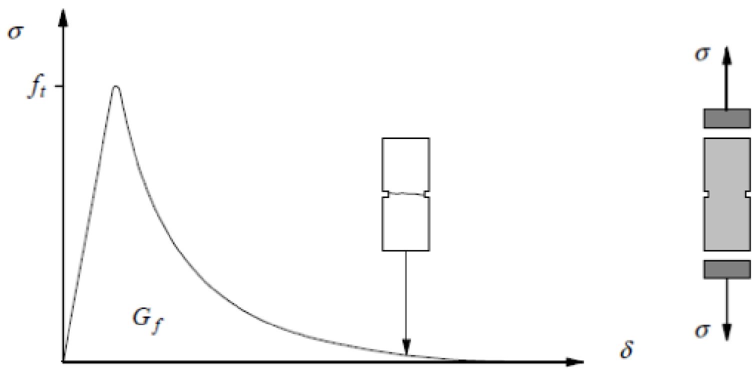


Figure 44: Tensile Behaviour of Stone-like Materials

The tensile failure of masonry can occur in different modes, influenced by the material properties of the joint and units. Backers identified two primary failure modes (Backes, 1985):

1. Stepped cracks through the head and bed joints
2. Vertical cracks through the head joint and units

Failure due to perpendicular tensile loads is often attributed to the low tensile bond strength between the mortar and the brick units. Van der Pluijm's test on tensile bond strength and fracture energy showed an exponential tension softening curve with fracture energies ranging form 0.005 to 0.02Nmm/mm^2. The tensile bond strength ranged form 0.3 to 0.9Nmm/mm^2. This type of failure, occurring between the mortar and brick units, is known as Mode I failure.

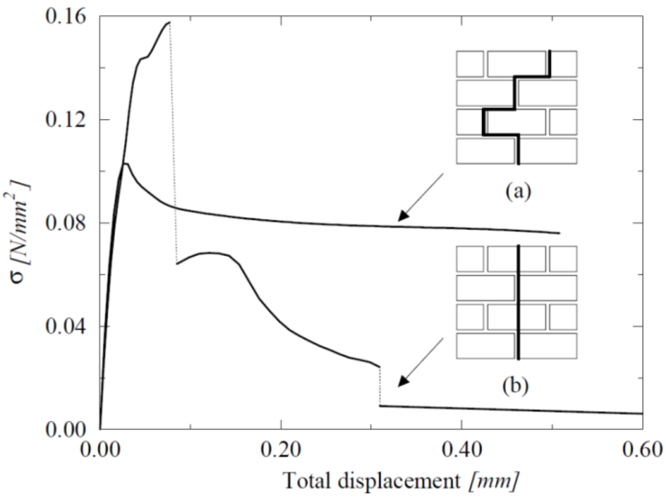


Figure 45: Tensional Stress-strain Curves (Backes, 1985)

Due to the masonry's inherently low tensile strength, accurately estimating the tensile bond strength of unreinforced masonry is crucial for finite element or analytical analyses, especially for structures subjected to in-plane lateral loads of out-of-plane bending, such as those induced by wind or seismic events. The most common measure of tensile bond strength, both in laboratory and on-site, is flexural tensile bond strength. However, this measure may not accurately represent the behaviour under direct tensile loading, a stress state often avoided in masonry design (Lewis J. Gooch, 2023).

5.1.1.3 Shear Strength

The shear behaviour of masonry is highly dependent on the quality of the brick-mortar interface. The shear resistance of masonry elements has a linear potential for the tensile strength of the mortar parallel to the ed joint. (Noortman, 2019). Borrie and Maria found that the roughness of the brick-mortar connection significantly influences shear resistance (Maria, 2012). Van der Pluijm's test on unreinforced masonry structures further illustrated this relationship. In these tests, shear stress was incrementally increased while maintaining constant compressive stresses at three different levels. The results, shown in Figure 46, indicate that higher compressive stresses lead to higher maximum shear stresses and shear fracture energies, ranging from 0.01 to 0.25Nmm/mm². This type of failure is known as Mode II failure.

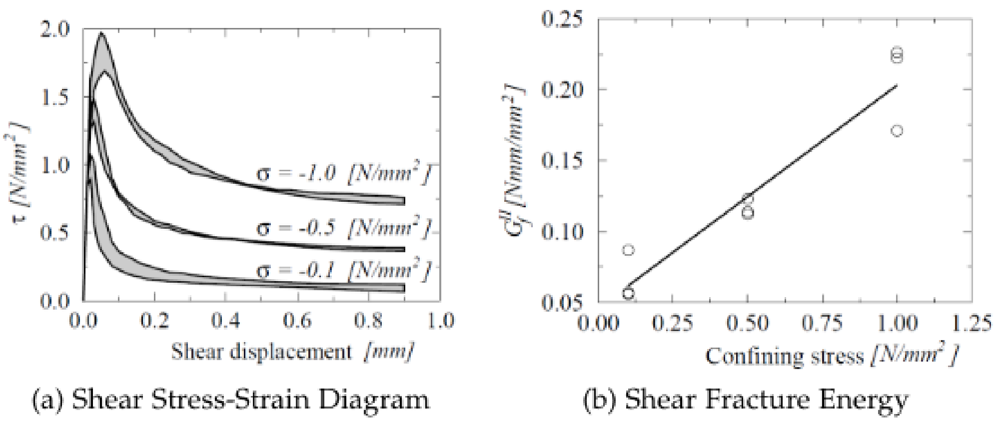


Figure 46: Typical Shear Bond Behaviour (Pluijm, 1992)

The maximum shear resistance is significantly influenced by the quality of the brick-mortar interface, which depends on factors such as mortar type, water/cement ratio, and workmanship

(Galanakis, 2019). Atkinson demonstrated that shear resistance also depends on normal stresses (R. Atkinson, 1989). At low normal stresses, mortar exhibits contraction and dilations, while at medium and high normal stresses, this effect is negligible.

Shear strength defines a masonry wall's resistance to lateral in-plane loads. The characteristic shear strength of masonry, denoted as f_{vk}, must be determined through physical testing, as outlined in standards such as EN 1052-3 or EN 1052-4. This testing provides the characteristic initial shear strength necessary for accurate structural analysis and design.

5.1.1.4 Interface Behaviour between Brick and Mortar

Water plays a vital role in the development of strength at the brick-mortar interface. When the mortar is applied to bricks during construction, water in the mortar is absorbed into the pores of the bricks (Noort, 2012). This movement carries cement particles along, spreading them over the brick surface and forming the bond between the mortar joint and the brick. However, if the water content in the mortar is too low, there will be less transport of cement particles, resulting in a weaker bond. Consequently, even if both brick and mortar have high individual strengths, the overall strength of the masonry can be relatively low if the interface bond is inadequate. The experiment by van der Pluijm (Pluijm, 1992) Revealed that the connection between bricks and mortar joints is not uniformly present across the entire contact surface. Figure 47 Illustrates examples of net bond surfaces from these experiments, showing that incomplete bonding leads to reduced strength. The results from these studies formed the basis of the CUR guidelines. (CUR, 1994).

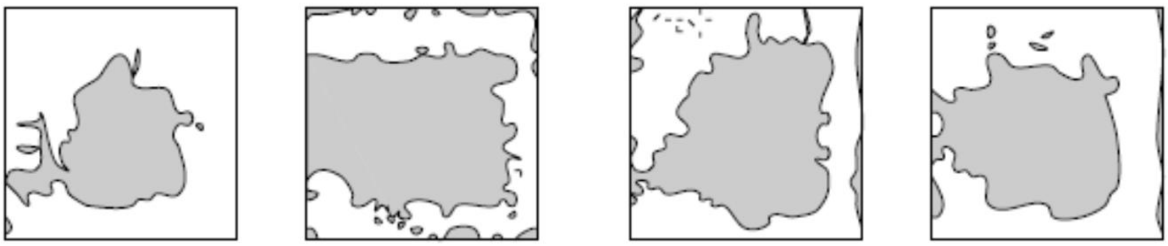


Figure 47: Typical net bond Surface Found by van der Pluijm (Pluijm, 1992)

The interface behaviour also significantly impacts the flexural strength of masonry, especially under out-of-plane bending conditions. The characteristic flexural strength of masonry, denoted as f_{xk1} and f_{xk2}, depends on the plane of failure relative to the bed joints. For failures parallel to the bed joint (f_{xk1}), the flexural strength can be determined using the bond wrench test. For failures perpendicular to the bed joints (f_{xk2}), the flexural strength is determined by the relationship $f_{xk2} = 2*f_{xk1}$, provided certain conditions regarding the brickwork patterns are met. These characteristic values must be determined according to EN 1052-2 standards.

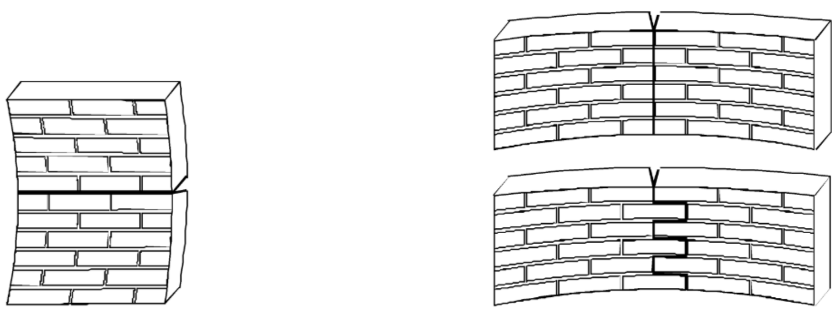


Figure 48: Left: plane of failure parallel to bed joints, f_{xk1}, ight: lane of failure perpendicular to bed joint, f_{xk2}.

5.1.2 Diana Modelling

5.1.2.1 Numerical Modelling Approaches of Masonry

Traditionally, the design and assessment of masonry structures have relied heavily on empirical formulae and rules of thumb. Numerical tools for masonry structures have only been applied over the last 30 years (Xie, 2020). The first step in the finite element method is to discretise the structure into a finite number of smaller elements. These elements can have various shapes depending on the nature of the structure. In the context of masonry structures, elements resembling bricks or blocks easily be applied in de FEM calculation. Each element has nodes at the corners or along the edges. The nodes act as points where the structural response, such as displacement or forces, is calculated. The behaviour of each element can be described using mathematical models based on the physical properties of the materials involved. In the case of nonlinear materials like masonry, specialised models are used to capture behaviour such as softening, cracking and crushing. As the elements are defined and modelled, equations governing the entire structure are set up. Such as boundary conditions. By making use of software packages like DIANA, the system of equations can be solved. It also makes it possible to visualise the deformed shape and analyse stress distributions. The complexity arises due to the anisotropic nature of masonry, which is composed of units and mortar joints that cannot be treated as isotropic materials like concrete. To better capture the anisotropic behaviour of units, mortar layers and their interactions, three types of numerical models are commonly used: detailed micro-modelling, simplified micro-modelling and macro-modelling.

- **Micro-modelling** (Figure 49b): Micro-modelling is a detailed numerical representation where all components of the masonry material are modelled separately. This means that the masonry units and the mortar joints are taken into account as distinct entities. The components are connected using an interface element, which represents the potential planes of weakness or crack planes between the units and the mortar. For the detailed micro-modelling, the units and mortar are represented using separate finite elements. These elements are connected by discontinuous interface elements, and the properties of both the units and the mortar must be defined separately. The interface elements represent possible crack planes, allowing for the simulation of realistic crack propagation and failure mechanisms. This method provides a highly accurate representation of masonry behaviour but requires significant computational resources.
- **Simplified micro-modelling** (Figure 49c): Simplified micro-modelling also represents the units with separate elements. However, the mortar and the connection between the mortar and the units are lumped into a continuous interface element. These new interface elements should adequately represent the behaviour of the mortar and the original interface. The masonry is modelled as a set of blocks connected by potential crack lines at the new interface elements. This method reduces the computational complexity while still capturing the essential mechanical behaviour of masonry structures.
- **Macro-modelling** (Figure 49d): Macro modelling is a more practical approach of large-scale finite element modelling of masonry structures. Due to the considerable computational time and difficulty in defining the properties of interface elements in micro-modelling, aeromodelling is often preferred for practical applications. In macro modelling, the masonry is modelled as a composite material without requiring distinct interface elements. One widely used continuum model is the smeared crack model. This model simplifies the masonry behaviour by describing it in terms of average stress and strains, assuming the material is homogenous. Cracking is represented as a continuous medium smeared over the finite elements rather than as discrete cracks. The material is considered to have anisotropic properties, meaning its properties vary with direction. This approach is beneficial for modelling large masonry structures where detailed micro-modelling would be computationally prohibitive. It allows for efficient analysis while still capturing the essential mechanical behaviour of masonry under various loading conditions.

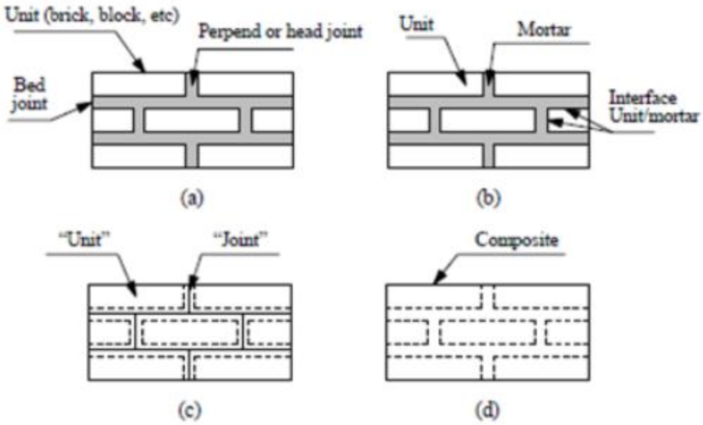


Figure 49: Different types of Modelling for Masonry Structures: (a) Part of a Masonry Wall; (b) Detailed Micro-model; (c) Simplified Micro-model; (d) Macro-model (Noort, 2012)

By assuming that the mortar will fail before the masonry unit, a simplified micro-model can be used. Here, it is assumed that the non-linear behaviour is concentrated in the joint, whereas the unit/blocks have a nearly linear-elastic behaviour. The units can then be represented by means of continuum elements and the joints by means of discontinued elements, also called interface elements.

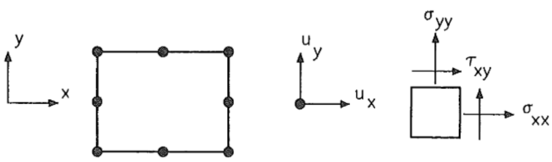


Figure 50: Continuum Elements, eight-node plane stress distribution with Gauss integration scheme **(Rots J. , 1997)**

Figure 51: Discontinued Elements, six-node interface element with Lobatto integration scheme **(Rots J. , 1997)**

Thus, masonry is a set of elastic blocks connected to each other by non-elastic joints. The joints are modelled by means of interface elements and thus have potential cracks and sliding surfaces. J.G. Rots noted that this approach agrees with experimental results from his research. Especially the joints and the areas of adhesion between joint and unit contribute to the deformation behaviour of masonry.

5.1.2.2 Failure Modes of Masonry

The failure mechanisms of masonry on a micro level can be categorised into five modes: Joint tension cracking, joint slip, unit direction tension crack, unit diagonal tension crack, and masonry crushing.

Joint tension cracking (Figure 52a)**:** The most common failure mode when the masonry is in tension

Joint slip (Figure 52b)**:** Sliding along the bed or head joint under low-value normal stress

Unit direct tension crack (Figure 52c)**:** Occurs when units are in tension longitudinally

Unit diagonal tension crack (Figure 52d)**:** Shear failure of the units when normal stress is sufficient to develop friction in the mortar joints

Masonry crushing (Figure 52e)**:** Splitting of units in tension due to mortar dilatancy under high compressive stress.

Phenomena a and be are joint mechanisms, c is a brick mechanism, and d and e are combined mechanisms involving bricks and joints.

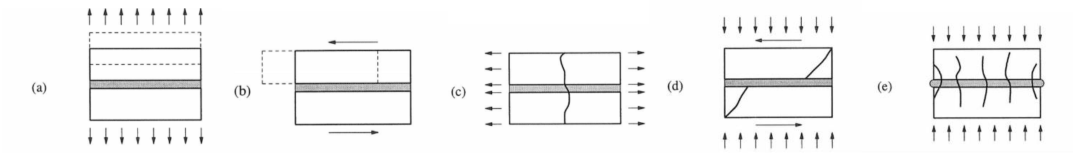


Figure 52: Failure Mechanisms of Masonry (a) Joint tension cracking, (b) Joints lip, (c) Unit direct tension crack, (d) Unit diagonal tension crack, (e) Masonry crushing (Rots P. B., 1997)

5.1.2.3 Combined Cracking-Shearing-Crushing

The combined cracking-shearing-crushing (CSC) model is a plane stress interface cap model specifically designed for analysing masonry structures. Originally formulated by Lourenço and Rots (Rots P. B., 1997), this model integrates multiple failure mechanisms, providing a framework for understanding and predicting the behaviour of masonry under various stress conditions. The CSC model is based on a multi-surface plasticity framework that encompasses several components:

- **Coulomb friction model:** This component addresses shear failure by considering the effects of friction and cohesion between the masonry units
- **Tension Cut-off:** This part of the model handles tensile cracking, recognising that masonry is weak under tensile stresses
- **Elliptical Compression Cap:** This element accounts for the compressive failure, recognising the high compressive strength but potential crushing of masonry.

This thesis applies a discontinue principle. This includes all the basic types of failure mechanisms. It concentrates all the damage in the weaker joints. The interface elements of the joints have to account for a combined failure of crack formation and slipping. The discrete cracking of the interface is dealt with a tension cut-off accompanied by some sort of softening behaviour if the maximum allowable stress has been reached. The shear stresses and combination with compressive stress are dealt with in a coulomb friction model, a failure envelope. This model is also accompanied by some kind of softening behaviour if the shear stress, dependent on the cohesion and internal friction, exceeds its maximum. To account for compressive criteria, a compressive cap can be placed on the combination of these models.

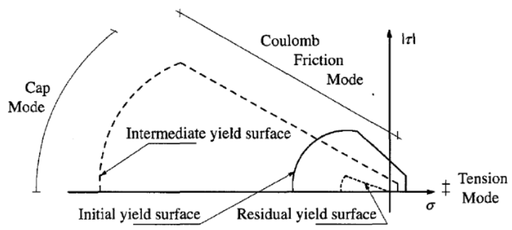


Figure 53: The Composite Interface Model, the Coulomb-friction Model (Rots P. B., 1997)

The SCS model's robustness can be challenged by the relative size of the masonry walls and the complexity of their layout. Larger and more complex structures may experience convergence issues during numerical analysis. (Xie, 2020). However, this is, in the case of this thesis, not a problem since the model is kept relatively simple, both in size and layout.

5.1.3 Applied Loading and Boundary Conditions

DIANA software is typically utilised for seismic assessment of masonry. However, under normal conditions, masonry structures, particularly the outer leaf, are not overly complex. These structures primarily carry their own weight and transfer wind forces through wall ties to the load-bearing wall.

In the old situation, the masonry works as one plane; it carries its own weight and transfers wind forces. This is vastly different from the reuse situation because it includes cutting, hoisting and transporting elements of existing masonry. When the masonry element is cut for reuse, its boundary condition alters notability. Typically, cuts are made on the left, right, top (if necessary), and bottom. After these cuts, the element remains resting on the row of bricks below, maintaining a condition similar to the traditional setup. However, this really changes during the hosting phase. As discussed in chapter 4.3.2, various methods for hoisting masonry elements exist. The images of that chapter show the elements of 1x1 meter or slightly larger, which are relatively simple from an engineering perspective. The complexity increases significantly with larger elements.

As part of the hoisting method, using a forklift or lifting straps, the element is temporarily supported by two supports. This changes the boundary condition significantly from the original situation. During lifting, the bottom of the masonry element is no longer fully supported, potentially causing displacement due to self-weight. Or leads to joint failure due to the moments induced by the overhanging weight.

Transport introduces additional challenges, particularly the vibrations. These vibrations necessitate a minimum flexural bond strength of 0.7N/mm^2, in the case of minimum support, akin to the strength found in flued mortar in masonry units. If the element can be supported all around during transport, it will behave as a single unit, minimising the risk of displacement and preventing individual elements from vibrating and falling apart.

The calculation is done in a serviceability limit state since it is about the outer leaf of the cavity wall; it is not load-bearing and represents the appearance of the building. The most important part is to test what the element can handle to ensure it stays durable during the lifting process. The loading on the panels during lifting is self-weight only. The values that result from the DIANA model are compared with

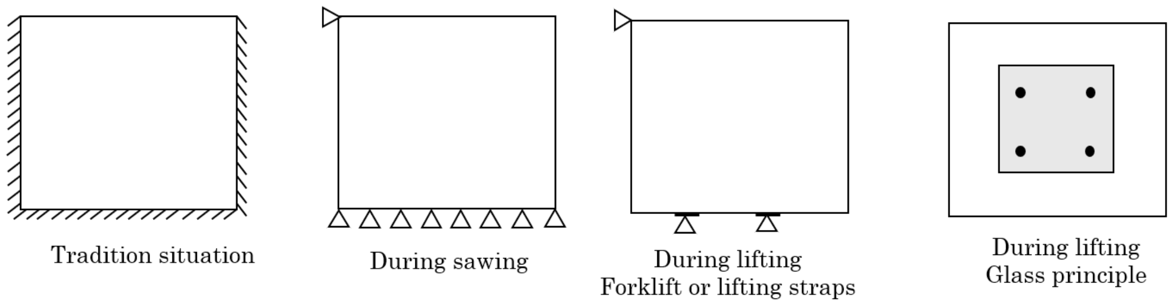


Figure 54: Different Boundary Conditions per Situation

5.1.4 Results Diana

5.1.4.1 Diana Input

Jafari's research gives recommendations for parameters for structural analysis of typical single-wythe Dutch houses. It gives a correlation between the interface properties, bond strength, and mortar properties. This calculation will use 0.3N/mm^2 as its bond strength since this is the minimal value that the flexural bond strength needs to have to be able to be applied in new construction.

Table 12: Mortar Properties

Properties	Equation	Value	Unit
Bond strength	Direct from test	0.3	N/mm²
Mortar compressive strength	$f_m = {f_w}/{0.036}$	8.33	N/mm²
Mortar Youngs modulus	$E_m = (200 - 240)f_m$	333	N/mm²
Mortar tensile strength	$f_{tm} = (0.15 - 0.32)f_m$	1.42	N/mm²
Mortar fracture energy in tension	$G_{f-tm} = 0.025({f_m}/{10})^{0.7}$	0.022	N/mm

This colouration between bond strength and mortar cannot be found for bricks. In this case, it depends on the brick's compressive strength, which needs to be determined with the destructive test. For this calculation, the mean post-1945 value will be used as the brick compressive strength. (Jafari, 2021). Other values, such as mass density and Poisson's ratio, are also included since this will be needed in further calculations.

Table 13: Brick Properties

Properties	Equation	Value	Unit
Brick compressive strength	Mean post-1945 value	23.25	N/mm²
Brick Youngs modulus	$E_b = (300 - 430)f_b$	3022.5	N/mm²
Brick tensile strength	$f_{tm} = (0.04 - 0.07)f_b$	0.7	N/mm²
Brick fraction energy in tension	$G_{f-tm} = 0{,}038 * f_{tm}$	0.0266	N/mm
Poisson's ratio		0.2	-
Mass density		$1.8x10^{-9}$	T/mm³

To determine the interface properties, the tensile strength of the masonry needs to be known. This depends on the bond strength of the interface.

Table 14: Masonry Properties

Properties	Equation	Value	Unit
Tensile strength	$f_{t1} = 0.8 * f_w$	0.24	N/mm²
Compressive fracture energy	Mean post-1945 value	20.58	N/mm

With this, the fracture energy in tension and shear can be determined.

Table 15: Interface Properties

Properties	Equation	Value	Unit
Fracture energy in tension	$G_{f-I} = 0.16f_{t1}$	0.0384	N/mm
Fracture energy in shear	$G_{f-II} = 10 * G_{f-I}$	0.384	N/mm

Other information that is needed for the model interface is as follows: The height of the joint is taken as 10mm.

Table 16: Properties Interphase DIANA (Rots J. , 1997)

Properties	Equation	Value	Unit
Normal stiffness modulus	$k_n = \frac{E_{unit} * E_{joint}}{h_{joint} * (E_{unit} - E_{joint})}$	37.4	N/mm^2
Shear modulus unit	$G_{unit} = \frac{E_{unit}}{2(1+v)}$	1259.4	N/mm^2
Shear modulus joint	$G_{joint} = \frac{E_{joint}}{2(1+v)}$	138.8	N/mm^2
Shear stiffness modulus	$k_t = \frac{G_{unit} * G_{joint}}{h_{joint} * (G_{unit} - G_{joint})}$	15,6	$N.mm^2$
Cohesion	(Rots J. , 1997)	0.3	N/mm^2
Friction angle	" … "	37	°
Dilatancy angle	" … "	22	°
Residual friction angle	" … "	37	°
Confining normal stress	" … "	-1.3	N/mm^2
Exponential degradation coefficient	" … "	5	-
Factor Cs	" … "	9	-
Equivalent plastic relative displacement	(Xie, 2020)	0.9	mm

5.1.4.2 How to Interpret Results

The two most important results in these calculations are the flexural bond strength (Cauchy total stress in Diana) and the Tensile strength (Interface Total Traction in Diana). The minimum values given in the Eurocode are the characteristic values. In a design calculation, the design load is compared with the maximum resistance of the loaded material. In this case, we do the same; the maximum resistance is, in this case, the flexural bond strength and shear stress. Both have a material safety factor of 2 (CC1 and masonry of bricks of categories I from EN1996-1-1).

Flexural bond strength

$$f_{xd1} = f_{xk1} / \gamma_m$$

$$f_{xd2} = 2 * f_{xd1}$$

The minimum value of the characteristic flexural bond strength needs to be larger than $0.3N/mm^2$. Therefore, all the elements that will be reused need to have this strength applied in the calculation, and due to the loading, the Cauchy total stress will not be higher than this minimum.

$$f_{xk1} > 0.3N/mm^2$$

$$f_{xd1} * \gamma_m < 0.3\ for\ bed\ joints$$

$$f_{xd1} * \gamma_m * \frac{1}{2} < 0.3\ for\ head\ joints$$

This means that for the bed joint, the Cauchy total stress needs to be smaller than $0.15N/mm^2$, and the head joints need to be smaller than $0.3N/mm^2$.

Shear stress

$$f_{vk0} = f_{xk1}$$

$$f_{vk} = 0.5 * f_{vk0} + 0.4 * \sigma_d\ but;$$

$$f_{vk} < 0.065 * f_b$$

The mean value for the shear strength found in the research of S. Jafari was 23.25 for the masonry built after 1945. With this value, the following characterise value is determined

$$f_{vk} = 1.51\ N/mm^2$$

$$f_{vd} = \frac{f_{vk}}{\gamma_m} = \frac{1.51}{2} = 0.76\ N/mm^2$$

5.1.4.3 Results

The main reason they perform the Dianna calculations is to determine the maximal span between the supports and the maximum overhang over the supports. This determines the maximal size of the masonry element based on the minimum and average values given in euro codes and previous research. The following values have been used:

In the calculation, the assumption is made that the support is placed under one brick. This is the worst-case scenario; the following options were below the maximum allowed values. It goes from smallest width to largest width

Table 17: Maximum Size Masonry Elements based on two Supports

Option	Width [m]	Height [m]	Total area [m²]
1	1.0	1.40	1.40
2	1.2	1.30	1.56
3	1.4	1.05	1.47
4	1.6	0.85	1.36
5	1.8	0.80	1.44
6	2.0	0.75	1.50

In this chapter, the two elements with the biggest area are discussed. Other sizes can be found in Appendix B.

Option 2

The element is 1.2m in width, 0.1m thick and 1.3m in height. It is only loaded with its own weight. This model makes use of a zero-thickness interface for the head joints and the bed joints.

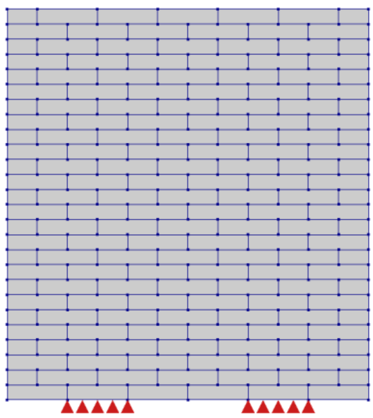


Figure 55: Option 2 - Masonry element 1.2x1.3m

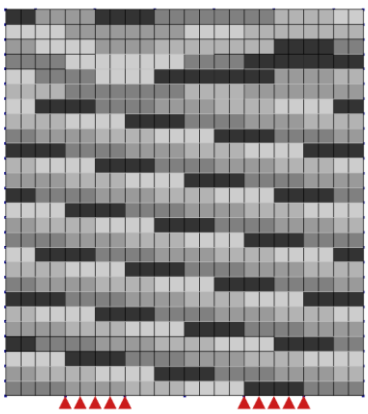


Figure 56: Option 2 - Finite element mesh with supports

In Figure 57 and Figure 58 The relative displacement of the interfaces is shown. Here, the displacements are very small, with the biggest displacement being 0.022mm. Making it so that there is no visible cracking during the process of lifting due to its own weight.

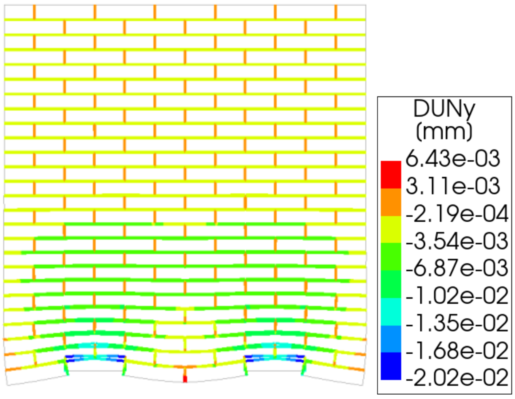


Figure 57: Option 2 – Normal relative displacement of the interface

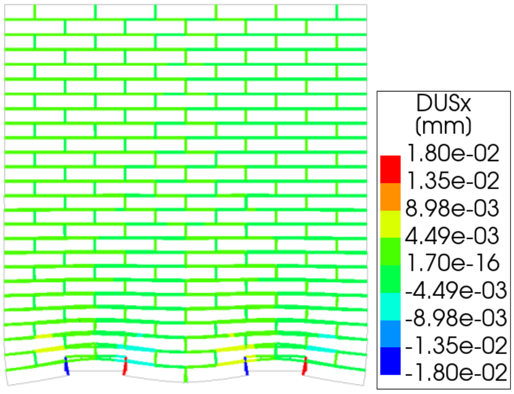


Figure 58: Option 2 – Shear relative displacement of the interface

Figure 59 and Figure 60 shows the stress of the bed joint and head joint. This value is comparable with the flexural bond strength. The flexural bond strength for the bed joint needs to be smaller than 0.15N/mm². This is the case with 0.094N/mm²; for the head joints, the value 0.14N/mm², which is significantly smaller than the 0.3N/mm² that was allowed.

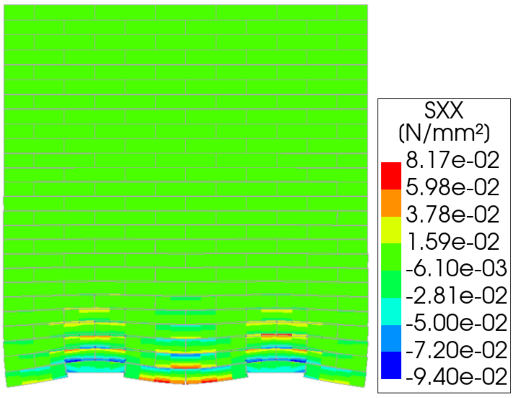


Figure 59: Option 2 – Cauchy total stress of bed joint

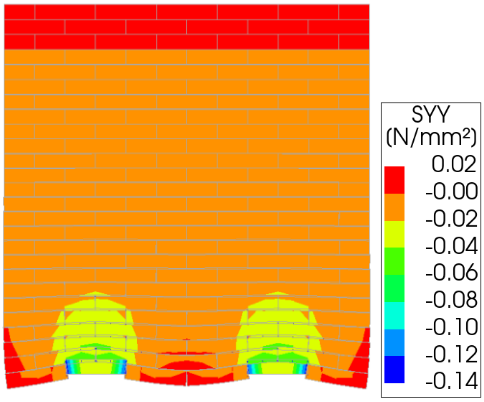


Figure 60: Option 2 – Cauchy total stress of head joints

The interface traction or shear stress was the determining factor in all calculations. While I initially assumed that the flexural bond strength would be the deciding factor, this was not exactly the case. However, the shear stress is very dependent on the strength of the flexural bond. In the end, the maximum size was determined by the interface total traction of the head joints (0.75N/mm² < 0.76N/mm²).

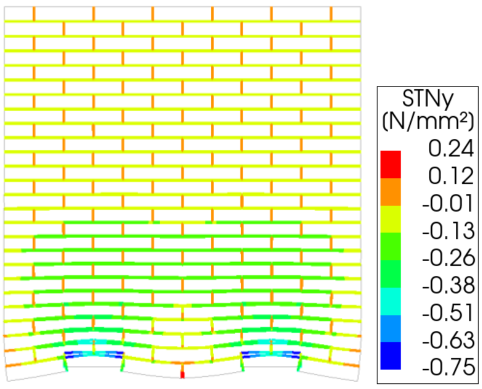


Figure 61: Option 2 - Interface total traction bed joints

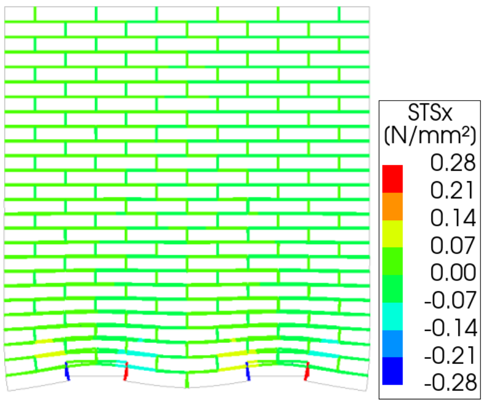


Figure 62: Option 2 - Interface total traction head joints

Option 6

The element is 2m in width, 0.1m thick and 0.75m in height. It is only loaded with its own weight. This model makes use of a zero-thickness interface for the head joints and the bed joints.

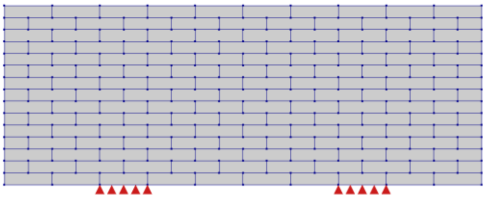


Figure 63: Option 6 – masonry element 2x0.75m

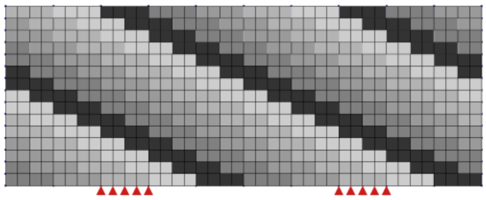


Figure 64: Option 6 – Finite element mesh with supports

In Figure 65 and Figure 66 The relative displacement of the interfaces is shown. Here, the displacements are very small, with the biggest displacement being 0.0201mm. Making it so that there is no visible cracking during the process of lifting due to its own weight.

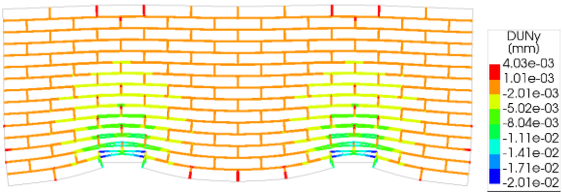


Figure 65: Option 6 – Normal relative displacement of the interface

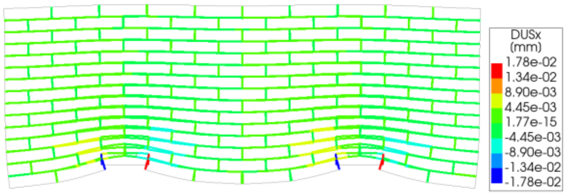


Figure 66: Option 6 – Shear relative displacement of the interface

Figure 67 and Figure 68 shows the stress of the bed joint and head joint. This value is comparable with the flexural bond strength. The flexural bond strength for the bed joint needs to be smaller than 0.15N/mm². This is the case with 0.11N/mm². This value is comparable to that of Option 2 because the span between the support is bigger, as well as the overhang on the sides of the supports. Because of this, the panel is less high. For the head joints, the value 0.15N/mm² is significantly smaller than the 0.3N/mm² that was allowed.

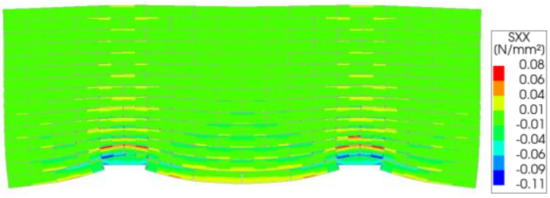


Figure 67: Option 6 – Cauchy total stress of bed joint

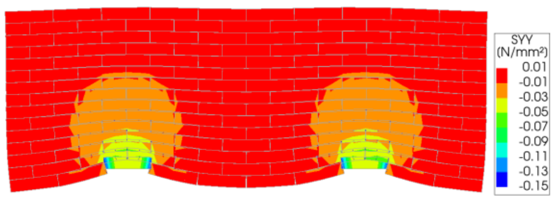


Figure 68: Option 6 – Cauchy total stress of head joints

Just as in option 2, the interface traction of shear stress was the determining factor. In the end, the maximum size was determined because the interface total traction of the bed joints reached 0.75N/mm², which is just within the bounds of 0.76N/mm² from chapter 5.1.4.2.

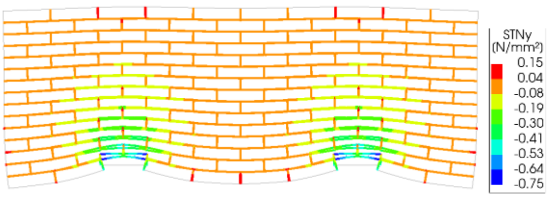


Figure 69: Option 6 - Interface total traction bed joint

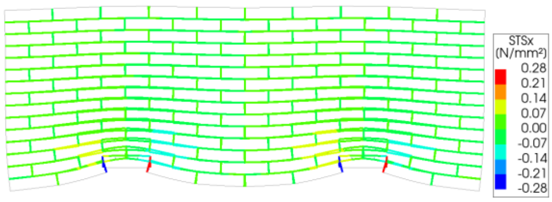


Figure 70: Option 6 - Interface total traction head joints

5.2 CLIMATE DURABILITY

The climate durability of masonry is a critical aspect that allows for its longevity and structural integrity. The façade is constantly exposed to varying environmental conditions, including temperature fluctuations, moisture, and physical stresses. These factors can significantly impact the performance and durability of masonry materials. Understanding the effects of climate on masonry and implementing appropriate measures to mitigate potential damage is essential for maintaining the strength and appearance of these structures. The most common elements that influence the climate durability of the masonry are frost/thaw cycles, moisture penetration and improper joint application. Another important factor for the masonry elements is the risk associated with sawing masonry.

5.2.1 Frost/Thaw Resistance

When water freezes, it expands by about 9% (PCA, n.d.). When the water freezes, it produces pressure in the brick process. If the pressure developed exceeds the tensile strength of the brick, the cavity will rupture, leading to damage over time. Bricks can be separated into two clear categories: frost-resistant or not frost-resistant. Frost-resistant bricks are durable in all normal building conditions when saturated and subjected to freezing and thawing. They are the best choice for environments in outside environments. On the other side of the spectrum, there are non-frost-resistant bricks; these bricks are mainly suitable for indoor use. They are not designed to withstand freezing and thawing cycles and should be protected from such exposures to avoid damage. Even if the brick is 'classified' as frost resistant, due to the fact that every brick is unique, there are instances that the bricks show spalling. Spalling means that the surface layer of the bricks flakes off due to the internal pressure from freezing water. This can expose the inner layers of masonry to further damage and degradation. Another damage could be the expansion of the already formed crack due to the same reason. It is important to use frost-resistant clay bricks in the appropriate situations. It is possible to use a hydrophilization. It involves treating the masonry with a hydrophobic (water-repelling) substance to reduce its water absorption.

5.2.2 Improper Joint Application

The joints between bricks are crucial for masonry structures' overall strength and durability. Improper application of mortar joints can lead to compromises in the masonry integrity. Poorly applied mortar can result in weak bonding between bricks, which compromises the strength of the masonry. In terms of environmental resistance, the joint hardness or the wrong environmental class applied in the joint can result in water penetration. Gaps or cracks in the joint can allow water to infiltrate, exacerbating issues related to moisture penetration and freeze/thaw cycles. When it is noticed in an early stage, it is an easy procedure to touch up the joint.

5.2.3 Risks During Masonry Sawing

When sawing the masonry elements, something known as spalling can happen. Spalling is characterised by chipping, cracking, crumbling, flaking, peeling and powdering of the bricks. When the bricks are cut or sawed, they are exposed to physical stresses that may cause them to peel or spall, particularly if there are some underlaying damages, such as small cracks or small damages due to frost and thaw instances.

5.2.4 Maintenance Strategies

Maintaining masonry is the best strategy for preventing damage. Keeping masonry clean and addressing repair in time will help prevent minor problems from escalating into major issues. Regularly inspect and repair mortar and joint gaps when needed to ensure the durability of the façade.

Chapter **6**
SUSTAINABILITY

6.1 LIFE CYCLE STAGES

EN 15643:2021 forms part of the series of European standards that provide a system for the sustainability assessment of buildings and civil engineering works using a life cycle approach. The sustainability assessment quantifies aspects and impacts to assess the environmental, social and economic performance of engineering works using quantifiable indicators measured without value judgements. The purpose of the standards developed under this framework is to enable comparability of the results of assessments. The results of a sustainability assessment of a building and/or civil engineering works provide information on the different types of indicators, the related work scenarios, and the life cycle stages included in the assessment. Assessments can be undertaken for the object under consideration, that is, a whole building or civil engineering works, a part of the works or a combination of several buildings and/or civil engineering works. In the case of this thesis, we assume part of the building, the masonry wall. This can also be described as construction products; in this case, EN 15804 also applies. The purpose of EN 15643 is to provide a framework with principles, requirements and guidelines for the assessment of the environmental, social and economic performance of a building and/or civil engineering works or a combination thereof. This framework applies to all types of construction works, and it is relevant for new construction works over their entire life cycle and for existing construction works over their remaining service life and end-of-life stages. The sustainability assessment can be performed to determine the sustainability aspect and impacts of the object of assessment with respect to its area of influence, but as to allow to make decisions and choices that will help to address the need for sustainability of construction works at each phase of the construction project, and to provide improvement of environmental performance as a contribution to sustainable development. For the assessment of the sustainability of the construction works, the life cycle starts with the preparatory works and administrative processes. It proceeds through the acquisition of design and specification, land/site acquisition (including deconstruction of existing construction works and clearing of the site for new and refurbishment projects), acquisition of raw materials, manufacturing and procurement of products, construction work process, handover for use, commissioning (muddles A0-A5). The life cycle continuous with actual use, including maintenance, repair, replacement, refurbishment, operation and user activities (modules B1 to B8) and finally, the life cycle ends with decommissioning, deconstruction or demolition, waste processing in preparation for reuse, recycling and energy recovery and other recovery operations, and disposal of waste (module C1-C4). As part of construction works assessment information, the benefits and loads resulting from the net flows arising from re-use, recycling, energy recovery, and other recovery operations of materials and substance, and the benefits and loads from exported utilities beyond the system boundary shall be assessed and reported in module D. In an article of it. Laetitia Delem, where the relevance of the recycling potential (module D) for building is discussed, it is noticed that module D makes it possible to provide additional information on the potential of materials beyond the buildings life cycle and can therefore represent a significant part of the total building impact. However, in the case of this thesis, not only the whole building impact is considered, but also the impact that the building method and the reuse method have on environmental analysis.

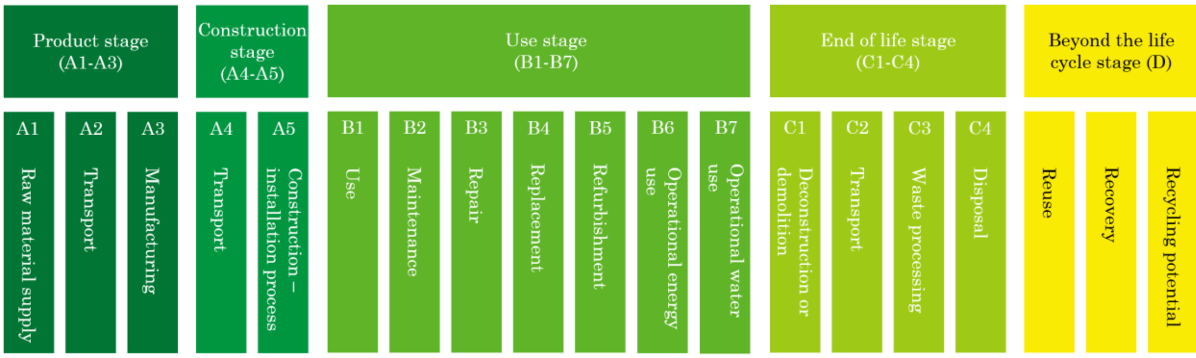


Figure 71: Life Cycle Stages

A1-A3 is the production stage, A1 includes raw material extraction and processing, A2 is the transport to the manufacturer, and A3 is the manufacturing. Thus, in the case of bricks. A1 would be the extraction of clay from the Dutch rivers, A2 would be transported to the factory, and A3 would be the forming and firing of the bricks. This is different in the case of mortar; here, the ingredients are extracted and brought to the manufacturer, and they are put in packaging to be transported to the construction location; only on-site ingredients are mixed and, therefore, manufactured. In that case, the biggest steps are performed for bricks in A1-A3, and this is A1-A5 for mortar. A4 is the transportation to the building site, and A5 is the installation into the building. In the case of an m^2 of masonry, it is also important to include the activities that are needed when bricklaying. A1-A5 needs to include the provision of all materials, products and energy, as well as waste processing up to the end of the waste stage or disposal for final residues during the construction process stage. The next stage, B, the use stage, can be split into the use or application of the installed product, maintenance, repair and replacement refurbishment. (B1-B5). The last two B stages are operational energy use (B6) and operational water use (B7). B stage is chosen to be left out of the environmental assessment of this thesis because this is bound to personal use. The end-of-life stage plays a big role in the assessment of the reusing masonry elements because it starts with these subjects. C1, de de-construction or demolition. C2 transport to waste processing; C3, waste processing for reuse, recovery and/or recycling; and C4 disposal. In Chapter 4, all the steps in the element reuse scenario are described.

6.2 EPD

An EPD provides quantified environmental information for a construction product or service on a harmonised and scientific basis. It also provides information on health-related emissions to indoor air, soil and water during the use stage of the building. The purpose of an EPD in the construction sector is to provide the basis for assessing buildings and other construction works and identifying those which cause less stress on the environment. All construction products and materials declare modules A1-A3, modules C1-C2 and module D. The EN 15804 gives five different 'roads':

- Cradle to gate.
- Cradle to grave.
- Cradle to Cradle.

Comparisons of products can be made based on their EPD. If the construction product is an integrated part of the whole structure, it can only be compared when comparing its impact on the building and all life cycle modules (A-D). In the case of a construction product that is an assembled system, components or a product for more than one life cycle, it can be seen as a stand-alone product. This makes it possible to compare the different systems with each other. For a fair comparison, the products need to have the same function, requirements and environmental performance. The product can have multiple functions, though the EPD is often related to a specific function or scenario. It can still be applied to multiple scenarios by using a common functional unit. For masonry, this would be 1m², but for mortar, it would be in kg. The functional unit provides a reference of the materials flow (input and output data) of the information modules. The function of the unit gives the reference for combining material flow attributes to the product's life cycle at the building level. This allows the functional unit to be clearly defined and measured.

When looking at the EPD for masonry, which includes the combination of mortar and bricks. There are two versions, an English and a Dutch version. The Dutch version came out in 2019 and will expire in 2024. It gives a distribution of masonry as follows:

Table 18: Masonry Ingredients Ratio

1m² masonry	Weight [kg]
Masonry Bricks	127.5
Masonry Mortar	45
Joint Mortar	7

The EPD of masonry also includes masonry mortar (M10) and Joint mortar (VH35). The Dutch version of the EPD describes that the mortar is taken as the industry average profiles from the NeMo (Nederlandse Mortel Organisatie). These MPRI publications were still valid during the time of publication of the masonry EPD, though that is not the case now. The documents from NeMo were published in 2014 and expired in 2019. As of now, new MPRI publications for mortar are not available, and because the EPD of masonry directly used these publications, this will be used to determine the values of mortar in the calculations. The following ingredients are used in the MPRI publications and EPD for masonry:

Table 19: Masonry Brick Ingredients Ratio

Component	[kg/kg ready product]
Clay	0.922
Sand	0.102
additives	0.035
LDPE foil (packaging)	0.000048 (English version)
Pallets	0.00036 (English version)

Table 20: Masonry Mortar Ingredients Ratio

Component	% of 1tonnes
CEM 1	11.6
CEMIII	0.6
additives	81
Limestone flour	6.8
Water*	12

Table 21: Joint Mortar Ingredients Ratio

Component	% of 1tonnes
CEM 1	15
CEMIII	3.3
additives	81
other	0.7
Water*	10

As mentioned before, there is also an English version of the masonry EPD. In this version, no distribution of masonry is given, as in Table 18. Another difference is a value given in the components of masonry, and then only in the packaging and pallet values; this is, in both cases, 1000 times smaller than in the Dutch version. However, this looks to be more realistic. As 0.36kg pallets, a very large number is needed for 1kg of bricks. Another important factor is that the MPRI publications are not mentioned in the English EPD, though the values of environmental impact are the exact same. This suggests that the same values have been used, though not mentioned. The English version does have a later date of issue, in 2021, with an expiry date in 2026.

The EPD gives a total of 11 environmental impacts in Table 22 These 11 environmental impacts with their unit and MKI weight factor can be found.

Table 22: Environmental Empact Categories

Environmental impact	Abbreviation	Unit	MKI weight factor
Abiotic Depletion Potential for non-fossil resources	ADPE	Kg Sb eq.	€0.16
Abiotic depletion potential for fossil resources	ADPF	MJ	€0.16
Global warming potential	GWP	Kg CO2 eq.	€0.05
Depletion potential of the stratospheric ozone layer	ODP	Kg CFC 11 eq.	€30.00
Formation potential of tropospheric ozone photochemical oxidants	POCP	Kg C2H4 eq.	€2.00
Acidification Potential of land and water	AP	Kg SO2 eq.	€4.00
Eutrophication potential	EP	Kg (PO4)3-eq.	€9.00
Human toxicity potential	HTP	Kg DCB-Eq.	€0.09
Freshwater aquatic ecotoxicity potential	FEATP	Kg DCB-Eq.	€0.03
Marine aquatic ecotoxicity potential	MAETP	Kg DCB-Eq.	€0.0001
Terrestrial ecotoxicity potential	TETP	Kg DCB-Eq.	€0.06

Because the EPD of masonry has not been recently published, it is not up to date with the most recent EN15804. It still goes by the impact categories of the previous version. The new impact category with new units and weights that the weight factors for global warming and depletion of raw materials are comparable higher than the old version. The old version applied a weight factor of €0.05 for global warming, while the new version applied €0.116, which is an increase of more than 132%. In the case of depletion of abiotic raw material, the increase is 87.5%. However, in some cases, the unit of the impact category is changed. The weighting factors cannot be directly compared due to the difference in impact category units and differences in the amount and type of impact categories. This makes comparing information of the EPD (old version) and the new weight factors more complicated. This is why the calculation is not done with the most up-to-date values, but it will still give an indication of the environmental impact all scenarios have

6.3 LIFE CYCLE SENARIOS

6.3.1 Scenario 1: Baseline Value – Traditional Masonry

The first scenario will be used as the baseline value. This is the representation of the traditional construction of a masonry wall. This is comparable with the EPD of masonry. The functional units are 1m^2 of new masonry. To be able to compare all scenarios, the next scenarios also need to end with 1m^2 of new masonry. For the baseline value, only the Product stage (A1-A3) and Construction stage (A4-A5) (Figure 72) are taken into account. The use stage is completely dependent on the type of building, how it was handled, and the purpose of the building. However, this does not affect 1m^2 of masonry itself and is therefore not included.

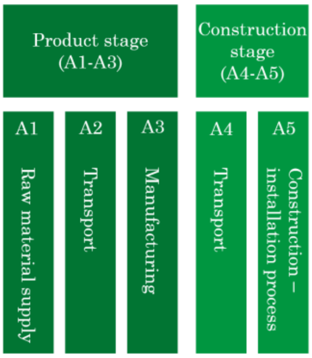


Figure 72: Life Cycle Stages Scenario 1

The total amount of MKI in scenario 1 is €2.70. The biggest contributor in this scenario is GWP, with its biggest output in A3, the manufacturing phase. Because no separate information was given about mortar voor A1-A3 but only the combined value, it is not known whether this high amount is present due to the firing of the bricks. However, it can be argued that mortar manufacturing does not fit into A3 at all because the dry ingredients were transported in A4 to be mixed with water and applied on the construction site. Therefore, with inference, it can be said that A3 is based on the firing process of the bricks. The smallest amount, €0.03, can be found in A2, with the biggest contributors being the GWP and HTP. A2 is the transport to the manufacturing; in the case of bricks, although a small amount, this is possible. Brick-firing factories are located near rivers where the clay is removed; this makes for less transportation. Not all environmental impacts are given in Figure 74, this is because the values for ADPE, ODP, FEATP, and TETP had little environmental impact together with a low MKI weight factor, resulting in a value of €0.00.

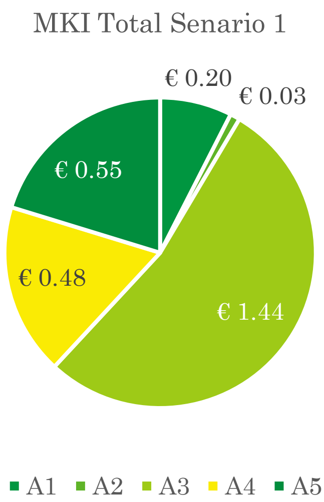


Figure 73: Totaal MKI cenario 1 based on life cycle stage A1-A5

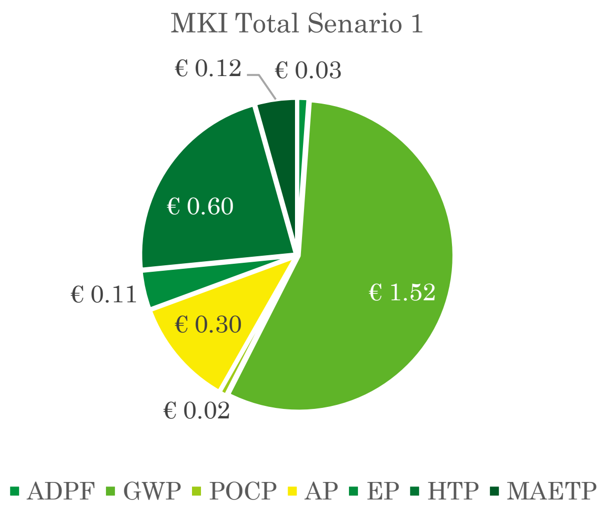


Figure 74: Total MKI scenario 1 based on environmental impact factors

Another interesting option is to see what part of the masonry contributed the most to the MKI value of the masonry. In this case, A1-A3 and A4 are split between mortar/joint mortar and masonry bricks. A5 is taken as a shared part of the process since this life cycle stage ultimately separates the components into masonry. When calculating the split between the mortar and masonry, it came to light that when subtracting the right amount of mortar and joint mortar from the masonry, two values become negative values in the case of bricks. This happens in the A1-A3 process for bricks, with a total of €0.01 for FEATP and in TETP with €0.0003; though a very small number, still some questions can be raised since in the Dutch version of the EDP they indicate that those specific documents where used. However, it is assumed that these values can be used for this research since they have a very small impact on the overall numbers.

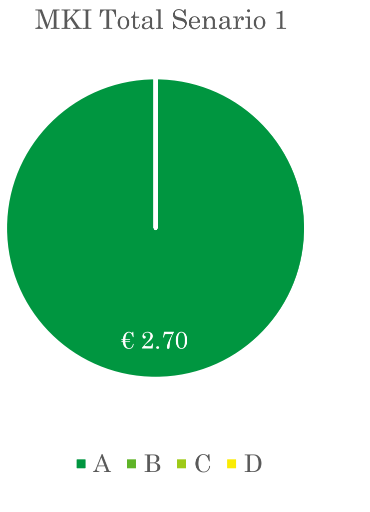


Figure 75: Total MKI Scenario 1 based on Product stage A-D

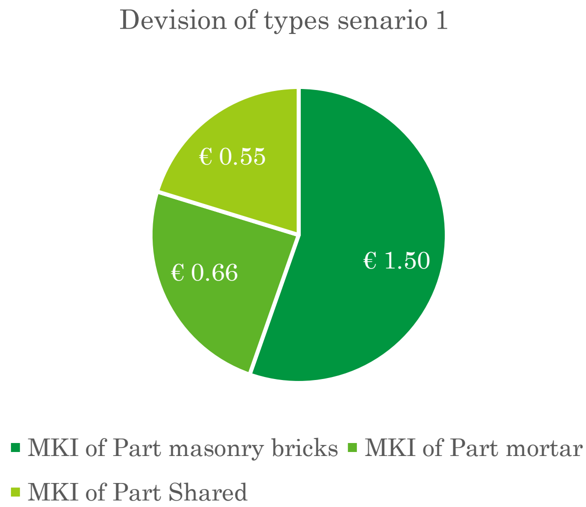


Figure 76: Total MKI scenario 1 based on division of types

Figure 76 describes the total MKI of scenario one divided in parts. It shows the amount of MKI that either brick, mortar or shared activities. This is to compare what has the biggest influence on the scenario when looking at the figure is that it is interesting to see that still 20% (€0.55) of the total MKI goes to the construction phase. In this case GWP (with €0.34) and AP (with €0.09) HTP (with €0.07). Though the direct distribution whether this due to the handling with mortar or bricks is not known. The graphs also shows that masonry bricks take 55% of the total MKI, which is not surprising due to the high GWP in stage A1-A3 due to firing the bricks.

6.3.2 Scenario 2: Reuse Masonry Bricks

In the second scenario, just like in scenario 1, the life cycle stages A1-A5 are taken into account. However, instead of firing new bricks, the bricks recovered from the demolition will be applied as the bricks used in A5. This makes for a new way of looking at the life cycle stages. In Figure 77 The life cycle stages for scenario two are portrayed.

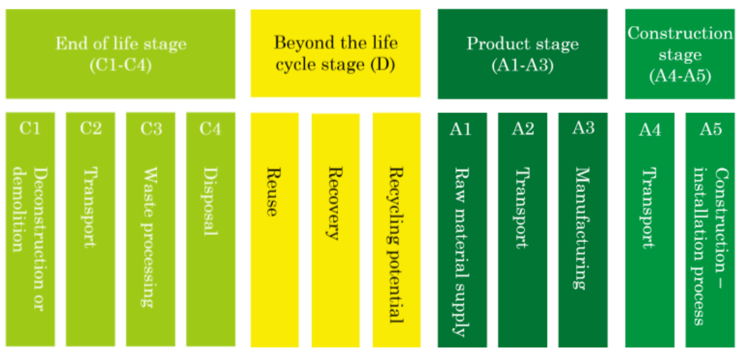


Figure 77: Life Cycle Stages Scenario 2

Though the EPD specifies that the C1-C4 stage is calculated for recycling, the demolition with scenario 2 is almost identical to demolition in a traditional situation. The only difference is that after the masonry is taken down, people will pick out the best bricks and remove the mortar (often by hand). Stage C2 can also be taken as the same value since transporting the weight per kilometre is the same. The weight hasn't changed, and when taken into account, the 50km already calculated in C2 makes this a good comparison. Though the way of transport could change, it will very likely still be some kind of truck. In this calculation, it is assumed that 35% of the final amount of masonry will be recycled since damages are bound to happen when tearing down the masonry. This allows for 65% of bricks to be reused. In C2, because the weight does not change, both the recycled and reused materials are included. The to-be-reused bricks will be transported to storage, while the to-be-recycled materials go to a recycling facility. 35% of the original $1m^2$ will thus be calculated as C3 and C4. Tough 65% of reused bricks is not enough to make a new $1m^2$ masonry. 65% of the masonry is 82.8kg, the total amount of bricks needed for $1m^2$ is 127.5kg (Table 18), which means that 44.7kg more bricks are needed. To get the $1m^2$ of new masonry with old bricks, the process of C1-C4 needs to be performed 1.54 times. At this point, we can start the life cycle stages from the product stage again. The reused bricks do not have any connection with A1-A3 anymore. They appear again in A4, where the bricks are transported from the storage location to the building site. This value is calculated by subtracting the A4 values for Mortar and Joint mortar from the masonry EPD. This is thus the transport impact of 127.5kg of bricks only. Mortar and Joint mortar still have an influence on the product stage. The MPRI sheets, where the unit value was 1tonnes, were changed to 45kg for mortar and 7kg for joint mortar. This allows for the right values for A1-A4 of $1m^2$ masonry. The last stage in the construction stage (A5) is the same as scenario 1; the reused bricks can be handled and constructed the same as newly fired bricks.

This results in a total MKI of €2.28, which is 16% lower than the baseline value. With, just like scenario 1, the GWP as their biggest output in A1-A3 in mortar (€0.54 in Figure 78). It is not known what the exact distribution between A1-A3 is since this is a combined value in the MPRI sheet. The smallest value can be found in the life cycle stage C4*; here, the value is so small that it results in a value of €0.00. other small value stages are C3* (€0.02), A4 mortar (€0.04) and A4 joint mortar (€0.01). C3 is to be expected since smaller quantities are recycled compared with the baseline value. The same can be said about A4 mortar and joint mortar since for $1m^2$, only 45kg and 7kg, respectively, are transported.

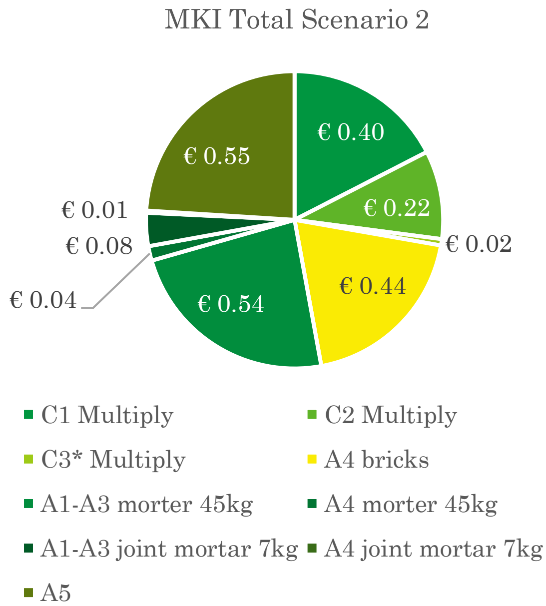


Figure 78: Total MKI scenario 2 based on life cycle stages C1-C4 and A1-A5

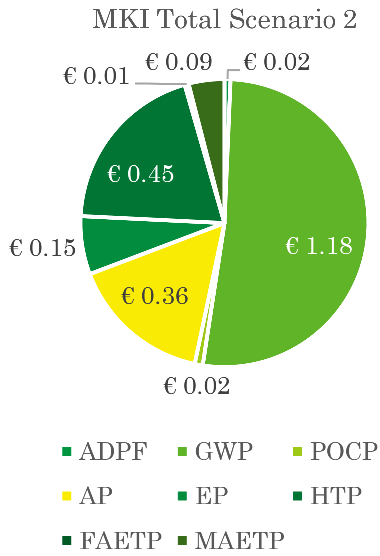


Figure 79: Total MKI scenario 2 based on environmental impact

Just like in scenario 1, part of the masonry has contributed to the MKI. The life cycle stage A5 has been taken as a shared part of the process; this is an identical value to scenario 1 because all actions are also the same. The mortar part only includes the A1-A4 mortar and A1-A4 joint mortar. The masonry bricks part includes all the previous life cycle stages (C1-C4), which need to be performed to get the bricks. It also includes the A4 transportation stage.

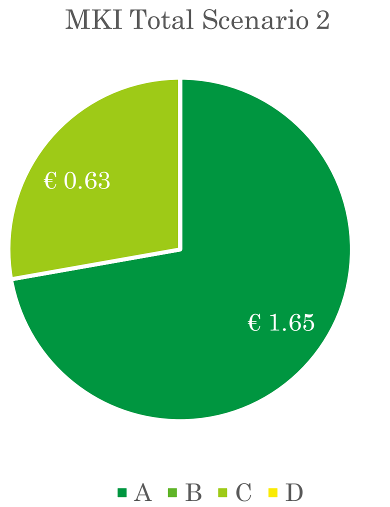


Figure 80: Total MKI Scenario 2 based on product stage A-D

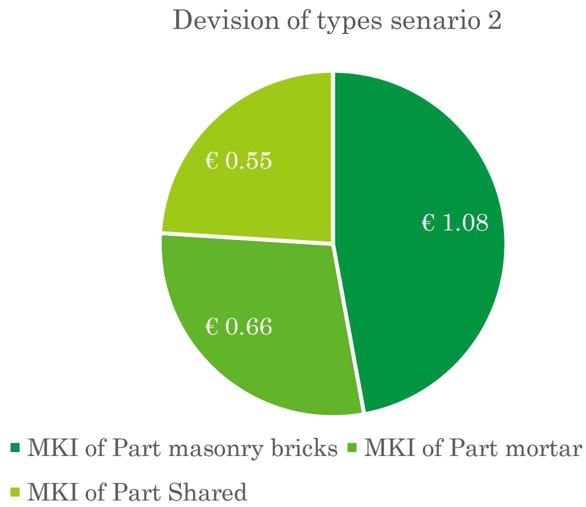


Figure 81: Total MKI scenario 2 based on division of types

With a look at Figure 81 It shows that the shared part has changed to 24% (€0.55) of the total MKI. The MKI value for the mortar and joint mortar part stayed the same, though this is not the case for the bricks. They see a reduction of €0.42. The biggest difference can be found in the GWP with a reduction of €0.34 and in HTP with a reduction of €0.15. but in some cases, it has an increase of MKI, such as in AP (€0.06)and EP (€0.04). This is because Stages such as C1-C4 needed to be repeated at least 1.54 times to get 1m^2 of new masonry.

6.3.3 Scenario 3: Reuse Masonry Elements

The third scenario is the furthest away from the first and second scenarios. However, the calculation does see some comparisons. Stages A1-A5 will make sure that this scenario is comparable with the other two. Scenario 2 had the same production process as the baseline value but took the bricks from life cycle stages C1-C4 and, during the production and construction stage, combined the reused bricks with new mortar. The scenario for this part of the chapter will make use of the same life cycle stages as the reuse of bricks but applies a different application. Reusing elements means that most of the mortar is also recycled. In the calculation, we assume the worst-case scenario, which would be that the joint mortar does not comply with regulations and needs to be redone. However, the masonry element collected from C1 is then transported during C2 to storage and, in A4, transported to the building site for the new construction. In **Error! Reference source not found.** the life cycle stages for scenario 3 are portrayed.

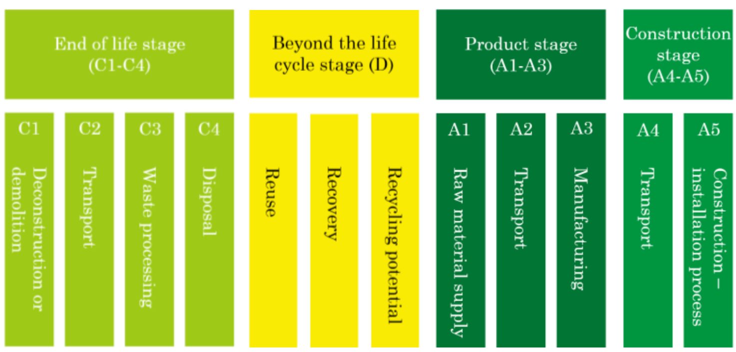


Figure 82: Life Cycle Stages Scenario 3

The most important change compared to the previous scenarios is that the way to demolish or dismantle is completely different. For scenario 2, the procedures were identical; both took down the masonry as in a traditional method. Reusing masonry elements calls for a more careful method of dismantling. It asks for a saw to dismantle the existing wall in elements and an excavator in the form of a crane to remove the elements and place them on transport. However, because of the limited time for this thesis and not exact enough information to get enough data to be able to compare it to the masonry EPD, some assumptions have been made. Even though the way of working is different in C1, the same type of material can be used. Therefore, it is assumed that the value for C1 is comparable with the other two scenarios. In the case of transport, C2 can also be taken as the same value since transport is per weight and kilometres; this is the same as in the brick reuse scenario. In this calculation, it is assumed that a total of 90% can be reused, and the other 10% gets recycled. In this, 10% are also the areas needed for the necessary test of the masonry. This means that 10% will be recycled and transported from C1 to C3. Because only 90% can be reused, more material is needed to create a new 1m² masonry. 90% of masonry equals 114.75kg, and 127.5kg is needed for 1m² of new masonry. Therefore, the stages C1-A4 are multiplied by 1.11. After this, the elements will appear again in stage A4 when the elements are transported from storage to the building site. This is comparable to the transport form C2. In the case of A5, this is the same situation as C1, where the way of building is completely different from the traditional way of building. However, since the same building materials are used as with the dismantling of the elements (C1), this would be a comparable value. One other part of the implementation is that the elements need to connect. It is assumed that 98% of the 1m² masonry exists of the masonry element, which implies that 2% mortar is needed to connect the masonry elements. To work with the worst-case scenarios, we assume that in 98% of cases, the right joint mortar hardness is not present. This would imply that the joint mortar needs to be re-applied. This is done in stage A5. There is no information for the mortars in the A5 life cycle stage. To be able to say something about the environmental impact, a percentage of the A5 of scenario 1 is used in this calculation. The mortar applied in this scenario is 6% of the total weight of 1m² masonry. Therefore, 6% of A5 (scenario 1) is counted as A5 for element reuse. For the mortar and joint mortar, the life cycle stages start at A1; this is not different compared with previous scenarios. However, because mortar is also reused in the element, less mortar is needed during the construction. Therefore, 2% of 45kg of mortar is taken into account. Joint mortar is taken into account fully.

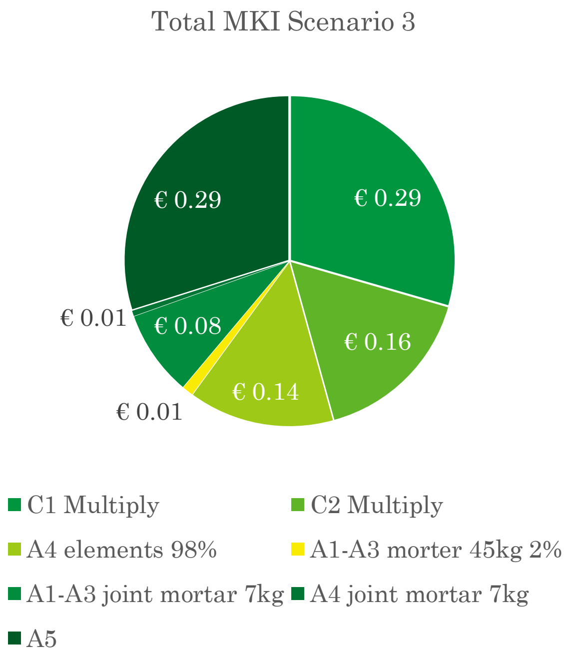


Figure 83: Total MKI scenario 3 based on life cycle stages C1-C4 and A1-A5

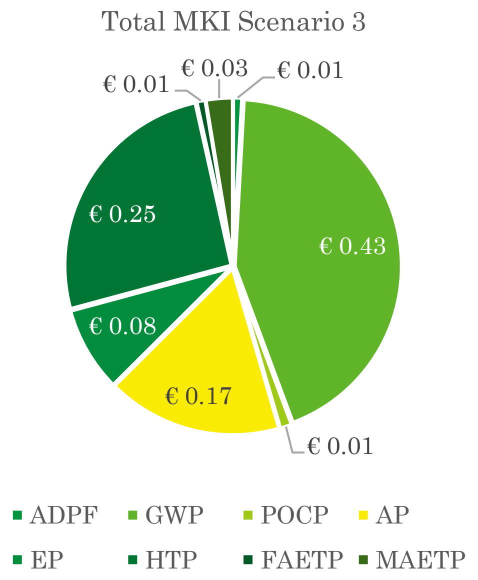


Figure 84: Total MKI scenario 3 based on environmental impact

This resulted in a total MKI of €0.98, which is 64% lower than the baseline value and 57% lower than scenario 2. However, for the calculation of scenario 3, more assumptions have been made to compare the three scenarios. This would normally mean that the value of scenario 3 is less certain, though with differences of 64% and 57% when the made assumption was not completely correct, it would make an impact on the total MKI but not as much on the fact that is has a significantly less impact compared with scenario 1 and 2. Scenario 2 had the most contribution in GWP from stages A1-A3, mainly from mortar 45kg production. This is, in the case of scenario 1, completely different since only 2% of mortar is used. Scenario 3 sees the biggest contribution to the MKI in stages C1 (€0.29) and A5 (€0.29), which is the demolition and reinstallation. Because the big emitters of the production of Portland cement and firing of the bricks are not or barely needed in the process, the total emission or scenario 3 is lower.

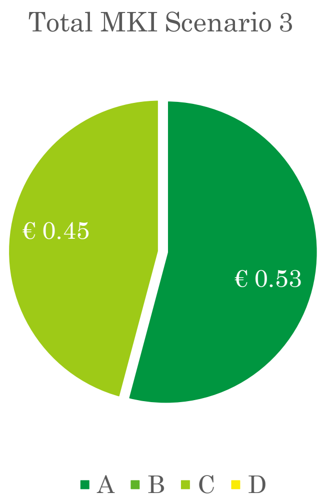


Figure 85: Total MKI Scenario 3 based on Product stage A-D

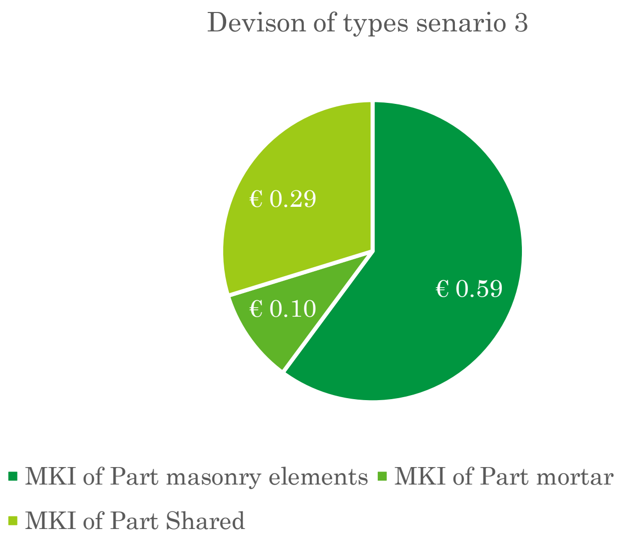


Figure 86: Total MKI scenario 3 based on the division of types

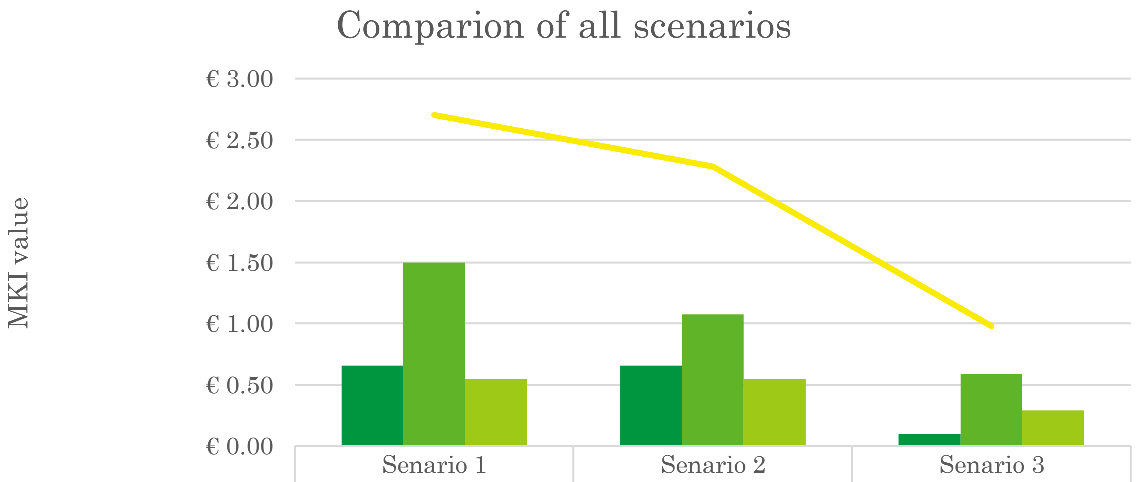
In the case of scenario 3, the mortar part of the total MKI is rather small (Figure 86); this means that the ratio of the masonry element is bigger than in comparison with scenarios 1 and 2. However, the MKI value is still smaller because the C1-C4 procedure is less repeated to get 1m^2 of new masonry. The same goes for the shared part, which also has a decrease. The masonry element part takes up to 60% (€0.59) of the total MKI, which is logical because 90% of the materials are reused, which means that most of the raw materials are not needed in this scenario.

6.4 COMPARISON

In the traditional building scenario, all materials are new. The primary stages of environmental impact are A1-A3 (raw material extraction, transport to the manufacturer, and manufacturing). The highest contribution is found in the production of the bricks, which includes activities such as the extraction of clay, transport and the firing of bricks. This scenario has the highest overall environmental impact.

The second scenario, reusing the bricks, reduces environmental impact by incorporating bricks recovered from demolition into new construction. This approach mitigates the need for brick production, which was the highest contributor in the baseline scenario. However, the environmental impact of recovering the bricks and preparing them for new construction does contribute to the overall impact of the bricks. Reused bricks have a 28% less MKI value than newly produced bricks. Masonry of reused bricks is constructed the same way as traditional building; thus, new mortar is applied in the building process, making sure that there is no reduction of environmental impact for the mortar section of the MKI. This is also the same for the building method.

Reusing masonry elements represents the most sustainable approach among the three scenarios. It involves dismantling entire masonry sections and reusing them with minimal processing. It reduces the need for new materials and the associated environmental impacts. Most of the mortar can be reused, further decreasing the need for new resources. The primary environmental impacts in this scenario are the dismantling and reinstallation processes (C1 and A5); these values were based on assumptions but are still considerably lower compared to the impacts of producing new materials.



	Senario 1	Senario 2	Senario 3
Mortar part	€ 0.66	€ 0.66	€ 0.10
Brick/element part	€ 1.50	€ 1.08	€ 0.59
Shared	€ 0.55	€ 0.55	€ 0.29
Total	€ 2.70	€ 2.28	€ 0.98

Figure 87: MKI Comparison of all Scenarios

Part III
Result and final remarks

Chapter 7
RESULTS

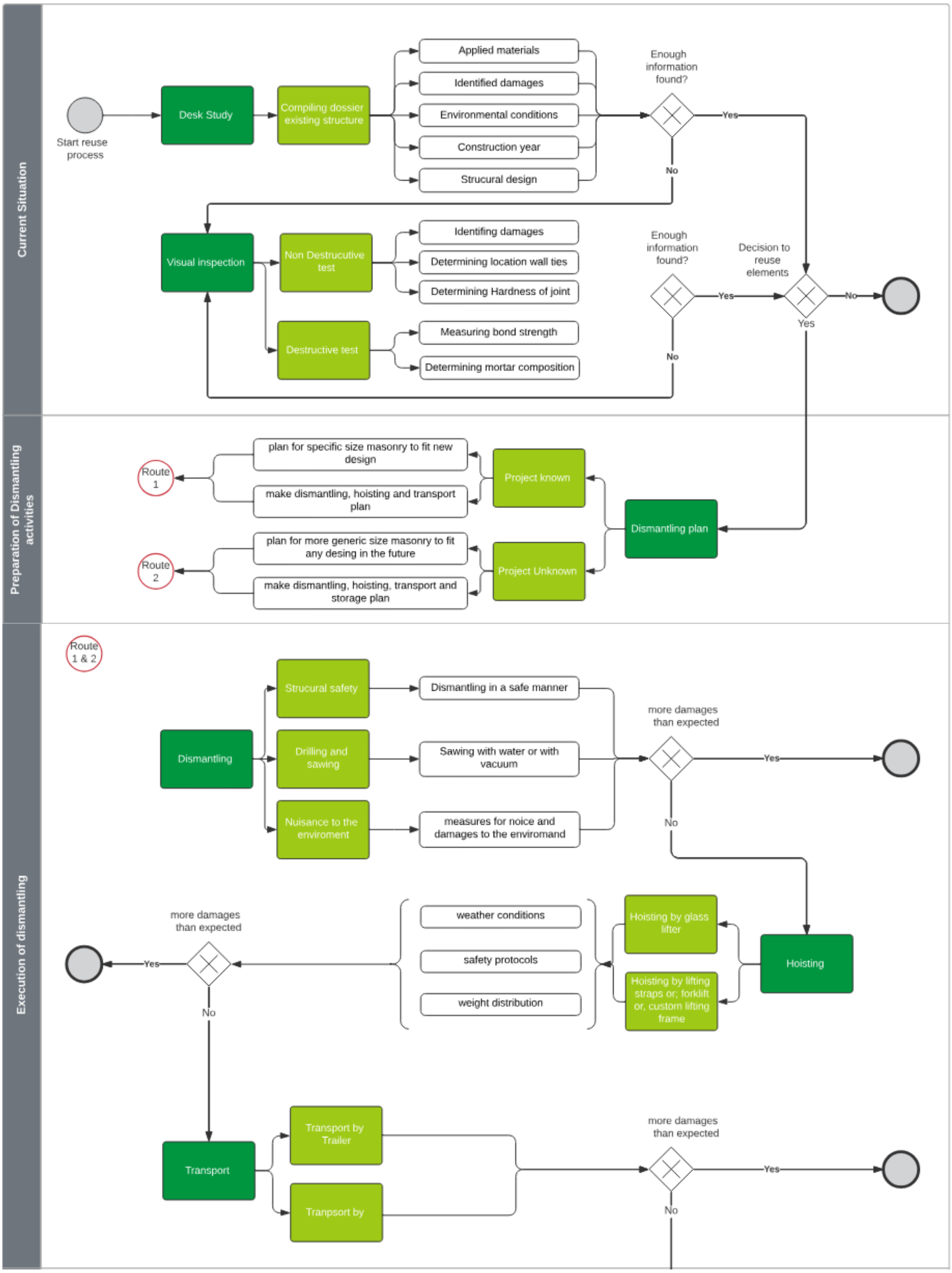
In this chapter, the results from the prior chapters are shown. The findings in Chapter 4 are translated into a guideline. The results of the durability of masonry and the environmental impact are compactly described.

7.1 REUSE GUIDELINE

This is done in the form of a flow chart that outlines the guidelines for the reuse of masonry. The whole guideline can be found in Appendix A. The flow chart (Figure 88) provides a step-by-step process based on the guideline to create a sustainable way to reuse masonry in components for new construction projects. The following summary describes the most important activities.

3. **Current situation:**
    - **Desk study:** Conduct a desk study to gather information about the site and its masonry elements, including historical data, previous inspection reports and construction plans
    - **Visual inspection:** Perform a visual inspection to identify and document existing masonry if it is suitable for reuse. This can be done with non-destructive tests and destructive tests.
4. **Preparation of dismantling activities:**
    - **On-site planning:** Develop a plan for the dismantling process, including methods, equipment and personnel required
    - **Desing planning:** In the case that the new construction project is known, make a disassembly plan for specific sizes. When the project is unknown, make a disassembly plan for the most valid sizes.
5. **Execution of dismantling:**
    - **Dismantling:** careful dismantling to avoid damages by using the appropriate techniques.
    - **Hoisting:** Handle the element with care to avoid damage; select the right method.
    - **Transport: Select the most appropriate way to transport the elements.**
6. **Activities between dismantling and implementation:**
    - **Storage:** Store the elements in a manner that preserves their condition until they are needed for the construction process. This may involve protective covering of climate-controlled environments.
    - **Further processing:** Conduct any necessary processing, such as cleaning, repair or modification of the element to prepare them for reuse.
7. **Preparation phase:**
    - **Integration plan into design:** Make a design that incorporates the reusable masonry elements into the new design. Ensure that the design accommodates the dimensions, shapes and quantities of the available elements. Prepare a wall tie application plan and a dilatation plan.
    - **Preparation element:** Prepare all elements before implementation by having mortar-free sides and matching mortar prepared for the implementation
    - **Logistics and coordination:** Coordinate logistics to ensure the timely delivery of the masonry element to the construction site when needed, as well as a transportation plan and on-site handling plan.
8. **Realization and handover**
    - **Installation:** Install the reused masonry element according to the design specifications and installation plan.
    - **Quality control:** Perform inspections to ensure that the reused masonry elements have been installed correctly and meet all necessary standards and specifications

- **Documentation and handover:** Document the entire reuse process, including the source, condition, and installation details of the masonry elements. Hand over the completed project along with all relevant documentation.



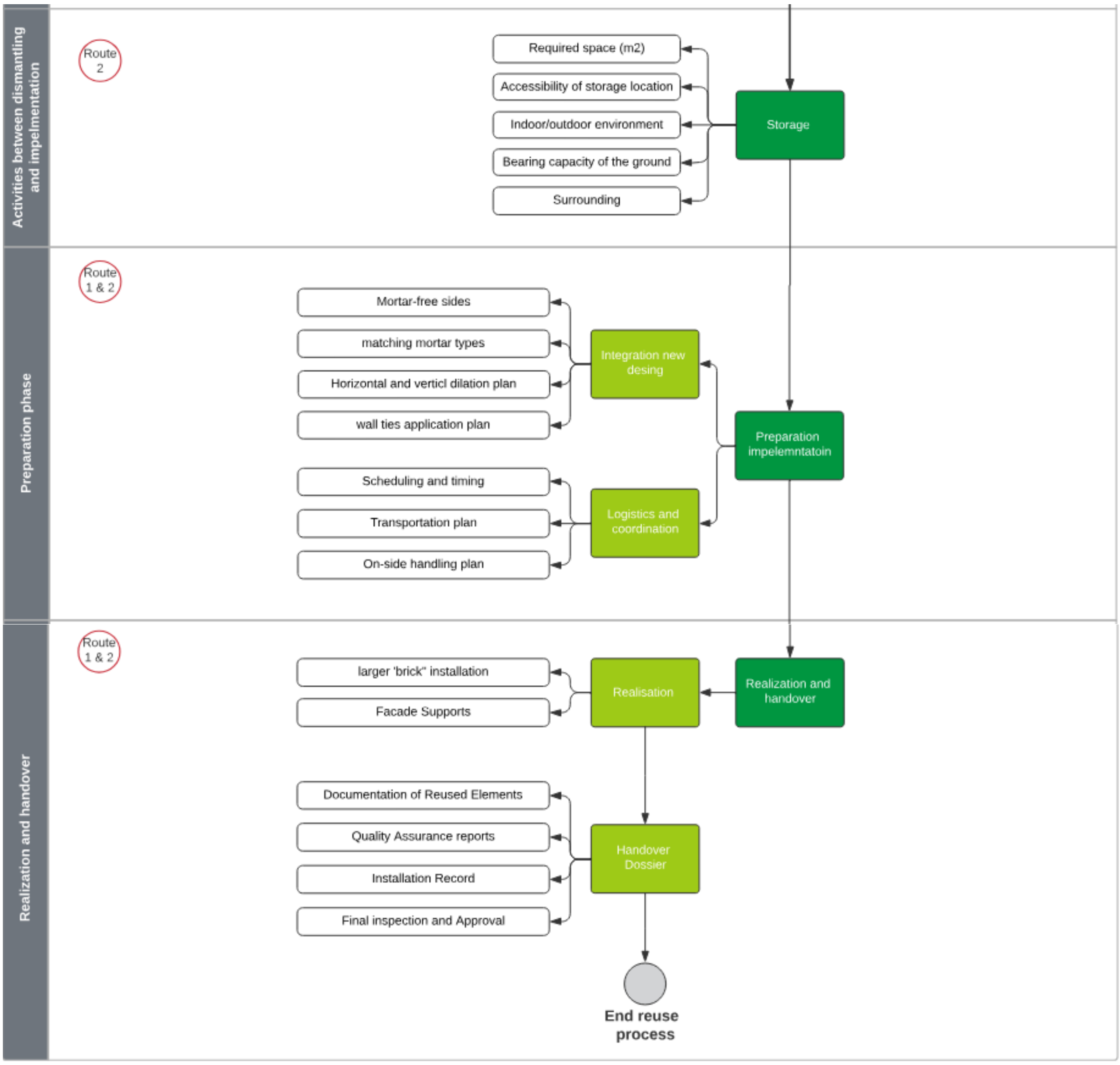


Figure 88: Flow Chart for the Guideline of Reuse of MasonryEelements

7.2 CALCULATION

In the calculation, a simplified micro-model is used combined with a combined cracking-shearing-crushing model to predict masonry behaviour under stress. The elements are testen for situations of unsupported lifting and are tested on joint displacement, flexural bond strength and shear stress. The model is based on mean values found in Dutch houses. This means that for a specific project, a different element size can be reached.

The result of this calculation is an overview of different sizes of masonry elements based on the flexural bond strength criteria and shear stress criteria. These are both the values for minimum situations. This means that the calculation determines the maximum size for the minimum situation. By situations with higher bond strength than the minimum 0.3N/mm^2, the sizes will be able to be bigger.

Table 23: Maximum size masonry element based on two supports and 0.3N/mm² bond strength

Option	Width [m]	Height [m]	Total area [m²]
1	1.0	1.40	1.40
2	1.2	1.30	1.56
3	1.4	1.05	1.47
4	1.6	0.85	1.36
5	1.8	0.80	1.44
6	2.0	0.75	1.50

7.3 ENVIRONMENTAL IMPACT

The comparison of the three scenarios highlights the degree of sustainability achieved through different construction methods. Each scenario has life cycle stages and processes that contribute to its overall environmental impact.

Scenario 1: The highest environmental impact is due to resource extraction and processing.

Scenario 2: Moderate reduction in environmental impact by avoiding new brick production.

Scenario 3: lowest environmental impact of the three. Efficient reuse of materials of both bricks and mortar leads to a significant reduction in all impact categories.

The comparison shows that the reuse of masonry elements is the most sustainable option, offering a substantial reduction in the environmental impact. Reusing bricks also provides notable benefits but is less effective than reusing entire masonry elements. The traditional building scenario has the highest environmental cost due to the production of new materials.

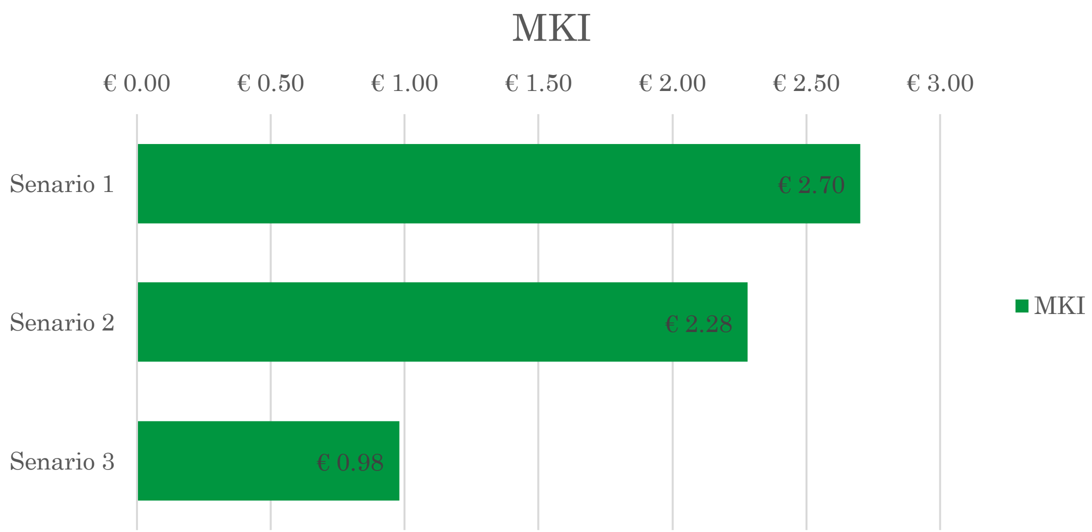


Figure 89: MKI all Scenarios

Chapter 8
VALIDATION

For validation, the first three chapters of the guideline will be tested in practice. This is not done with the last three chapters. These chapters include storage, pre-implementation activities and the implementation. This choice was made because of the limited time required for this thesis. Multiple checks over time are needed to arrive at a conclusion about the storage period. The contents of the part about implementation are based on theoretical background and on the project 'kantoor vol afval', where they applied reused masonry for the outer façade, inner walls and a balustrade. The project on which the validation is applied is a demolition project of Markus in Zaandam, where a total of 45 terras houses will be demolished. The following addresses are going to be demolished: D.Doniastraat 40-66 and 93-119, C.Th.Kamphuijsstraat 1-19 and 22-34.

The first chapter of the guideline is called the current situation. To have a successful information exchange overall activities, a dossier of the existing structure must first be made. The following information should be found in this dossier: it is split into information found during the desk study and information found during the visual inspection.

Table 24: Overview Desk Study and Visual Inspection

Desk Study	Visual Inspection
Construction year	Applied materials
Structural design	Identified damages and defects
Modifications/Repairs	Modifications/Repairs
Additional restrictions and conditions	Environmental conditions

8.1 CURRENT SITUATION

8.1.1 Desk Study

First, the desk study is performed with a quick look at Google Maps, which gives a first impression of the streets.

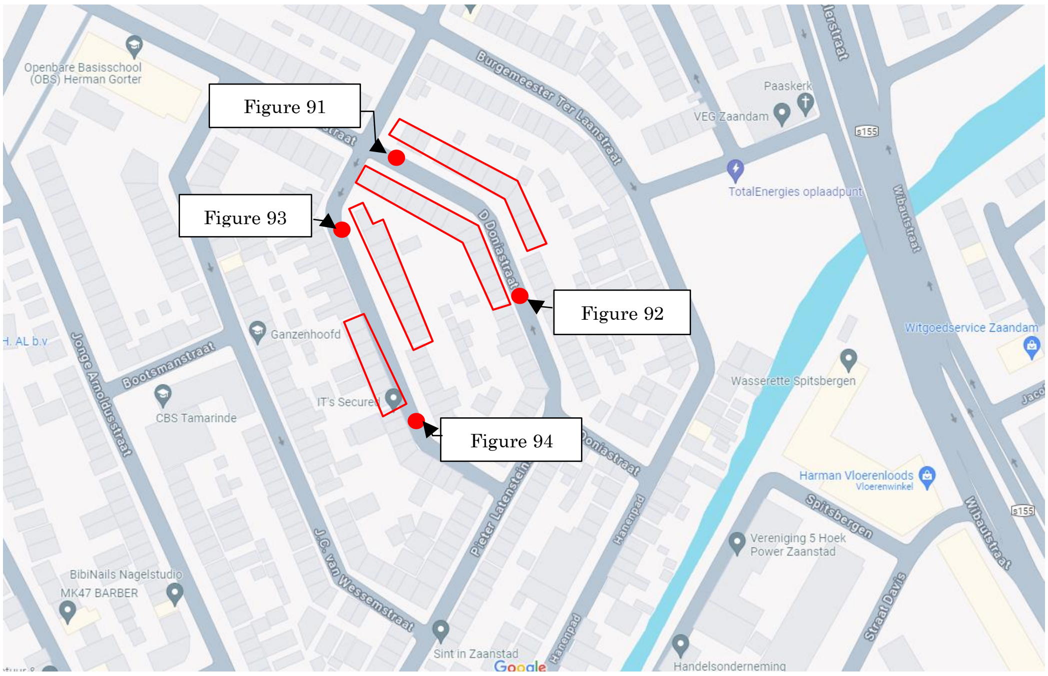


Figure 90: Google Maps Overview

Figure 91: Maps View D. Doniastraat from the Northside

Figure 92: Maps View D. Doniastraat from the South side

Figure 93: Maps View C. Th Kamphuijsstraat from the Northside

Figure 94: Maps View C. Th Kamphuijsstraat from the South side

8.1.1.1 Construction Year

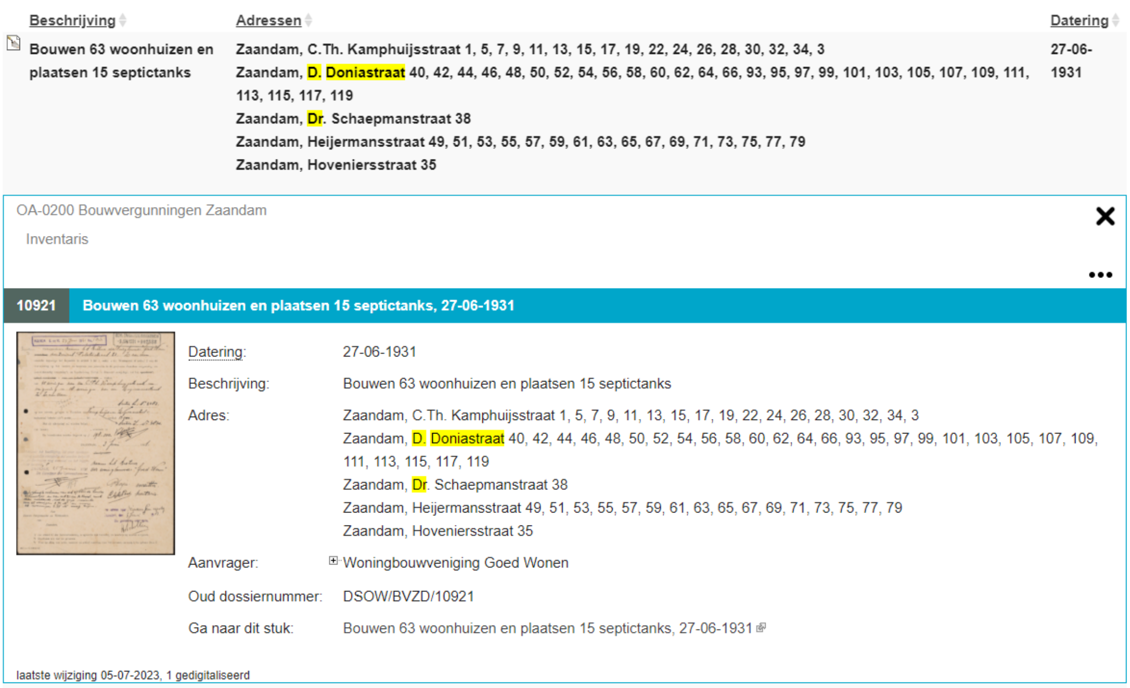
The building year can be found with the bag viewer of the Kadaster. This gives the following:

Table 25: Building Year

Address	Year
D.Doniastraat 40-66	1931
D.Doniastraat 93-119	1931
C.Th.Kamphuijsstraat 1-19	1931
C.Th.Kamphuijsstraat 22-34	1931

8.1.1.2 Structural Design

The houses are located in Zaandam, the municipality of this city is called Zaanstad. The municipality has a public digital archive where information about the houses can be retrieved.



Beschrijving	Adressen	Datering
Bouwen 63 woonhuizen en plaatsen 15 septictanks	Zaandam, C.Th. Kamphuijsstraat 1, 5, 7, 9, 11, 13, 15, 17, 19, 22, 24, 26, 28, 30, 32, 34, 3 Zaandam, D. Doniastraat 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 93, 95, 97, 99, 101, 103, 105, 107, 109, 111, 113, 115, 117, 119 Zaandam, Dr. Schaepmanstraat 38 Zaandam, Heijermansstraat 49, 51, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71, 73, 75, 77, 79 Zaandam, Hoveniersstraat 35	27-06-1931

OA-0200 Bouwvergunningen Zaandam

Inventaris

10921 Bouwen 63 woonhuizen en plaatsen 15 septictanks, 27-06-1931

Datering: 27-06-1931

Beschrijving: Bouwen 63 woonhuizen en plaatsen 15 septictanks

Adres: Zaandam, C.Th. Kamphuijsstraat 1, 5, 7, 9, 11, 13, 15, 17, 19, 22, 24, 26, 28, 30, 32, 34, 3
Zaandam, D. Doniastraat 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 93, 95, 97, 99, 101, 103, 105, 107, 109, 111, 113, 115, 117, 119
Zaandam, Dr. Schaepmanstraat 38
Zaandam, Heijermansstraat 49, 51, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71, 73, 75, 77, 79
Zaandam, Hoveniersstraat 35

Aanvrager: Woningbouwveniging Goed Wonen

Oud dossiernummer: DSOW/BVZD/10921

Ga naar dit stuk: Bouwen 63 woonhuizen en plaatsen 15 septictanks, 27-06-1931

laatste wijziging 05-07-2023, 1 gedigitaliseerd

Figure 95: Information Archive

With the information from the archive, the following conclusions can be made: The houses were built in 1931, which was also found in the bag viewer of the Kadaster. The building association “goed wonen” (good living) put the 24 houses out to tender. The following design conditions and building conditions were stated:

The houses consist of mainly timber, the foundation, floors, beams, roof and ceilings. The bricks used are Belgian bricks in a Waal-red colour. Cavity walls with wall ties; the outer walls only bear their own weight. The cavity has a gap of 4cm. The mortar that should be applied is a bastard mortar with a dry distribution of 1 Portland cement, 1/8 lime and 3 sand. The (pointing) joint is a flattened joint with cut edges that is slightly recessed. It has a dry distribution of 1 Portland cement, a very small addition of lime, and 2.5 sand.

8.1.1.3 Modifications/Repairs and Additional Restrictions and Conditions

In the case of this project, it is known that the 45 old houses are to be demolished due to foundation problems. This would suggest damage to the façade is present. This can be obtained from the visual inspection.

8.1.2 Visual Inspection

The visual inspection is done on all buildings, though in the main document, only the two locations where masonry has been removed are shown.

8.1.2.1 Location 1

Adress: D. Doniastraat 111

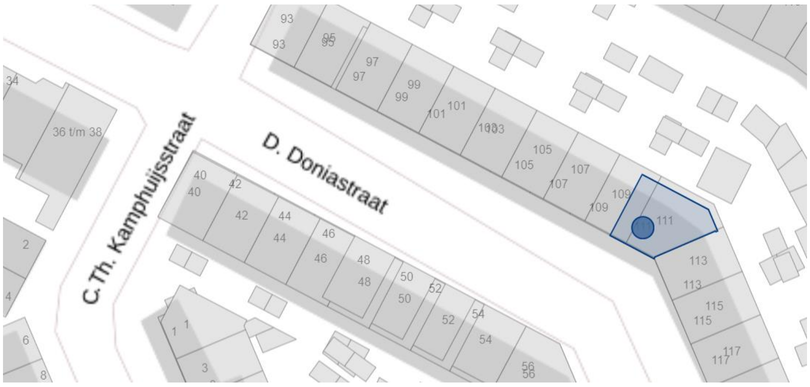


Figure 96: Location 1 Map View

Frond view - East

Figure 97: Location 1: Frond View

Detailed photos

Figure 98: Location 1 Frond View Detail 1

Figure 99: Location 1 Frond View Detail 2

As can be seen in Figure 97, this house has a side façade, though because this hall was quite small, making it not possible to get the right picture, this is excluded. The backside of the house was not photographed because Marcus had started by stripping everything inside the house and putting it in the back garden.

8.1.2.2 Location 2

Adress: C. Th. Kamphuijsstraat 1

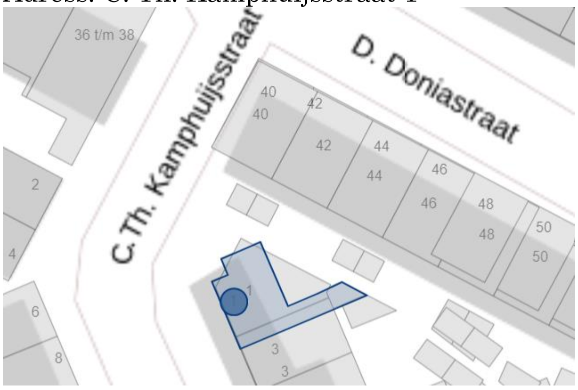


Figure 100: Location 2 Map View

Frond view - East

Figure 101: Location 2 Frond View

Figure 102: Location 2 Frond View Details

Side view – South

Figure 103: Location 2 Side View

Back view - West

Figure 104: Location 2 Back View

Detail

Figure 105: Location 2 Side View Details

Detail

Figure 106: Location 2 Back View Detail 2

In the case of location 2, three sides were available for a visual check. The gardens were already demolished, the ground was very uneven, and some obstacles were in front of the façade; these obstacles were removed before we started the removal of the elements.

8.1.2.3 Previous Testing Location

Adress: D. Doniastraat 64

Figure 107: Previous Test Location – Map View

Frond View - West

Figure 108: Previous Test Location Front View

Back view – East

Figure 109: Previous Test Location Back View

Detail

Figure 110: Previous Test Location Frond View Detail

Detail

Figure 111: Previous Test Location Detail 1

On the previous testing location a small element was removed from the frond façade, while on three location on the back side lever test were performed.

8.1.3 Non-Destructive Test

The non-destructive test was only performed in one location, on the previous testing location.

8.1.3.1 Hardness Joint

The calculation of the joint hardness is performed based on CUR-61-2013. The required joint hardness is VH45, meaning that the minimal joint hardness in the calculation above the number 35 needs to be.

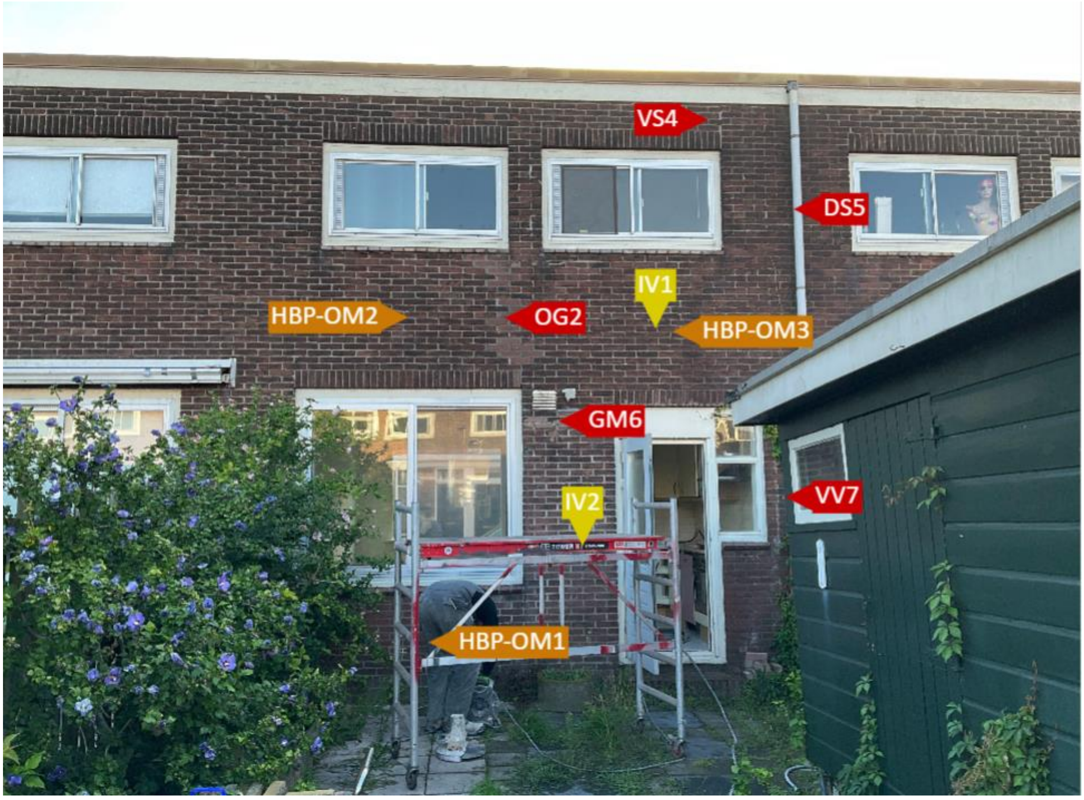


Figure 112: Façade Back Side of the Building, from testing August 2023

Table 26: Joint Hardness Calculation IV1 Bed Joint

IV1 (bed joint)			Location:		D. Doniastraat 64					
Zero value		3	4	5	5	1	4		Median	approval
63	48	49	57	54	63	57	51	40	50	V

Table 27: Joint Hardness Calculation IV2 Bed Joint

IV2 (bed joint)			Location:		D. Doniastraat 64					
Zero value		5	4	3	4	3	4		Median	approval
67	58	50	64	63	44	52	62	64	58	V

Table 28: Joint Hardness Calculation IV1 Head Joint

IV1 (head joint)			Location:		D. Doniastraat 64					
Zero value		3	4	5	5	1	4		Median	approval
43	32	46	39	30	39	39	35	35	35	V

Table 29: Joint Hardness Calculation IV2 Head Joint

IV2 (head joint)			Location:		D. Doniastraat 64					
Zero value		5	4	3	4	3	4		Median	approval
66	43	48	49	48	65	35	58	49	45	V

8.1.4 Destructive Test

8.1.4.1 Location 1

Figure 113: Location 1 Destructive Test Location

Figure 114: Location 1 Brick 1 Overview

Figure 115: Location 1 Brick 1 Collapse Method


Figure 116: Location 1 Brick 2 Overview


Figure 117: Location 1 Brick 2 Collapse Method


Figure 118: Location 1 Brick 3 overview


Figure 119: Location 1 Brick 3 Collapse Method

Table 30: Calculation Flexural Bond Strength Location 1

	Measured value	Average joint depth [mm]	Average room behind mortar [mm]	Flexural bond strength [N/mm²]	Collapse method
Brick 1	250	10	5	1.010	A1
Brick 2	350	10	5	1.408	A2
Brick 4	435	10	5	1.746	A2
Average				1.39	
Standard deviation				0.368	
X average ;characteristic				0.77	

We chose to do less lever test than is officially given in the Eurocode. Though in this case, with the three test we did on this wall and the results of the previous test (in chapter 8.1.4.3) together with the results of the desk study this result was not beyond expectations.

8.1.4.2 Location 2

Figure 120: Location 2 Destructive Test Location

Figure 121 Location 2 Brick 1 Overview

Figure 122: Location 3 Brick 1 Collapse Method

Figure 123: Location 2 Brick 2 Overview

Figure 124: Location 2 Brick 2 Collapse Method

Table 31: Calculation Flexural Strength Location 2

	Measured value	Average joint depth [mm]	Average room behind mortar [mm]	Flexural bond strength [N/mm²]	Collapse method
Brick 1	359.6	10	5	1.446	A5
Brick 2	415.4	10	5	1.668	A5
Average				1.56	
Standard deviation				0.157	
X average ;characteristic				0.86	

We chose to do less lever test than is officially given in the Eurocode. In this case, with the two test we did on this wall and the results of the previous test (in chapter 8.1.4.3) and location 1, together with the results of the desk study this result was not beyond expectations.

8.1.4.3 Previous Test Location

Table 32: Calculation of Flexural Strength in the Previous Test Location

	Measured value	Average joint depth [mm]	Average room behind mortar [mm]	Flexural bond strength [N/mm²]	Collapse method
HBP-OM1 (1)	55.4	7	15	0.275	A5
HBP-OM1 (2)	50.7	8	35	0.465	A4
HBP-OM1 (3)	227.3	6	7	1.060	A3
HBP-OM2 (1)	298	x	x	0.859	A4
HBP-OM2 (2)	391.6	x	x	1.126	A4
HBP-OM2 (3)	177	4	60	1.162	A3
HBP-OM3 (1)	352.6	x	x	1.014	A4
HBP-OM3 (2)	267.3	x	x	0.771	A4
HBP-OM3 (3)	234.4	6	3	0.824	A4
Average				0.84	
Standard deviation				0.302	
X average ;characteristic				0.65	

8.2 PREPARATION OF DISMANTLING ACTIVITIES

8.2.1 Project is Unknown

For the verification, only the first 3 chapters of the guideline are tested. This implies that the project is unknown. It would, therefore, be better to cut either the biggest possible elements or the easiest-to-apply size, which would be 1x1. The biggest possible elements would allow for the reshaping of the element later, though this would result in less efficiency in the reuse since some material is lost. The maximum size is based on structural safety and available masonry area. In the case of the guideline, it is specified that it is most effective to dismantle from the top to the bottom. To remove the roof first; this way, the wall ties are easier to remove. This is not an option for this verification. Therefore, removing the wall ties is an extra variable.

8.2.2 Selecting Location

With the selection of the location, the most important factor was to avoid damage to the masonry. Since this demolition project is to be demolished partly due to foundation problems, damages are to be expected. Location 1 was chosen to allow the free cutting of an element with more width than height. The location is below the window frame. The inner wall bears the window frame. Therefore, the removal can be performed while still retaining the structural safety of the residence. The second location was chosen for an element that was higher in height than in width. There were also two side facades with big areas of masonry, though these were not safely accessible due to the close proximity of the road that was still used. Therefore, the second best option was taken. This was in between two windows and had a total of two storeys of masonry. We were also limited to what was possible to see from the ground level. To secure the structural safety of the entire wall, at least 3 stones were left next to the window frame.

Figure 125: Selecting Location 1

Figure 126: Selecting Location 2

8.2.3 Finding Wall Ties

The wall ties were found by using a wall tie detector (metal detector). In the case of location 1, initially 2, wall ties were found; after cutting the element, it was found that more were connected to the element. This was not because the detector did not detect the wall ties. This was due to poor handling of the detector. Two more wall ties were discovered when performing it the second time; for the second location, only three wall ties were found.

8.2.4 Decision to Dismantle

With the information above, the choice was made to dismantle. The bond strength test has not been performed enough times as an experimental value, though all tests did show a very high value, which is also expected since a large amount of the total distribution of the mortar is Portland cement.

8.3 EXECUTION OF DISMANTLING

8.3.1 Drilling, Sawing, Cutting, etc

8.3.1.1 Location 1

The first thing to notice is that sawing was a heavy load. Especially the lower cut. Because the cut needs to be made on the knees. The uppercut and the side cuts were easier to perform. One thing that was noticed was that the saw combined with the vacuum gets really hot when used consecutively. In that case, a saw with water combination would be a better option because this eliminates dust and cools the saw.


Figure 127: Location 1, ower saw cut


Figure 128: Location 1, upper saw cut

After the cuts were made, the row above the element was removed to get to the wall ties.


Figure 129: Removal row above element


Figure 130: Removal row above finished

The removal of the upper wall ties was carried out but with difficulty. We used one phone to look in the cavity and another phone for extra light. The bolt cutters that we brought were difficult to use in the cavity. Since the cavity was very small, the bolt cutter needed to be very wide open to get the ties between the blade. But for the upper wall ties, this was still a success. This problem was also mainly due to the lack of space above the element. If, as described in the guideline, you start on the top, with the room removed. It would be easier to use a bolt cutter to remove the wall ties.


Figure 131: Bolt cutter


Figure 132: Small bolt cutter in the cavity

Figure 133: Small bolt cutter reach

Figure 134: Small bolt cutter around wall tie

Figure 135: Wall tie cut

For the wall ties that are located lower, we wanted to use a larger bolt cutter. This was impossible mainly because the cavity was not big enough but also because the cutter didn't fully close. The wall ties were too small to be damaged by the larger bolt cutter. Since it was not doable with the smaller and larger bolt cutter, we decided to drill the wall tie out. This is also visible in Figure 130.

8.3.1.2 Location 2

In the case of location two, sawing was also a heavy load, especially because, in this case, we decided to saw high and low.

Figure 136: Location 2, lower cut

Figure 137: Location 2, uppercut

After the upper and lower cuts were made, we decided to first drill out the wall ties just as we did in the case of location 1. Manly, it was because we saw no option to remove the wall ties with the bolt cutter.

Figure 138: Drilling to remove wall ties

Figure 139: Total holes element

This resulted in three holes in the element, though this can be restored at a later stage. The holes did not impact the total strength of the element. After all the wall ties were drilled, the Vertical cuts were made.

Figure 140: Vertical cut low position

Figure 141: Vertical cut standing position

8.3.2 Nuisance to the Environment

Since this is a demolition project in the middle of a residential area, there is a nuisance to be expected. However, the noise that we produced with the removal was minimal compared with the noise the demolition produced. We made sure to stay clear of where the public access was and to stay within the barrier that was placed by Marcus.

8.3.3 Hoisting

8.3.3.1 Location 1

Because the bricks above the element had already been removed, it was quite easy to remove the element from the wall. We placed three bricks next to the façade and slowly slid the elements on the bricks. This went without trouble. However, because it was really removed from the wall and already on the ground, we decided not to test the lifting with a small shovel. Since this would be no different than the situation we already had. Furthermore, the small shovel was not able to get to location 2, which, due to its size, would have been the better location to test with a shovel. No damages besides the hole for the wall ties have been noticed during the removal process.

Figure 142: Element resting on 3 bricks

Figure 143: Side view of masonry element

8.3.3.2 Location 2

We tried to remove the element in location 2 without removing more bricks, as we had done in location 1. To remove the element, we used a screwdriver to pry out the existing wall. The bricks above them were not resting on the element; thus, this was an option. With considerable effort and force, we managed to extract the element. Due to the inaccessibility of the location for a small shovel, we utilised nearby demolition waste as a platform to support the element when it was free of the wall. Given the heavy weight due to the size of the masonry element, we placed the 'supports' as close as possible to minimise the distance the element needs to be lowered. This ensures that the element only needs to descend a very short distance, making the removal process more manageable for us.

Figure 144: The cut element still in the wall

Figure 145: Element removed from the wall

The first thing I noticed when the element was removed was that the brick on the bottom left had fallen off. However, this could very well be due to the prying with the screwdriver. When prying on one side, the element shifted a bit, and then, on the other side, the same happened. Bit by bit, the element came out of the wall. However, this did give extra friction on the bottom bricks. This possible is one of the reasons. Another reason is that the flexural bond strength was not strong enough. However, seeing that the rest of the masonry was not showing any other damages, even at the location where the wall ties were drilled out, this would then be very localised.

Figure 146: Damage to bottom left brick

Figure 147: Damage due to removal of wall ties

When we took a look at the backside of the element, we noticed that the wall ties that we supposedly had drilled out of the wall were still connected to the other leaf. However, the removal of the element did not damage the element itself. So this suggests that even the wall ties were already corroded, or the force of prying the element out, the wall ties at the inner wall instead of the outer wall. The drill that was used to drill out the wall ties has a very small diameter. Which also resulted in more damage than only one whole, as can be seen in Figure 147.

Figure 148: Wall ties still is connected to the outer leaf

Figure 149: Backside of the element

8.4 FURTHER OBSERVATIONS

8.4.1 Location 1

When all the tests for the verification were performed, we wanted to make sure no accidents could happen because the masonry was standing upright. This was the reason why we decided to place the elements parallel to the ground. This way, the masonry cannot fall onto the work people. While the masonry was parallel, we decided to perform a small test. We could easily stand atop the element. The element was placed on three other bricks (one located at the camera site in Figure 150, and two on the furthest side of the camera). Even small jumps did nothing to the masonry. This was a pleasant surprise. When talking to people who have a hand in parts of the masonry field, some reactions are sceptical of the principle of reusing elements. Some argue that it will fall apart the moment it is separated from the wall. In the case of this validation project, we were very lucky with a project that revealed to have a very good flexural bond strength. It could have a very different outcome in a project where the bare minimum is found. Such a project would also be a very good option for testing, the test where the limitations are. However, this verification does show that it is indeed possible to remove all the elements of masonry.

Figure 150: Standing on the element of location 1

Figure 151: View under the masonry element of location 1

8.4.2 Location 2

For the second location, it was also important to place the element in a horizontal direction so that it would not fall on workpeople walking by. However, in the case of the second location, the element was too heavy to place on the ground with care. Furthermore, there were obstacles in the way. It was not possible to apply the same principle as in location 1. We were able to lower the element halfway and, from there, decided to let the element go in, which was one of the concrete blocks that were in the middle of the element at that point. Figure 153 shows the concrete block. We couldn't remove this block because the steel part was stuck under an other object. This resulted in the end in the separation of the masonry. Though to my surprise did the element separate in 6 parts, where each part was still fairly large and good connected.

Figure 152: Ruins of element location 2

Figure 153: The reason element 2 brock apart

Chapter **9** DISCUSSION

In this chapter, the results that were obtained are discussed. It starts by discussing the relevance of the research and further describes the limitations of both durability and sustainable calculation. Further, the validity of the guideline is discussed.

9.1 RESEARCH RELEVANCE

The Dutch government has implemented two goals to reach climate goals. The two most important ones are the lowering of raw material usage by 50% in 2030 and the desire to have a fully circular economy by 2050. The Dutch economy is currently not on track to reach these goals. There are still a lot of raw materials used, and this will not change unless action is taken quickly. A possible way forward towards less raw material usage could be the reuse of materials. This is also a step toward a more circular economy. The finding of this study emphasises the potential environmental benefits of reusing masonry elements, aligning with government sustainability goals.

However, there is a gap in the literature regarding the reuse of masonry materials. While masonry is one of the most applied building materials in the Netherlands, no notable efforts have been made for the reusability of the material. A guideline has been created as a result of this thesis to enhance the practical reuse potential of masonry materials. However, for this guideline to have any standing, durability and sustainability need to be proven. The durability is based on the current regulation of structures but also the climate durability. Different types of tests are needed to ensure that these regulations are kept. This is given in Chapter 5, where maximum element sizes are also given. This means that when the regulations are satisfied, basis values of panel elements are available. To ensure the sustainability of the whole procedure, reusing masonry panels, reusing masonry bricks and traditional buildings are compared. It was found that reusing masonry has a significant reduction of environmental impact compared to the other two options. This is mainly because there are no production costs and raw materials needed to reuse elements. In that case, the main contributors are the removal and implementation, which are mainly due to transport and machine use. So, more optimisations can be made using more sustainable materials.

Though reusing is not always an option, in the case of weak bond strength between brick and mortar, reusing the bricks is a better option. The mortar is more easily removed from the brick, and further cleaning will result in a reusable brick. Or when there is too much unrepairable damage to the façade because of foundation settlements, the choice can be made to recycle. Reusing elements is not an all-for-one solution, but having this guideline will make an educated decision can be made.

9.2 RESEARCH LIMITATIONS

The main limitation of this research is the scope boundary. Besides these scope boundaries, different limitations were found throughout the process. During the validation process, it was found that the guideline does not cover all aspects which are involved in the reuse process. The instability of the donor building is an important factor during the validation or the practicality of removing wall ties. The guideline is meant for total deconstruction, meaning that the roof is removed before demounting the masonry. This means that all the weight is removed, even for load-bearing masonry. It also makes removing wall ties easier since it is accessible from above without obstacles.

9.2.1 Durability

During the calculation of the masonry elements, different assumptions were made. Average values were used to create a representation of the average masonry. There is so much difference in material properties between the mortar ratio, types of bricks, the porosity of the brick, and the flexural bond strength of the masonry. It would mean that all new reuse situations need extensive testing and calculations. However, based on this calculation, the maximum size is based on its own weight, the location of the supports and the flexural bond strength. The calculation is done for a flexural bond strength of 0.3N/mm^2. This is the minimum value needed to confirm the regulations. In the case that the bond strength has a higher value, the mortar properties in the DIANA model get higher as well, resulting in bigger possible elements.

9.2.2 Environmental Impact

The calculation of the environmental impact of the EPD of masonry made by KNB shows that this is the only available EPD of masonry in the Netherlands. It is based on the previous edition of the EN15804+A1, which only had 11 weight factors. The new edition, +A2, has a total of 16 weight factors. The main difference between the EDI weighting factor for global warming and depletion (both high emitters) is that they are significantly higher than before. This would mean that the MKI calculation with the new weight factors would have a higher result. And would highlight the reusability option in a (even) more positive light.

Another point is the assumption made for the reuse element scenario. This is an assumption based on comparable proceedings. Because not enough information was available to create a comparable life cycle stage with the EPD, furthermore it was not completely clear what exact information was used in the EPD since the EPD specified that two specific MPRI sheets had been used, though, in the English translation of the same document, this was not mentioned anymore. However, for the comparison of the three scenarios, this was not a problem. However, with both the edition of the EN15804 and some inconsistencies of the masonry EPD, it is not an official MKI value.

9.2.3 Validity of the Guideline

Only the first three chapters of the guideline were included in the validation. The other three chapters that have not been tested are about storage, preparation for implementation, and implementation. All three needed time to be able to verify completely. In the case of implementation, there are two ways to go about it. The first is in the case the receiving project is known, and the other is when it is unknown. In the case that the receiving project is unknown, the cost of testing the masonry is on the client that did the dismantling. The highest cost is expected during the property testing and dismantling. However, with no buyer insight, this is a risk a client would possibly not want to make.

Chapter **10**
CONCLUSION

This chapter gives the conclusion of this research. The main objective of this research was given in

"aims to lower the overall environmental burden by promoting the practical reuse of masonry materials."

This forms the basis for the main research question. This question can be split into three parts, which are subdivided into sub-questions. The answer to all sub question combined form the answer to the main research question. First all the conclusions for the sub question are given, leading to the conclusion of the main research question.

10.1 SUB-QUESTIONS

10.1.1 How does the historical, present, and future evolution of masonry impact the viability of its reuse?

This subchapter is divided into four sub-subchapters.

How did masonry develop over the years?
In the 12th century, brick production started in the Netherlands. Advancements occurred in the mid-19th century with new firing and moulding methods. The post-WWII era brought innovations like machine-made and lighter bricks. By the late 1980s, the industry had evolved into a modern process with precise firing control.

What kind of masonry is applied in the Netherlands?
In the Netherlands, traditional clay bricks, calcium silicate bricks, and various tone bonds are used. Clay bricks are often applied as the outer façade, and calcium silicate bricks as the load-bearing inner wall. Masonry bonds like Norse, Flemish, and English bonds have been historically used, and the running (half-bond) pattern is common today.

What is the material flow in the Netherlands now and in the future?
The future perspective for 2030 and 2050 shows a convergence of the inflow and outflow of clay masonry materials. As of now, all recycled masonry aggregates are used in the GWW sector.

What does the reuse process of masonry look like?
Based on the guidelines of CB23. The preliminary phase is assessing suitability through desk studies and visual inspection; the matchmaking phase is ensuring the right match between supply and demand; the quality research phase is detailed investigations to meet new structure requirements; and the implementation phase is dismantling, sorting and processing masonry elements correctly.

How does the historical, present, and future evolution of masonry impact the viability of its reuse?
Masonry was initially used as a primary structural material, but it evolved into a decorative layer. Traditional bonds and mortar types have given way to more efficient, albeit less structurally demanding, techniques. The emphasis on sustainability has highlighted the importance of reusing building materials. Drystacking is one of the innovations that will allow for easier dismantling and reuse, though it is only for the reusability of future projects, while the already existing traditional masonry presents challenges of reuse. Future masonry could involve further technological advancements in production methods, such as prefabrication and robotic assistance.

10.1.2 How can masonry panel elements be removed from existing houses and applied in new construction?

What are the steps to remove an element from the existing wall and later apply it in new construction?

- *Desk research and visual inspection:* inspection to assess the state of the wall
- *Physical inspection:* Perform a test to determine the strength of the wall
- *Removal of the panel:* with the “outside-in” or “inside-out” method (chapter 4.3.3 and 4.3.4)
- *Hoisting and transport:* using forklifts, glass lifters or lifting straps on trailers or indoor loader
- *Storage:* stored in conditions similar to the original environment to prevent damages
- *Implementation in new construction:* applied as large ‘bricks’ or integrated using façade supports

How can the panel be safely removed from the existing structure?

- Choosing the right method of the situation
- Disconnection wall ties to avoid damages during the removal.
- Cutting the panel with the right tools
- Hoisting uses the appropriate method for the situation and monitors for any signs of instability.

In what way can the element be applied in new construction?

In two primary ways

- Large brick installation
- Façade supports

Both sides need to be mortar-free to achieve a new bond with other elements.

10.1.3 How can the durability of masonry panel elements be ensured?

What are the current standards and regulations regarding masonry?

The Eurocode (EN 1996) and NEN-EN standards, such as EN 1052-5 and EN 1052-5 for flexural bond strength. These regulations ensure the safety and performance of new and reused masonry elements.

What test must be performed to ensure the masonry elements correlate with the current standards and regulations?

- *Hardness test*: assessing mortar joint hardness using a round hammer
- *Flexural bond strength test*: Uses the lever test (EN 1052-5)
- *Mortar composition analysis*: checks chemical and physical compatibility
- *Compression test:* measures brick compressive strength

What is the minimum flexural bond strength needed during reuse to ensure the structural durability of the masonry panel?

For structural durability for new implementation the bond strength needs to be above the minimum value of the EN 1996-1: $0.3 N/mm^2$. Always take precautionary actions to minimize damages during transport by sufficiently supporting the element.

What is needed of the masonry to ensure climate durability of the masonry?

- Environmental class assessment
- Frost-thaw resistance
- Moisture protection
- Mortar compatibility

10.1.4 How can the environmental impact of the reuse of masonry for this concept be quantified?

What is the environmental impact of reusing masonry in element form?
Results in MKI of €0.98. This is mainly because the production impact of new products is (almost) not included in this variant.

What is the difference between the environmental impact of reusing masonry in element form and brick reusing?
MKI reusing bricks is €2.28, which means that reusing masonry in element form has a reduction of 57% MKI

What is the difference between the environmental impact of reusing masonry in element form and traditional building
MKI traditional building is €2.70, which means that reusing masonry in element form has a reduction of 65% MKI

10.2 MAIN RESEARCH QUESTION

The main research question reads:

> ***"How can existing clay masonry walls of houses with half-brick bonds be reused as panel elements in a sustainable and durable way?"***

From this research, we can conclude that masonry can be reused. How it can be done can be done with different methods. However, the guideline created in this thesis can be helpful in the process. The proposed guideline is made to increase the reuse of masonry. This thesis, especially the validation, shows that a lot is possible with the reuse of masonry.

However, reusing a material must be a more sustainable solution than currently applied, which is indeed the case. When comparing the reuse of masonry elements with the reuse of masonry bricks and traditional masonry, the reuse of masonry stands head and shoulders above the other options. Reusing only the bricks gives a 16% less MKI value than traditional building, while reusing the masonry, including the mortar, shows a 64% less MKI value than traditional building. This can be explained due to the fewer raw materials used.

How the masonry is reused depends mainly on the bond strength. Diana's calculation showed that shear stress was determinative for the maximum size of masonry elements. The strength of the mortar, which was assumed to break first, highly depends on the bond strength.

To reuse masonry, the bond strength needs to be at least $0.3N/mm^2$; therefore, all masonry with less bond strength is not applicable for reusing masonry elements. However, this does not disclose all other forms of reuse. Since the reuse of masonry bricks is still an option. It comes with the fact that removing the mortar from the bricks is more accessible when the masonry has a bond strength of $0.3N/mm^2$ or less. This, in turn, leads to adequate procedures for reusing masonry bricks as the cleaning is less valid. The bond strength cannot be determined entirely without performing a test. This is because even if stronger mortar is applied (with more cement), lower bond strength can still be found when the water distribution was incorrect during construction.

This was not the case for the validation project. In the Zaandam, the mortar was rich with cement; the test performed reflected this. The strength exceeded the needed $0.3N/mm^2$ (with $0.86N/mm^2$ and $0.65N/mm^2$ for two locations). And it shows a positive image of the reuse of masonry. Since this validation is not done on a borderline case, this could result in different results.

The main research question specified the half-brick bond wall as one of the most applied bonds, though it is not the only bond used in the Netherlands. Applying this study to other types of bonds will not create much difference. There is a different quantity of bricks and mortar in $1m^2$; therefore, some changes will be found in the sustainability study, though not enough to negate that reusing masonry is a more sustainable option. The same goes for the durability of the masonry; this can create a difference in the maximum sizes, but it won't differentiate too much, so it is no longer a suitable option.

However, as revealed during validation, not all process steps have been tested in practice. Every project is different, though. The guidelines set the approach for reusing masonry in motion. Based on the above-stated aspect, it can be concluded that the potential reuse of masonry elements in new houses is promising.

Chapter **11**

RECOMMENDATION

Recommendations can be made based on the validation findings, discussion, and conclusion. This thesis has shown that there is a lot of potential for reusing masonry. To reflect that, recommendations for the guideline and advice for future research can be given. It is essential to develop this process further to allow for easier and more durable ways of reusing masonry.

11.1 GUIDELINE DEVELOPMENT

Method of reuse
In this thesis, the main focus was on the reuse of masonry elements. However, reusing masonry bricks has also been discussed and applied as a scenario for the environmental comparison. The results show that reusing masonry elements is the most sustainable option. However, this option is not always applicable, as it could be when the flexural bond strength is not high enough, or the masonry is in poor condition. At that moment, reuse of masonry bricks, which is still a more sustainable option than traditional building, will be newly produced products. Therefore, both methods should be developed to allow masonry reuse in good and bad conditions.

Widen the scope of the guideline.
Expanding the scope of the research to various types of masonry and masonry bricks creates a more comprehensive understanding of multiple masonry types, which broadens the applicability and relevance of the guideline. For example, this thesis mainly focused on half-brick bond masonry, though this is not the only bond applied in the Netherlands. This could have implications on, for example, element size. Furthermore, a guideline that includes reusing bricks would allow for the most educated decision.

Verification of additional chapter
Ensure verification and testing of the last three chapters of the guideline, focusing on storage, pre-implementation activities, and the implementation of reused masonry elements. Time is also an important factor in this verification, which may determine a different course of action regarding storage and implementation from that discussed in this thesis.

More practical tests
The practical tests done on reusing masonry in this thesis are scarce. Not much is currently being done to experiment with reusing masonry. The guideline will need to be updated when more practical tests are performed. More practical testing will give a broader insight into the behaviour of masonry in different cases than discussed in this thesis.

11.2 FURTHER RESEARCH

Elaboration on implementation Process
Further elaboration on the implementation process, including storage and reinstallation of masonry elements. This should also cover cost analysis and optimisation to make the process economically viable.

Making a tool for quickly calculating element size
Develop a user-friendly tool to easily calculate the maximum size of masonry elements that can be safely reused. This tool should consider factors such as structural integrity and hoisting capacities. This tool will help streamline the reuse process and ensure compliance with safety standards by providing clear guidelines on element size.

Do research into the connection of element size masonry
In the reuse process, the dismantled elements need to be connected to other structures of other elements. This can be done with mortar. In that case, the permeability of the bricks in the element is essential. Reusing elements can only be applied when the bond strength is higher than $0.3N/mm^2$, which would imply that the mortar is well penetrated. Therefore, further research into the bond strength when part of the pores are still penetrated by mortar is not only applicable for the implementation of masonry elements but also for the reuse of masonry bricks. Therefore the question can be asked, in what capacity is it possible to get the minimum required bond strength when part of the pores are still penetrated?

Research bottleneck situation
In this thesis and in the guideline different situations can cause the reuse process to be less effective. This can happen when the supply is more than the demand. In that case, there will be leftover masonry that can be reused. Two different questions can be asked about leftover masonry that can be reused. How can the elements be cut to allow for a bigger chance of reusing in another project, and how can the storage locations be accommodated? How to accommodate the reused materials in storage locations is an important question for all reused materials. With further research in the above-called situations, the reuse of masonry can be elevated to a bigger scale.

Investigate the liabilities and guarantees.
Investigate the liabilities, guarantees, and forms of collaboration necessary for the successful reuse of masonry elements. This report or guideline does not treat legal aspects, which can have a major effect on the potential for practical reuse. It is advised to look into different legal aspects as well as the collaboration form used during the project's execution.

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Appendix A
THE GUIDLINE

INTRODUCTION

GOAL

The purpose of this guideline is to instil more confidence in the chain regarding quality assurance in the reuse of masonry elements. It aims to provide practical value. Consequently, the document is structured as a facilitating guideline rather than a protocol, recommendation or standard, granting users the flexibility to apply it according to their specific needs and circumstances. This guideline provides general considerations for the reuse of masonry elements, recognising that it is impossible to cover every possible scenario exhaustively. Users are encouraged to independently verify and assess whether the guideline sufficiently addresses and elaborates on all relevant aspect for their particular products and application. The reuse of masonry elements is an emerging field, characterized by continuous advancement sin circularity and 'closing the loop' within the construction industry. As such, this guideline should be seen as a living document that evolves in response to new developments and insights; users are advised to stay informed about the latest progress in the field and incorporate new findings and best practices into their applications as appropriate.

SCOPE

This guideline focuses on the reuse of masonry clay elements, mainly in stretcher bond form. It includes masonry elements originating from buildings that are again applied in buildings. It assumes total demolition. For assessing the structural safety of an existing building, the NEN-8700 series applies. This document primarily focuses on the high-quality reuse of elements in a new or renovated building. Practical guidance is provided for successfully completing the reuse process. This document does not serve as a structural assessment like the NEN-8700 series.

READERS GUIDE

The guideline organises various topics into six main categories as defined in the 'reuse decision three' (beslisboon) as described by Cirkelstad. These six main categories are also used as the basis for the guidance 'quality assessment and assurance' of the action team 'future reuse' of CB23. This chapter structure was chosen to align with other documents, ensuring consistency and ease of reference for users familiar with these frameworks. The chapters are, therefore, numbers from 1 to 6, but this does not mean that the steps must necessarily be taken in chronological order. The order of chapters may vary per project. Therefore, it is important, regardless of the reader's role, to review all content since there are various intersections between steps and roles in the process. Chapter One addresses the collection and documentation of data on the masonry. It includes methods for assessing the condition and characteristics of existing masonry elements to determine their suitability for reuse. Chapter two covers the preparation for the dismantling process. It provides guidelines on planning, safety considerations, and the necessary tools and techniques to carefully dismantle masonry elements. The execution of the dismantling process and the associated procedures are covered in chapter three. It outlines step-by-step instructions and best practices to ensure the integrity of the masonry elements is maintained. In chapter four, activities between dismantling and integration into the new design are described. It includes storage, transportation and preliminary treatment of the masonry elements to prepare them for reuse. The preparation of the oof-take project is discussed in chapter five. It focuses on the planning and logistics involved in the incorporation of the reused masonry elements into new construction projects. In the final chapter (chapter six), the realisation and delivery of the project are discussed. This includes quality assurance measures and final inspections.

It is essential to carefully preserve and link data on reusable elements throughout the process. Elements can be reused in different locations, increasing the risk of data loss, which is undesirable as it significantly devalues the element. Therefore, meticulous documentation and tracking are crucial to maintaining the value and integrity of the reused masonry elements. Various inspection and testing moments for masonry are recommended during the process, such as visual inspection, testing of the durability of the masonry, inspection during dismantling, after dismantling and the final inspection with the implementation.

Table of Contents

1. CURRENT SITUATION

A connection can be established with the proactive of high-quality reuse, encompassing the entire process from when a potentially reusable product is still in its "old situation" to the "new situation" where it is reused. This process includes the interim storage and processing phase. The decision tree, although sequentially listed, is not strictly chronological; some steps should occur concurrently. The decision tree provides insights into all possible steps but can also be consulted based on specific roles or moments in the process. The process begins with the current situation, emphasising that initial quality assessment should occur early, ideally while the old building is still in use. This increases the chances of high-quality reuse and can save costs by avoiding unnecessary tests.

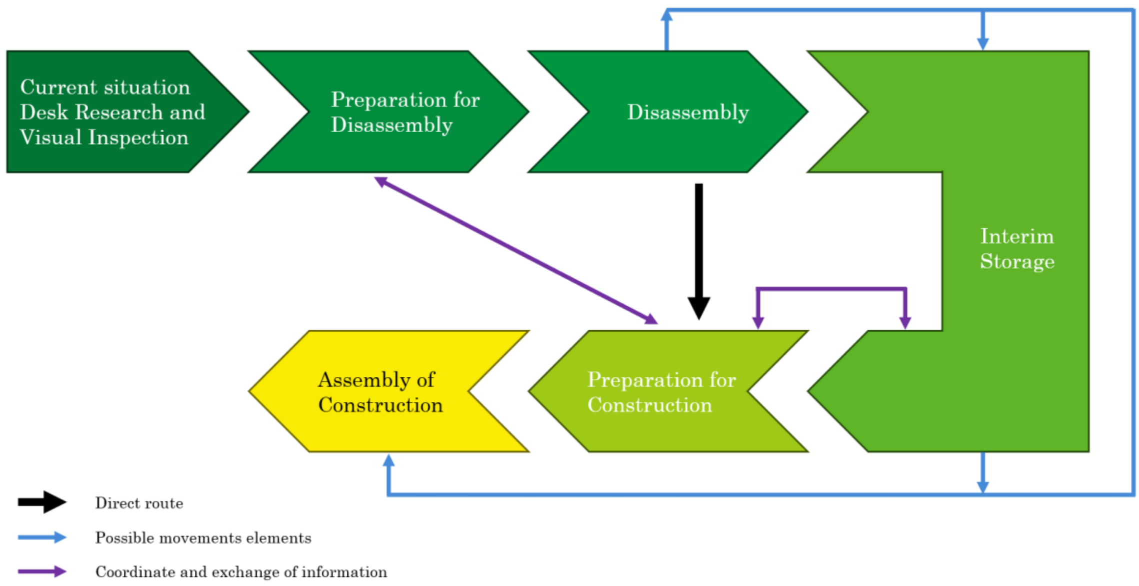


Figure A 1: Decision tree reuse

The decision tree includes a dossier for the building's original compliance and a dossier for pre-demolition qualitative research. Visual inspections are critical for assessing the potential of construction products for reuse. If initial inspections suggest potential for reuse, further detailed investigations are conducted. The decision tree also guides the selection of reuse strategies and dismantling methods based on product quality. Proper dismantling, storage, and transport are crucial for maintaining quality. The tree supports intermediaries in quality control and provides insights for formal and informal quality assessment during new construction projects. The goal is to reduce uncertainty and risks associated with reusing construction elements, ensuring quality through systematic inspections and documentation.

1.1 Compiling dossier of existing structure

In general, having comprehensive information about the existing structure and elements significantly enhances the potential for reuse and informed decision-making. While reuse may still be possible without complete information, this can lead to increased uncertainties and higher costs due to the need for additional non-destructive or destructive testing to fill in the gaps. Information on masonry can possibly be obtained through archive research. This might include examining the archives of the current building or accessing available data from design authorities or the original manufacturer. Such research can provide valuable insights and relevant information about the masonry.

To effectively describe the existing structure of the potentially dismantled masonry, the dossier should include the following data, as far as known:

11.2.1.1 **Applied Materials:** Information about the types of mortar and bricks used
11.2.1.2 **Structural Design:** Details of the original design of the structure
11.2.1.3 **Construction year:** The year the structure was erected
11.2.1.4 **Modifications/Repairs:** Records of any modifications or repairs made during the operational phase, including maintenance data of visual proof
11.2.1.5 **Identified Damages and Defects:** Documentation of any damages or defects identified in the masonry
11.2.1.6 **Environmental Conditions:** Description of the environments and conditions in which the structure or element was located
11.2.1.7 **Original Location:** The specific location of the element within the structure and the location of the structure itself
11.2.1.8 **Additional Restrictions and Conditions:** Any other relevant restrictions or conditions that might affect reuse.

Note: The above list should be assessed for completeness on a project-specific basis

If there is limited or no design data available, further investigations may be necessary to enable reuse.

It is crucial to link the obtained information to the respective individual elements through proper labelling. This ensures traceability, as elements are likely to be separated from the donor project and, in some cases, form each other. To avoid data loss, data can be linked to elements in various ways. Although there is currently no standardised approach, It is desirable that data stored is handled digitally in a material passport. This digital record can be linked to a material bank, ensuring that all relevant information is easily accessible and preserved, as proposed in the CROW-CUR guideline for reused structural concrete prefab elements. By meticulously comping and maintaining a detailed dossier, stakeholders can make well-informed decisions regarding the reuse of masonry elements, thereby optimising their potential and ensuring a more sustainable approach to construction.

1.2 Compiling quality dossier for masonry elements

In section 1.1. the primary focus is on gathering available data, which can often be accomplished through a desk study. This involves collecting information from existing documents, archives, and records related to the masonry elements. However, it is possible that not all the desired data will be available due to incomplete or missing documentation. In such cases, it may be necessary to conduct additional research, including both non-destructive and destructive testing, to retrieve the missing information. The masonry elements for which this guideline is prepared are often not used in structural roles, but it is still crucial to assess their load-bearing capacity and residual life. This is important to ensure that the elements are safe, reliable, and suitable for their intended reuse applications. Understanding the structural integrity and condition of the elements helps in making informed decisions about their reuse and guarantees that they meet the required standards for their new applications. To supplement missing data and assess the quality of the masonry elements, the following investigations may be relevant.

1. **Visual inspection:** Assessing the general condition and identifying any visible damages or defects
2. **Determining the location and condition of wall ties:** Checking the presence and state of wall ties to understand their role in the structural stability
3. **Determining the hardness of the Joint:** Measuring the hardness of the mortar joint to assess the durability of the masonry

4. **Measuring the bond strength:** Evaluating the bonding strength/adhesion between the masonry units and the mortar
5. **Determining the mortar composition:** analysing the composition of the mortar to understand its properties and suitability for new applications.

These investigations do not need to be carried out if the necessary data can be determined or excluded based on the dossier form section 1.1. Though even if the data is found during the desk study, it is always advisable to verify this information through further testing. It is also a fact that some tests, such as the hardness of joint and bond strength, still need to be tested to guarantee durability. The sample size for these investigations should be adjusted based on the surface area of the masonry. It is important to determine the appropriate sample size in consultation with a structural engineer to ensure that the testing is representative and provides accurate insights into the condition of the masonry elements. In this document, some examples of methods that can be applied are given.

1.2.1 Visual Inspection

The purpose of visual inspection is to gain insight into the current condition of the masonry. Various defects can be observed during visual inspection, such as

- Cracking in the masonry
- Presence of filling voids indicating post-insulation
- Visibility of corrosive material
- Presence of loose masonry
- Visibly repaired masonry
- Damage due to frost

It is essential to determine and record the extent, severity, and (possible) cause of these potential defects in the dossier. If some detects cannot be repaired, they can result in a negative reuse recommendation.

1.2.2 Determining the location and condition of wall ties

Understanding the configuration of wall ties is crucial before the element can be reused. Mapping of the wall ties configuration can be done using non-destructive methods, such as a metal detector (e.g., a wall tie locator from Fisher). Destructive testing is necessary to assess the condition of the wall ties. During this test, an intuitive indication of the bond strength can also be obtained.

1.2.3 Determining the hardness of the joint

The joint hardness value indicates whether the masonry joint meets the specified application class, as assessed based on recommendation CUR61:2013. Measuring the joint hardness is done using a rebound hammer. Masonry with relatively low quality and/or superficial joints will be susceptible to erosion and weathering, increasing the risk of moisture ingress and potential corrosion of the wall ties.

1.2.4 Measuring the flexural bond strength

The bond strength is crucial for maintaining the integrity of the masonry element during all reuse activities. Most importantly, it is sufficiently strong to comply with the regulation of new construction. Testing the flexural bond strength can be done by means of a lever test or laboratory test. The lever test is most often applied in practice. The lever test determines the flexural bond strength of the masonry. This procedure for the lever test is described in NEN-EN 1052-5

1.2.5 Determining the mortar composition

Determining the mortar composition is critical when reinstalling masonry elements to ensure compatibility and durability. The composition of the mortar affects the physical and chemical properties of the masonry, including strength, permeability, and weather resistance. Analysing the mortar composition involves chemical analysis and physical testing. A chemical analysis is needed to identify the components and properties of materials in the mortar, such as lime, cement, sand and any additives. This helps replicate the original mix for new mortar applications. The physical testing is done to determine properties like compressive strength, tensile strength and flexibility. These properties are crucial for ensuring the mortar applied during the implementation behaves similarly to the original mortar. By ensuring the new mortar has a composition comparable to the original, the risk of incompatibility issues is minimised. This is particularly important for maintaining the façade's physical behaviour, such as thermal expansion, moisture movement and overall durability. When this is not applied in the correct way, there is the possibility of cracking in the masonry.

2. PREPARATION OF DISMANTLING ACTIVITIES

The preparation for dismantling masonry elements builds directly upon the foundational work established in Chapter 1, where the current situation and initial quality assessment are conducted. This preparatory phase ensures that the condition, functionality, and history of the masonry elements are well-documented, forming a solid basis for remaining informed decisions about dismantling for reuse. This includes assessing the reusability of the element and its applications. This is determined, among other factors, by the environmental class and application of the element. Ultimately the decision to reuse the masonry is made in this chapter.

2.1 Functioning of Masonry

Understanding the current application of masonry is vital before considering its reuse. The functionality of masonry in its existing context must be assessed. Knowing how the masonry performs in its current setting helps in determining its suitability for reuse in new applications, ensuring that the elements meet the necessary performance criteria in their new roles. Therefore, prior to dismantling, the following questions are relevant:

- **In what type of construction and or situation is the masonry applied?** Determining the type of construction (e.g. residential, commercial, industrial) and the specific situation (e.g., load-bearing wall, façade) helps in understanding the performance requirements of the masonry in its current application.
- **What (durability) loading is currently applied on the masonry:** Assessing the loads (e.g., structural, thermal, weather resistance) that the masonry is currently subjected to is essential for determining its durability and suitability for reuse in similar or different conditions
- **What environmental classes are applicable to the element in its current application?** Identifying the environmental exposure (e.g., interior, exterior, marine, industrial) helps in understanding the wear and degradation the masonry has undergone, which impacts its potential for reuse.
- **What methods of removal are best suitable for the current situation, outside in or inside out:** Planning the dismantling method is crucial. Whether to remove the masonry with the method inside out or outside in can depend on the accessibility, the construction type, and the preservation of the element's integrity.
- **Determining how much masonry can be reused:** Evaluating the extent of reusable masonry involves assessing the condition and quality of the elements that can be salvaged without compromising their structural and aesthetic qualities.

By thoroughly answering these questions, a comprehensive understanding of the masonry's current function is achieved, aiding in the decision-making process for its potential reuse.

2.2 Intended Take-off

The process of reuse can vary significantly depending on whether the project where the masonry will be implemented is known or not.

When the Project is Known

When the project is known, specific requirements and constraints of the new project can be taken into account. This allows the masonry elements to be tailored to fit the new design, ensuring compatibility and performance.

When the Project is Unknown:

When the project is unknown, a more generic approach to dismantling must be adopted to maintain the broadest possible usability of the masonry. Flexibility in the handling and storage of masonry elements has become critical, allowing them to be adaptable for various future applications. Extra attention is needed to preserve the masonry's versatility, considering different potential uses and specifications. Without a specific project, the properties of the donor element cannot be tested against the new application, making it essential to decide which investigations to carry out. Conducting more investigations can provide more information about the element, facilitating future matchmaking. However, this requires more upfront investment. Knowledge of the new application may limit the types and number of tests that need to be performed, influencing the cost-effectiveness of the process. In all cases, it is important to document the reports of the test and result and link them to the respective masonry. This documentation aids in future assessment and enhances the commercial value of the reusable elements. It is recommended that an indicative estimate or assessment of the environmental class, dimensions, type of stone, mortar composition, bond strength, and other relevant factors be made during the matchmaking process to determine the potential applications of the masonry.

2.3 Dismantlability of Masonry

The ease and feasibility of dismantling masonry elements are crucial factors in the reuse process. Before the decision to dismantle is made, the dismantlability needs to be examined. For recommendations on dismantling elements, refer to Chapter 3. The dismantlability of masonry depends on the following:

- **Type of Mortar:** The strength and type of mortar used can significantly impact the dismantling process. Masonry with a strong (cement) mortar has a higher chance of success due to a strong coherence between brick and mortar
- **Type of Brick:** In case of glazed bricks or hollow bricks, some damages can occur during the cutting process.
- **Accessibility:** How easy it is to manoeuvre at the location. Accessibility can greatly affect the efficiency and safety of the dismantling process.

2.4 Value for Reuse

Evaluating the value of masonry for reuse involves several dimensions, such as Technical value, environmental value, material use and energy use. Each of these values contributes to the overall decision-making process, balancing the benefits and costs associated with the reuse of masonry elements.

Technical value
The technical or structural properties of the donor element largely determine its technical value. This includes load-bearing capacity, detachability, and overall condition. The availability and reliability of data on these aspects are crucial indicators. The technical value represents the relative worth of the masonry compared to other applications, influenced by how well it meets the necessary performance criteria for new projects.

Environmental Value
Reusing masonry contributes to environmental sustainability by reducing the need for new materials. This results in a lower environmental impact, as it decreases the consumption of raw materials and the associated environmental degradation. By conserving existing resources, the reuse of masonry supports broader ecological goals.

Material Use
When masonry is reused, there is no need to produce new elements, meaning that no new materials are added to the cycle. Reuse of elements, therefore, resulting in a reduction in material use, which,

for a similar application, is usually equivalent to the amount of reuse material. It should be noted that bricks or mortar produced with recycled materials can also result in a reduction in material use.

Energy use
Energy is used in the production process of new masonry. This process is not necessary when masonry is reused. Therefor, reuse of masonry can result in a decrease in energy use. However, the various actions required in the reuse process can also result in energy use. It is possible to make a comparison between energy use in reuse and that in the production process.

By assessing these values, stakeholders can make informed decisions about the feasibility and benefits of reusing masonry elements in new construction projects.

2.5 Decision to dismantle

Once all aspects have been considered, a decision is made on whether the masonry will be dismantled for reuse. The preceding paragraphs address various aspects that are important in the choice between dismantling for reuse or demolition for recycling. Based on the above-mentioned aspects, the responsible party must decide whether dismantling for reuse is desirable. The criteria for making this decision may vary depending on the party and the assignment. If it is decided that (part of) the masonry will be dismantled for reuse, it is important that the original location of the element in the doner object is known. This information is valuable in the reuse process, as discussed in Chapter 1. Additionally, it must be clear to the demolition contractor which elements need to be dismantled and which parts need to be recycled. A preliminary design calculation can contribute to the assessment of the reuse of donor elements. This can vary in assessment levels and methods of application. By carefully weighing these factors, stakeholders can make well-informed choices that promote sustainability and efficiency in the construction industry.

3. EXECUTION OF DISMANTLING

The dismantling of masonry structures requires careful planning and execution to ensure safety, quality, and minimal environmental impact. This chapter outlines the necessary steps and considerations for a successful dismantling process.

3.1 Demontage plan

Prior to dismantling, a plan must be developed detailing the matters explained in the following paragraphs. Such as structural safety, removal options, environmental nuisance, and quality assurance.

3.1.1 Structural Safety During Dismantling

Ensuring the structural safety of masonry elements during dismantling involves planning, understanding the inherent properties of the masonry and implementing appropriate safety protocols. It is important to demonstrate structural safety during the dismantling process. In most cases, the dismantling is done when the project is demolished completely. This means that the roof can be first removed, and the method will be to start above and work downwards. This way, there is less of a danger of structural failure due to unstable walls. In the case that part of the masonry is removed, without removing the masonry above, there is a change of instability and, therefore, unsafe practices. Though not recommended, if this is the case, discuss with the structural engineer how much masonry can be removed without consequence and otherwise which temporary supports need to be placed to protect the stability of the walls.

3.1.2 Drilling, Sawing, and Chiselling

Different methods, such as sawing with water or using a vacuum saw, should be considered based on the specific needs of the project.

- **Sawing with water:** Water is used for cooling during sawing and drilling operations to prevent overheating of equipment and reduce dust. If there is no water supply at the location, water containers can be used to provide the necessary cooling
- **Vacuum Sawing:** This method is often sufficient for sawing masonry and has the added benefit of reducing the spread of dust, which is important for maintaining a clean and safe work environment. Though this is often not a good method for sawing large areas, since the blades can get to hot. With no water colling the blade down as with the sawing with water option.

Sawing or drilling at temperatures around or below freezing point (0 degrees Celsius) is practically infeasible due to the risk of slipping and safety concerns. Another consideration during these operations is the potential release of harmful substances. An assessment should be conducted to identify any hazardous materials present, and appropriate measures should be taken to mitigate these risks.

3.1.3 Nuisance to the Environment

Dismantling activities may cause nuisance to the surrounding environment, including noise, dust and vibrations. These potential nuisances should be identified in advance, and appropriate measures should be taken to minimize their impact. This may include scheduling work during less disruptive times, using noise reducing equipment, and implementing dus control strategies.

3.1.4 Quality Assurance

During the reuse process, it is important to conduct an inspection to ensure the quality of the masonry. Various actions during the dismantling process may result in damage to the masonry. To maintain high standards of quality, the following steps should be taken.

- **Inspection Schedule:** Figure A 2 Provides an overview of different inspection moments and considerations. Regular inspection should be carried out at key stages of the dismantling process.
- **Documentation:** Any deviations or defects observed during inspection should be documented in the element dossier. This documentation will help in tracking the quality and condition of the materials being reused.
- **Guideline Compliance:** The guideline 'quality assessment and assurance in the reuse of existing construction' by CB23 can provide additional guidance for quality assurance. This guideline should be referred to ensure that all quality assurance measures are up-to-date and in line with industry standards.

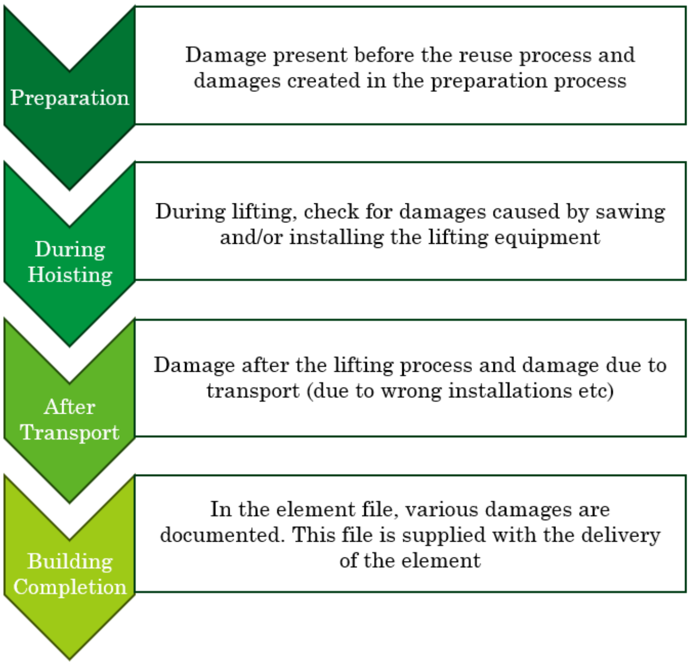


Figure A 2: Roadmap quality assurance

3.2 Disassembly of masonry

In the donor project, the masonry to be reused is still integrated into the structure. This masonry must be detached form the structure before it can be dismantled and transported. There are limited methods available for dismantling masonry, The most common and most practiced methods is sawing. Such as described in chapter 3.1.3.

3.3 Hoisting

Hoisting of masonry elements is a critical phase in the dismantling process, requiring planning and execution to ensure the integrity of the elements and the safety of the operation. This section will delve into the various methods of hoisting masonry, the equipment used, and the specific considerations that must be taken into account.

3.3.1 Hoisting methods

Hosting methods can vary significantly based on the size, weight, and location of the masonry element. The primary methods include hoisting by forklift, glass lifter, lifting straps and custom lifting frames. Each method has its advantages and limitations, which will be discussed in detail.

Hoisting by Forklift

Forklifts are commonly used in construction and demolition sites for their versatility and ease of operation. When hoisting masonry elements with a forklift, first cut the lower cut of the masonry element. Remove four stones under the cut; this way, space is created for the extended forks to lift the masonry at a later stage. Then, make the upper horizontal and vertical cuts. When there is still masonry located above the uppercut, remove one row of masonry. The extended forks move in the made space underneath the element and lift it out of the façade. It is important to give guidance by hand to the elements so they don't fall down.

Hoisting by Glass Lifter
Glass lifters, typically used for handling large glass panels, can also be adapted for masonry element with the use of additional attachments. First attach wooden plates to masonry elements to create a surface suitable for the suction pads of the glass lifter. Make sure the two wood plates are connected with each other. Ensure that the wooden plates are securely fastened, and the glass lifters suction pads are properly attached to the plates. Ensure that the load is evenly distributed to prevent tilting or slippage.

Hoisting by Lifting Straps
Lifting straps offer a flexible and robust method for hoisting masonry elements, especially useful for irregularly shaped or larger elements. The work setup is the same as hoisting by forklift, but instead of the extended forks moving into place, the lifting straps will be placed around the masonry element. The straps are attached to a crone or other lifting machinery. Lift the element slowly and steadily, keeping an eye on the straps for any signs of slippage or imbalance. In this case, some guidance by hand is recommended.

Hoisting by Custom Lifting Frame
Custom lifting frames provide additional support and stability during the hoisting process, making them ideal for large masonry elements. First the lifting frame needs to be designed and constructed, tailored to the dimensions and weight of the masonry element. The lifting frame is placed around the masonry element and is held in place with bolts, clamps and other securing mechanisms. The frame can be lifted by a crane, same as with the lifting straps, some caution is needed to ensure balance within the frame.


Figure A 3: Hoisting by glass lifter @VINK bouw


Figure A 4: Hoisting by lifting straps @VINK bouw


Figure A 5: Hoisting by forklift

3.3.2 Considerations for Hoisting

When hoisting masonry elements, several critical factors must be considered to ensure the safety and integrity of the operation.

1. **Weight Distribution:** Properly assess the weight of the masonry element and ensure the hoisting method can handle the load. Incorrect weight distribution can lead to tipping or dropping of the element
2. **Structural Integrity:** Evaluate the structural integrity of the masonry before hoisting. Elements with significant cracks or weaknesses may require additional support or alternative methods
3. **Weather conditions:** Avoid hoisting during adverse weather conditions such as high winds or heavy rain, which can increase the risk of accidents
4. **Safety protocols:** Adhere to all safety protocols, including wearing personal protective equipment (PPE) and ensuring the hoisting area is clear of unnecessary personnel.

3.4 Transportation

Transportation involves transporting the masonry elements to the recipient project or temporary storage location. This guideline assumes that elements will be transported over public roads. Of course, other transportation methods are also possible. For transport, the mass and geometry (length, width and height) are relevant. If the combination of mass and geometry allows it, multiple elements can be transported in one shipment. Safety and preventing damage and breakage (part of the dismantling plan) should always be a priority. It is important to properly support the elements during transport. Incorrect support (in numbers or position) of the elements can result in damage, such as cracking or even breakage. Two forms of road transport are described in this guideline.

3.4.1 Indoor loader

An indoor loader is a viable option for transporting numerous large elements quickly and safely. This method involves using a specialised vehicle designed to handle prefabricated elements.

Advantages: Quick loading and unloading, safe handling, minimal need for additional equipment

Limitations: best suited for elements with a height up to 3.7m, may not be ideal for unreinforced masonry without any additional supports

First the masonry elements need to be secured with wood pallets and tie-down straps to protect hem during transit. The indoor loader uses the hydraulic lifting mechanism to load the elements on the vehicle.

Figure A 6: Indoor loader

Figure A 7: Element ready for transport on a trailer

Figure A 8: Element on transport

3.4.2 Trailer

For smaller projects, short distances, or fewer elements, using a trailer is a practical and low-cost option. This method involves towing a trailer behind a vehicle.

Advantages: Cost-effective, simple setup, suitable for small quantities and short distances.

Limitations: It is not suitable for large or heavy elements; careful securing is required to avoid damage.

The masonry element is placed on a frame, supported by wood pallets to prevent movement. This frame is placed on the trailer. Tie-down straps are used to minimise vibrations and secure the element during transport.

4. ACTIVITIES BETWEEN DISMANTLING AND IMPLEMENTATION

After dismantling, when the masonry elements are not directly going to the new construction project, storage will allow the elements to maintain their integrity and quality and be ready for reimplementation when the time comes. This chapter explores the steps taken to ensure that each masonry element is traceable, stored correctly, processed properly, and handed over seamlessly. These activities bridge the gap between dismantling and reimplementation, maintaining the continuity and quality necessary for successful reuse.

4.1 Traceability

Traceability is the process of maintaining records of dismantled masonry elements from the point of removal through storage and eventual reimplementation. This ensures that each element can be identified, its origin verified, and its history tracked, which is crucial for quality control, accountability, and the integrity of historical or structural data. The first step in traceability is documentation. Each document should have its original location and position within the structure. Images of the original location of the masonry elements should also be provided. Other records such as dimensions, conditions, unique features or markings, date of dismantling, and observations made during the process also need to be recorded.

Any adjustments, processing, and repair works on the elements must be recorded and documented in the handover dossier. Implementing a digital tracking system enhances accuracy and efficiency. A robust database management system should be employed to store and manage all records, making them accessible to all relevant personnel and regularly updated. Advanced tracking technologies such as QR codes or RFID tags can further improve traceability, ensuring that each element is easily identifiable throughout its lifecycle.

4.2 Intake

The intake process involves receiving and initially assessing the dismantled masonry elements before they are moved to storage. Each element is check for any immediate damages or deterioration that may have occurred during dismantling or transport. The documentation and records for each element are updated based on the initial assessment findings. Sorting and categorization follows, with elements being stored based on their appearance and condition. The elements are then categorized into groups for storage, processing, repair or direct reimplementation.

4.3 Storage

Storage is mainly needed when the elements can not be transported directly to the new construction site after dismantling. Thus, the element will need to be temporarily stored first. The primary reason for this is the scheduling in the matchmaking. The timing of dismantling and the realisation of the new construction do not necessarily align. Various aspects need to be considered for the temporary storage of elements:

- Required space (m^2)
- Accessibility of the location
- Indoor/outdoor environment
- Bearing capacity of the ground
- Surrounding

Proper storage of dismantled masonry elements is done to prevent damage and deterioration, ensuring they are preserved in the right conditions until they are needed for reimplementation. A difference can be made in storage options for the inner walls and the façade wall. The inner wall in the original situation is in dry and inside temperature conditions. Therefore, the storage location needs to be in similar conditions. For the outer wall or façade, the original location is in weather conditions on one side and dry conditions on the other. Therefore, if the outer façade is stored in a sheltered location, this should be enough. However, when it is stored in a dry environment, less degradation will take place over a longer period of time. For both types of walls, it is important to secure the position of the element to prevent movement or shifting that could cause damage.

4.4 Processing of the element

Processing involves preparing the dismantled masonry elements for reimplementation, which may include cleaning, recutting, reshaping or other modifications. For example, reshaping to fit their new placement. Any required drilling or carving should be performed with precision to avoid weakening the element. Surface cleaning is necessary to remove dirt, grime, and other contaminants, using appropriate methods that do not damage the material.

4.5 Finishing and repair of damages

After processing, elements may require finishing touches and repairs to address any damage sustained during dismantling or storage. Surface finishing, such as refilling mortar or sealing. Repair techniques include addressing cracks or minor damages using appropriate methods, such as epoxy injections or mortar fills. For elements with significant structural damage, reinforcement methods like using steel reinforcement can be considered as a supportive measure.

4.6 Handover

For the handover, the documentation and records of everything that has been performed on the element should be complete. A final inspection is conducted to ensure all elements meet the required quality and safety standards and verification that all records and documentation accurately reflect the current condition and history of each element. The handover process is done to ensure a smooth transition from storage to implementation. It involves coordinating between teams and ensuring all parties are informed and prepared for the next steps.

5. PREPARATION PHASE (NEW) CONSTRUCTION POJECT – APPLICAION OF REUSED ELEMENTS

The preparation phase of a new construction project involving reused masonry elements is critical for ensuring the seamless integration of these elements into the new design. This phase involves detailed planning, coordination and adherence to building regulations to achieve a sustainable and functional outcome. This chapter outlines the processes and considerations necessary for effectively incorporating reused masonry elements into new construction projects.

5.1 Integration of Masonry Elements into New Design

Integrating reused masonry elements into a new design requires a comprehensive understanding of both the structural properties of the reused materials and the aesthetic goals of the new construction. Architects and engineers must work collaboratively to ensure that the reused elements not only fit within the new design but also meet the structural requirements.

- **Desing compatibility:** The first steps involve assessing the compatibility of the reused masonry element with the new design. This includes matching the dimensions, texture, and colour of the reused elements with the design specifications of the new project.
- **Structural Analysis:** Engineers must conduct a structural analysis to determine the load-bearing capacity and determine the needed wall ties, and what type of wall tie need to be used.
- **Customization and modifications:** In some cases, the reused masonry elements may need to be modified to fit the new design. This can include cutting, resizing, or treating the materials to ensure they meet the required specifications.

5.2 Logistics and Coordination

Efficient logistics and coordination are essential to ensure that the reused masonry elements are delivered, handled and installed correctly.

- **Scheduling and Timing:** Proper scheduling is crucial to align the delivery of reused elements with the construction timeline. This helps avoid delays and ensures that materials are available when needed
- **Transportation plan:** Reused masonry elements must be transported carefully to prevent damage. When making a transportation plan, make sure enough space is available to manoeuvre and temporarily store the masonry elements. The transportation plan also describes what kind of transportation is used and in what state the masonry elements will arrive (how it is packaged or how they are placed on transport)
- **On-side handling plan:** In addition to the transport plan, a construction plan must be made. This includes a plan for where each masonry element will be applied as well as continuities plans in case some masonry element do not make it or are not repairable. Also, a description of how and in which steps the masonry elements will be placed is required.

6. REALIZATION AND HANDOVER – APPLICATION OF REUSED ELEMENTS

6.1 Realisation

The implementation of reused masonry elements can be approached in two primary ways. Each method has its specific considerations and requirements to ensure structural integrity and proper integration into new construction.

6.1.1 Method 1: Large 'Brick' Installation

In this method, the reused masonry elements are treated as large bricks, suitable for low-rise buildings such as terraced houses. Key factors for this approach include:

- **Mortar-Free sides:** The sides of the masonry elements must be free of old mortar, as well as the pores of the bricks. This is crucial for achieving a strong bond with the new mortar. If the pores are filled with old mortar, there will be no space for the new mortar to settle, resulting in a weak bond.
- **Matching Mortar Types:** The new mortar applied must be similar to the original mortar used in the masonry elements. This ensures compatibility and prevents cracks due to differential movements. It also ensured that the appropriate type of mortar was matched with the brick.
- **Horizontal and vertical Dilatation:** Proper placement of horizontal (for high-rise buildings) and vertical dilatation joints is essential. These should be planned during the design phase to accommodate movement and prevent cracking.
- **Wall ties:** Traditional masonry ties are placed between bricks during construction. However, with reused masonry elements, alternative methods are necessary:
  - **Inside-Out Method:** This involves constructing the load-bearing wall first, followed by the placement of masonry elements. Wall ties are placed at the edges of the masonry panels. Even with 1m² panels, additional ties are required within the panel field, necessitating renovation of wall ties.
  - **Outside in Method:** Here, the masonry panel wall is constructed first. Wall ties are applied at the panel edges, and standard wall ties are used with plugs. The load-bearing wall is then constructed, embedding the wall ties to form a functional cavity wall.

6.1.2 Method 2: Façade Supports

Alternatively, reused masonry elements can be integrated using façade supports, either exclusively or in combination with the large brick method, for optimal results. This method provides flexibility in design and can be tailored to specific project requirements.

Figure A 9: Masonry elements in wall @VINK Bouw

Figure A 10: Masonry element in wall @VINK bouw

6.2 Handover Dossier

The handover dossier is, after the whole process, a comprehensive document that provides all necessary information about the reused elements. It ensures transparency and traceability for future references. The following information should be presented in the handover dossier:

- **Documentation of Reused Elements:** It includes detailed records of all reused elements, including their origin, previous usage, and any modifications or repairs carried out during the project. This documentation ensures traceability and can be used for future maintenance or renovations
- **Quality Assurance Reports:** All quality assurance checks and inspections conducted on the reuse element should be documented. This includes structural integrity tests, compliance with building codes, and any certification obtained.
- **Installation Records:** records of the installation process, highlighting any challenges encountered and how they were addressed. This information is crucial for understanding the integration process and ensuring that the installation meets the required standards
- **Final Inspection and Approval:** The final inspection is carried out to ensure that all reused elements are properly installed and that the construction meets all design specifications. Any deficiencies identified during the inspection should be promptly addressed. This may involve repairs, replacements or additional testing to ensure compliance with quality standards. Once all inspections and necessary corrections are completed, a quality control sign-off is required. This indicates that the project meets all specified requirements and is ready for handover.

Appendix B
MASONRY DEVELOPMED

Non-residential application in the Netherlands

Masonry can be found in residential and non-residential buildings. The main rapport discusses residential housing; this appendix discusses non-residential buildings.

Table B 1: Type and functions of non-residential buildings

Non-residential
Commercial buildings
Offices
Educational building
Care facilities
Shops
other

Non-residential buildings consist of commercial buildings, offices, educational buildings, care facilities, shops, and other miscellaneous structures that collectively contribute to the diverse built environment. In **Error! Reference source not found.**, the current stock numbers can be s een.

Table B 2: Current stock of non-residential buildings **(CBS, 2023)**

	2023
Commercial buildings	62884
Offices	94802
Educational building	13474
Care facilities	22868
Shops	127613
others	441955

Non-residential demolition

Moving beyond residential structures, non-residential buildings also undergo a dynamic demolition process. The numbers, meticulously categorised by construction year class, reveal patterns within various sectors.

Table B 3: Demolition number of non-residential buildings **(EIB, Metabolic and SGS Search, 2022)**

	<1945	<1945-1970	1971-2000	>2000	Total
Commercial buildings	140	420	570	140	1270
Offices	30	140	260	60	490
Educational building	10	80	80	20	190
Care facilities	0	20	140	80	240
Shops	50	150	110	20	330
Other	260	1190	1120	340	2910
Total	**490**	**2000**	**2280**	**660**	**5430**

Future perspective: non-residential buildings

Non-residential construction is expected to reach a higher level in 2030 than 2019. Until 2024, new construction in this sector is anticipated to increase with economic developments. However, after 2024, the new construction production is expected to decline. Not all functions within non-residential construction will evolve similarly, as various economic and demographic determinants influence different subsectors. For instance, commercial buildings are expected to decrease in 2030 and 2050, while new construction of educational and healthcare buildings will increase. The growth in the education sector is attributed to the need to replace the qualitatively inferior current building stock in the coming years. Healthcare real estate development is related to the increasing demand for quality healthcare and the ageing population. While new construction of non-residential buildings is decreasing, the demolition of non-residential buildings across all sectors is increasing

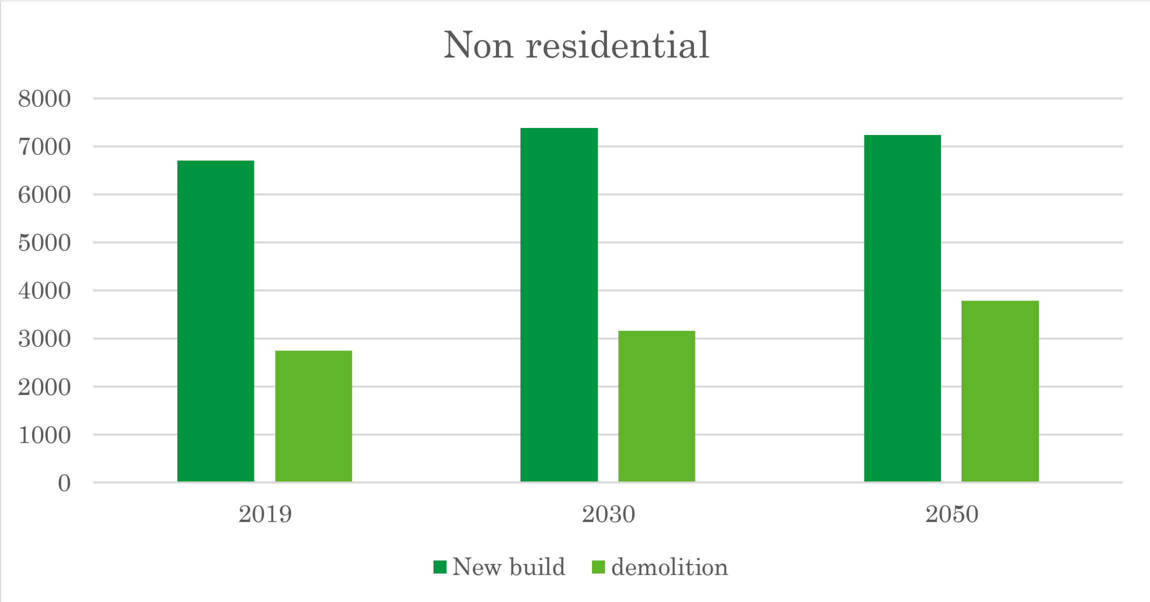


Figure B 1: Non-residential comparison of new construction vs demolition **(EIB, Metabolic and SGS Search, 2022)**

The situation is slightly different for non-residential construction. Here, demolitions increase somewhat, but the overall pattern remains the same: new constructions will be approximately twice as many as demolitions.

Table B 4: New construction and demolition non-residential **(EIB, Metabolic and SGS Search, 2022)**

	New Construction			demolition		
Non residential	**6710**	**7380**	**7240**	**2740**	**3160**	**3780**
Commercial buildings	4730	4220	4470	1250	1400	1700
Offices	200	430	460	300	310	330
Care facilities	230	460	530	180	200	310
Educational building	240	580	440	190	400	470
Shops	200	210	210	260	180	200
Other	1110	1480	1130	560	670	770

Appendix C
DIANA CALCULATION

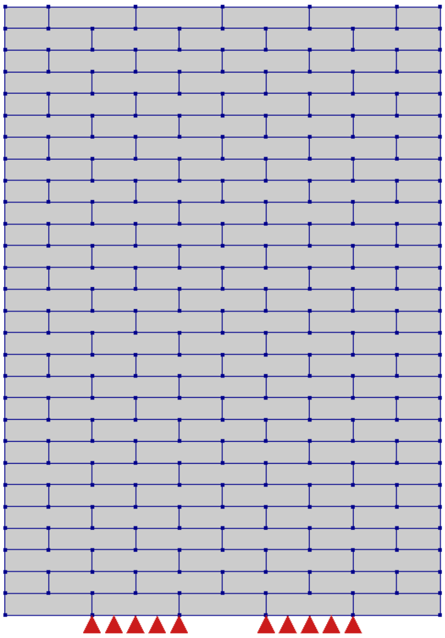
Table C 1: Size options elements

Option	Width [m]	Height [m]	Total area [m^2]
1	1.0	1.40	1.40
2	1.2	1.30	1.56
3	1.4	1.05	1.47
4	1.6	0.85	1.36
5	1.8	0.80	1.44
6	2.0	0.75	1.50

Table C 2: Overview calculation values

Option		Value	Unit
1	DUNy	0.02	mm
	DUSx	0.017	mm
	Sxx	0.10	N/mm^2
	Syy	0.14	N/mm^2
	STNy	0.75	N/mm^2
	STSx	0.27	N/mm^2
2	DUNy	0.02	mm
	DUSx	0.018	mm
	Sxx	0.10	N/mm^2
	Syy	0.14	N/mm^2
	STNy	0.74	N/mm^2
	STSx	0.25	N/mm^2
3	DUNy	0.02	mm
	DUSx	0.018	mm
	Sxx	0.10	N/mm^2
	Syy	0.14	N/mm^2
	STNy	0.74	N/mm^2
	STSx	0.25	N/mm^2
4	DUNy	0.02	mm
	DUSx	0.018	mm
	Sxx	0.11	N/mm^2
	Syy	0.15	N/mm^2
	STNy	0.74	N/mm^2
	STSx	0.28	N/mm^2
5	DUNy	0.02	mm
	DUSx	0.18	mm
	Sxx	0.11	N/mm^2
	Syy	0.15	N/mm^2
	STNy	0.75	N/mm^2
	STSx	0.28	N/mm^2
6	DUNy	0.02	mm
	DUSx	0.018	mm
	Sxx	0.11	N/mm^2
	Syy	0.15	N/mm^2
	STNy	0.75	N/mm^2
	STSx	0.28	N/mm^2

Option 1



c

Figure C 1: Option 1 - Masonry element

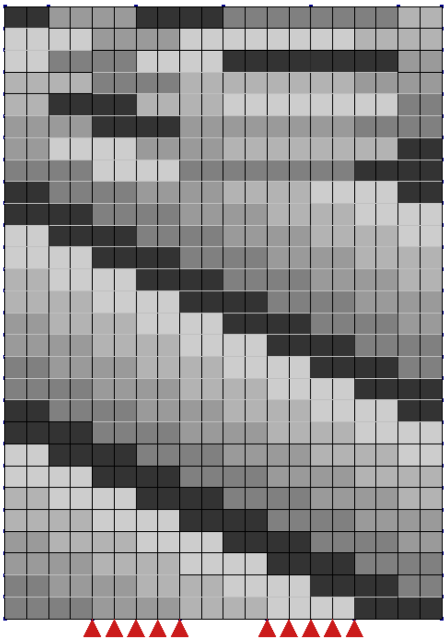


Figure C 2: Option 1 - Finite element mesh with supports

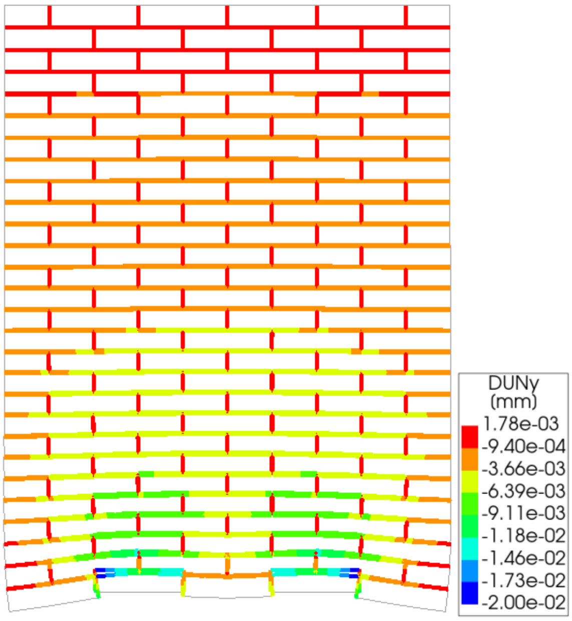


Figure C 3: Option 1 – Normal relative displacement of the interface

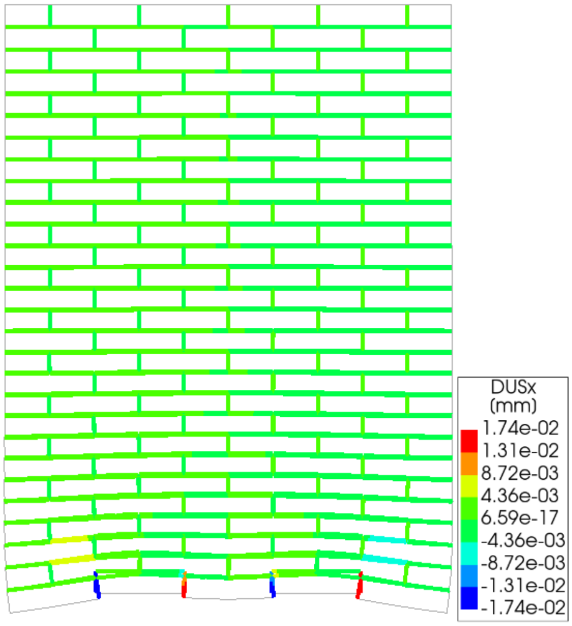


Figure C 4: Option 1 – Shear relative displacement of the interface

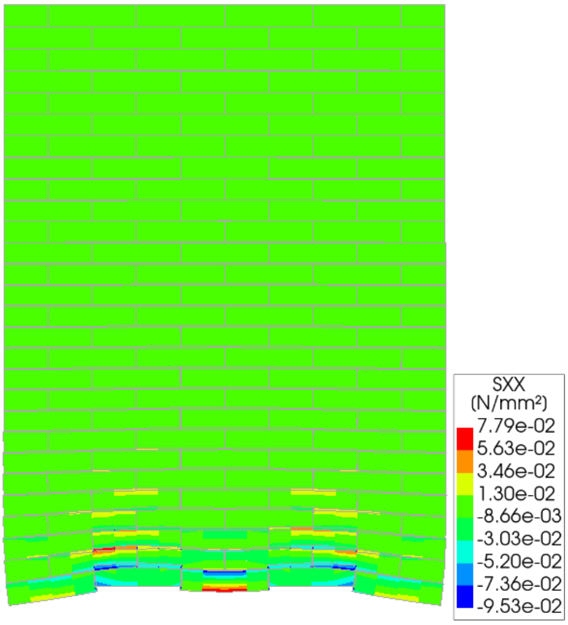


Figure C 5 Option 1 – Cauchy total stress of bed joint

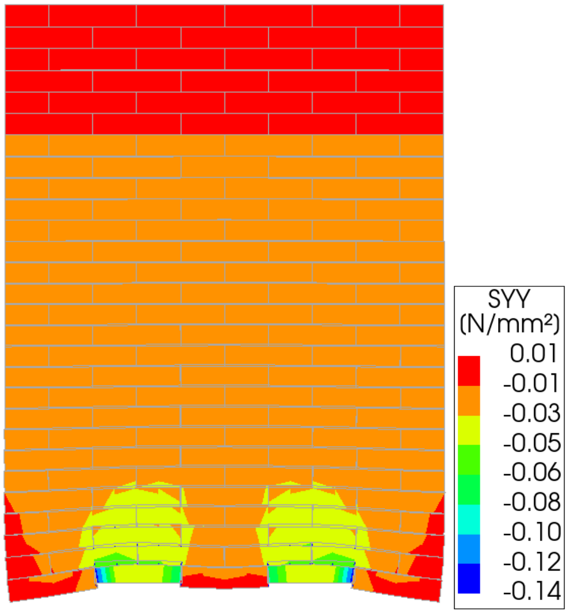


Figure C 6: Option 1 – Cauchy total stress of head joints

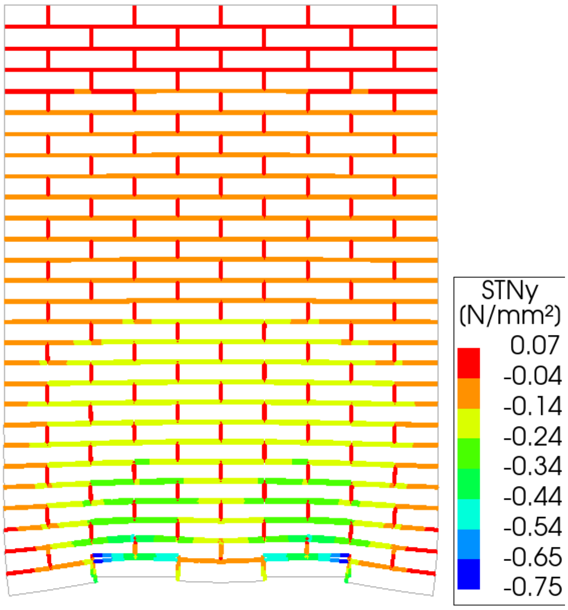


Figure C 7: Option 1 - Interface total traction bed joints

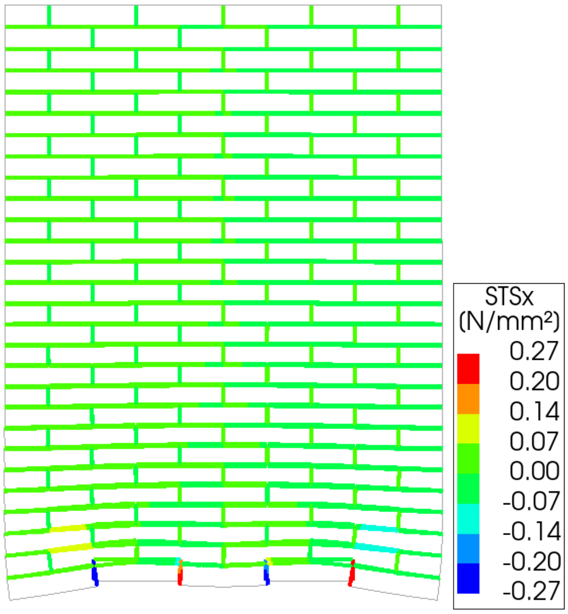


Figure C 8: Option 1 -Interface total traction head joints

Option 2

See 5.1.4.3

Option 3

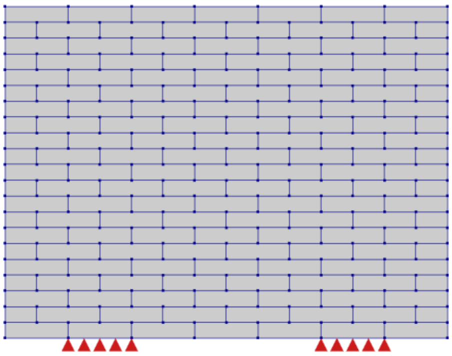


Figure C 9: Option 3 - Masonry element

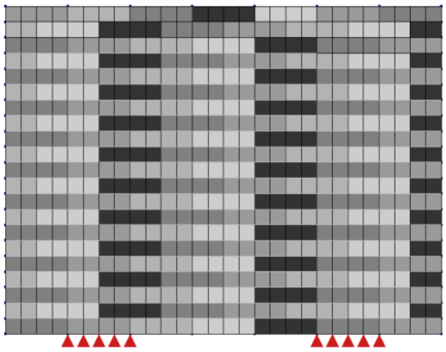


Figure C 10: Option 3 - Finite element mesh with supports

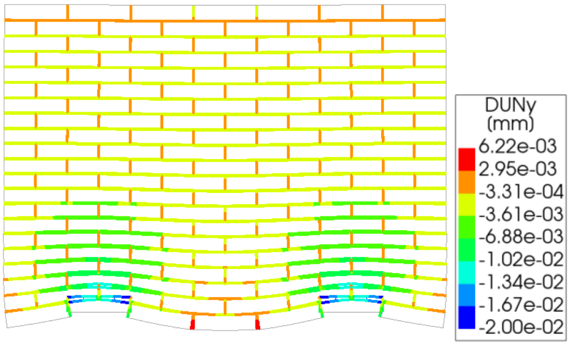


Figure C 11: Option 3 – Normal relative displacement of the interface

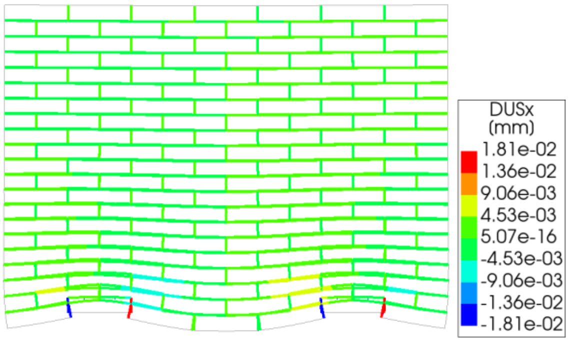


Figure C 12: Option 3 – Shear relative displacement of the interface

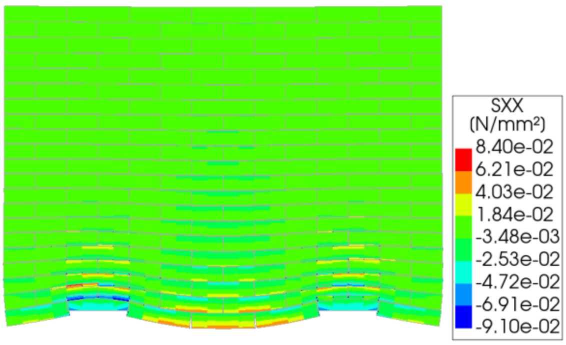


Figure C 13: Option 3 – Cauchy total stress of bed joint

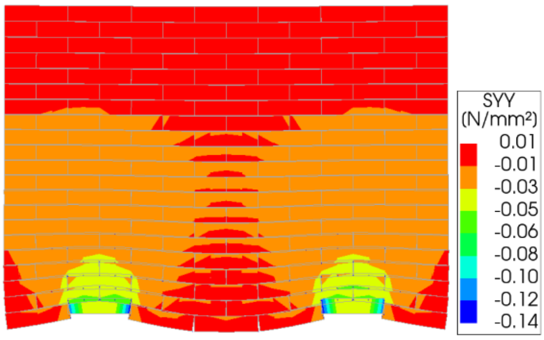


Figure C 14: Option 3 – Cauchy total stress of head joints

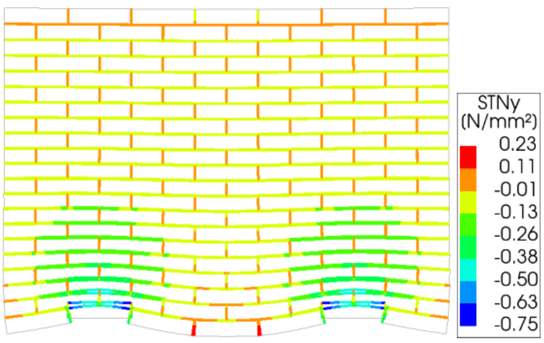


Figure C 15: Option 3 - Interface total traction bed joints

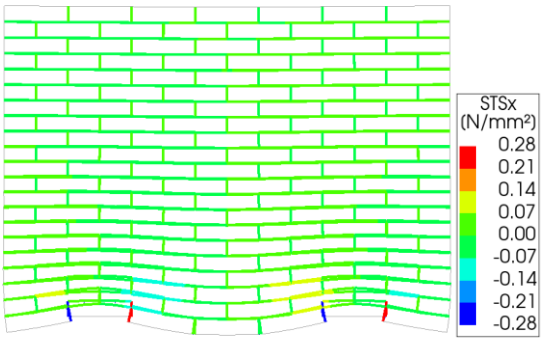


Figure C 16: Option 3 - Interface total traction head joints

Option 4

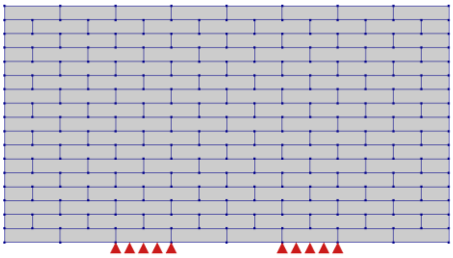


Figure C 17: Option 4 - Masonry element

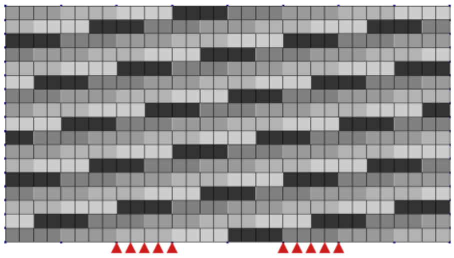


Figure C 18: Option 4 - Finite element mesh with supports

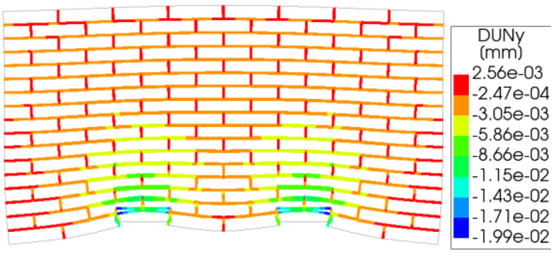


Figure C 19: Option 4 – Normal relative displacement of the interface

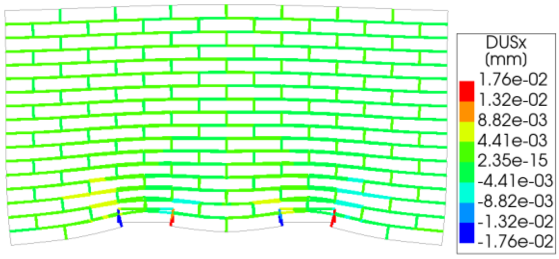


Figure C 20: Option 4 – Shear relative displacement of the interface

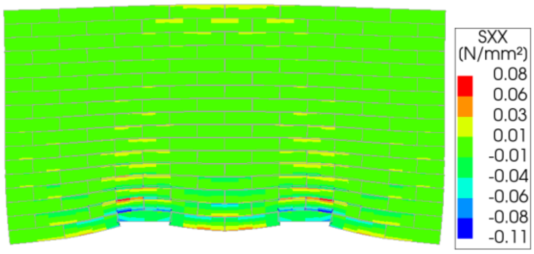


Figure C 21 Option 4 – Cauchy total stress of bed joint

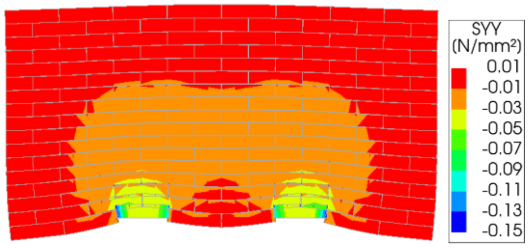


Figure C 22: Option 4 – Cauchy total stress of head joints

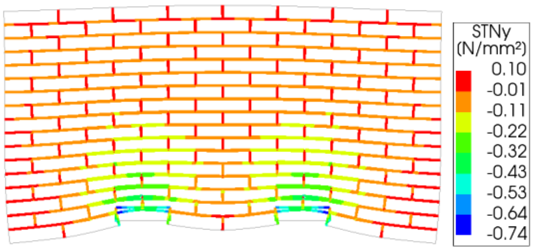


Figure C 23: Option 4 - Interface total traction bed joints

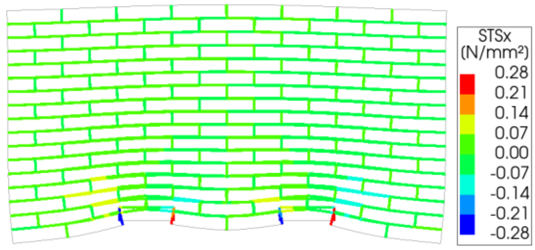


Figure C 24: Option 4 - Interface total traction head joints

Option 5

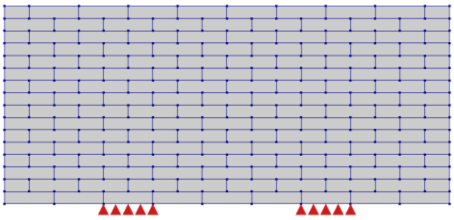


Figure C 25: Option 5 - Masonry element

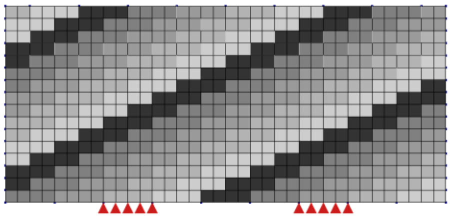


Figure C 26: Option 5 - Finite element mesh with supports

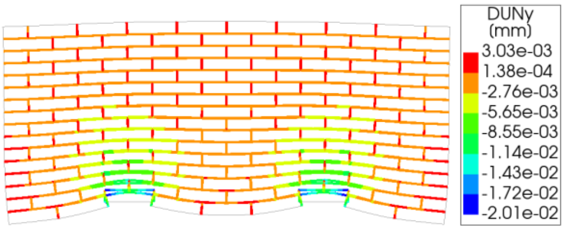


Figure C 27: Option 5 – Normal relative displacement of the interface

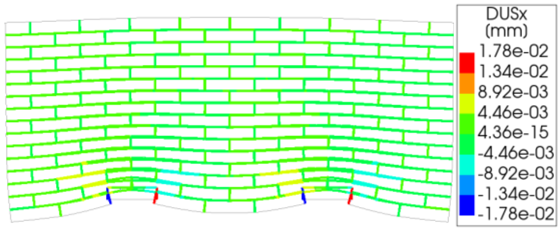


Figure C 28: Option 5 – Shear relative displacement of the interface

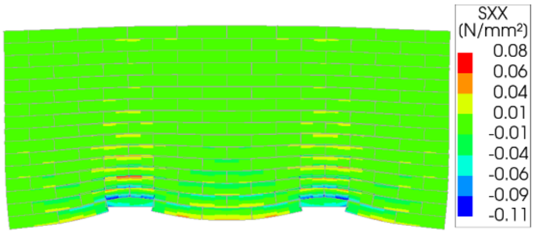


Figure C 29 Option 5 – Cauchy total stress of bed joint

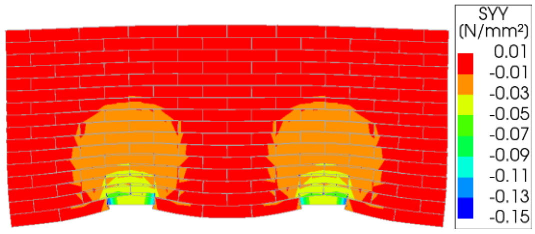


Figure C 30: Option 5 – Cauchy total stress of head joints

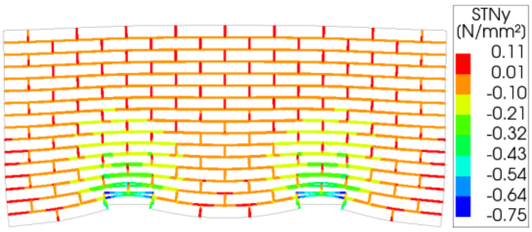


Figure C 31: Option 5 - Interface total traction bed joints

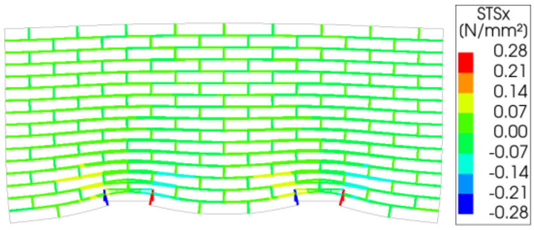


Figure C 32: Option 5 - Interface total traction head joints

Option 6

See 5.1.4.3

Appendix D
LCA CALCULATION

EPD Masonry, Mortar and Joint mortar

ADPE	Abiotic Depletion Potential for non-fossil resources
ADPF	Abiotic Depletion Potential for Fossil Resources
GWP	Global Warming Potential
ODP	Depletion potential of the stratospheric ozone layer
POCP	Formation potential of tropospheric ozone photochemical oxidants
AP	Acidification potential of land and water
EP	Eutrophication potential
HTP	Human Toxicity Potential
FAETP	Freshwater aquatic ecotoxicity potential
MAETP	Marine aquatic ecotoxicity potential
TETP	Terrestrial ecotoxicity potential

PERE	Use of renewable energy, excluding renewable primary energy resources
PERM	Use of renewable energy resources used as raw materials
PERT	Total use of renewable primary energy resources
PENRE	Use of non-renewable primary energy resources, excluding non-renewable energy resources used as raw materials
PENRM	Use of non-renewable primary energy resources used as raw material
PENRT	total use of non-renewable primary energy resources
SM	Use of secondary materials
RSF	Use of renewable secondary fuels
NRSF	Use of non-renewable secondary fuels
FW	Use of net fresh water

HWD	Hazardous waste disposed
NHWD	Non-hazardous waste disposed.
RWD	Radioactive waste disposed
CRU	Components for reuse
MFR	Materials for recycling
MER	Materials for energy recovery
EEE	Exported Electrical Energy
EET	Exported Thermal energy

Table D 1: EPD Masonry

Masonry [1m2]

Masonry inlcuding mortar: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	5.71E-06	5.36E-07	1.88E-06	8.13E-06	1.09E-05	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.61E-06	3.43E-06	1.74E-07	1.09E-08	-9.37E-07
ADPF	MJ	1.20E-02	1.66E-03	1.36E-01	1.50E-01	2.82E-02	1.57E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.44E-02	8.90E-03	2.16E-03	1.30E-04	-2.00E-02
GWP	kg CO2 eq	1.66E+00	2.33E-01	1.79E+01	1.98E+01	3.83E+00	6.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E+00	1.21E+00	2.86E-01	9.59E-03	-2.90E+00
ODP	kg CFC 11 eq	2.43E-07	4.09E-08	1.46E-06	1.74E-06	7.05E-07	1.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E-07	2.22E-07	3.33E-08	3.17E-09	-5.23E-07
POCP	kg ethene eq	1.30E-03	1.37E-04	4.26E-03	5.70E-03	2.26E-03	1.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.73E-03	7.12E-04	1.60E-04	1.02E-05	-2.93E-03
AP	kg SO2 eq	1.08E-02	1.17E-03	2.44E-02	3.64E-02	1.66E-02	2.23E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E-02	5.23E-03	1.32E-03	7.09E-05	-2.20E-02
EP	kg (PO4)3- eq	2.24E-03	2.42E-04	2.97E-03	5.45E-03	3.31E-03	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.81E-03	1.04E-01	2.97E-04	1.33E-05	-4.92E-03
HTP	kg DCB-Eq	5.36E-01	8.33E-02	3.76E+00	4.38E+00	1.53E+00	7.47E-01	4.39E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.57E-01	4.82E-01	6.26E-02	3.91E-05	-1.03E+00
FAETP	kg DCB-Eq	7.79E-03	2.40E-03	1.35E-02	2.37E-02	4.49E-02	1.37E-02	9.44E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.53E-02	1.41E-02	1.05E-03	9.72E-05	-1.44E-02
MAETP	kg DCB-Eq	2.95E+01	8.50E+00	5.35E+02	5.73E+02	4.62E+02	1.40E+02	9.38E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.38E+01	5.11E+01	4.01E+00	3.34E-01	-4.87E+01
TETP	kg DCB-Eq	1.51E-03	3.15E-04	8.97E-03	1.08E-02	9.64E-03	9.64E-03	2.19E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.84E-03	1.71E-03	8.45E-04	1.16E-05	-1.72E-03

Masonry including mortar: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	8.90E-01	5.29E-02	1.46E+01	1.55E+01	8.06E-01	6.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.67E-01	2.54E-01	2.32E-01	6.99E-03	-2.41E-01
PERM	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PERT	MJ	8.90E-01	5.29E-02	1.46E+01	1.55E+01	6.08E-01	6.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.67E-01	2.54E-01	2.32E-01	6.99E-03	-2.41E-01
PENRE	MJ	2.67E+01	3.70E+00	2.90E+02	3.20E+02	6.30E+01	6.66E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.23E+01	1.98E+01	4.52E+00	2.92E-01	-4.49E+01
PENRM	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PENRT	MJ	2.67E+01	3.70E+00	2.90E+02	3.20E+02	3.21E+02	6.66E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.23E+01	1.98E+01	4.52E+00	2.92E-01	-4.49E+01
SM	kg	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	6.55E-04	2.55E-05	4.47E-04	1.13E-03	4.35E-04	1.53E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-04	1.37E-04	2.62E-05	1.98E-06	-3.11E-04

Masonry inlcluding mortar: output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	6.55E-04	2.55E-05	4.47E-04	1.13E-03	4.35E-04	1.53E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-04	1.37E-04	2.62E-05	1.98E-06	-3.11E-04
NHWD	kg	1.26E-01	1.70E-01	1.97E-01	4.93E-01	3.62E+00	3.69E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.47E-01	1.14E+00	5.46E-01	1.79E+00	-4.59E-02
RWD	kg	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 2: EPD Mortar [tonnes]

Mortar [1tonnes]

Mortar: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	ND	ND	ND	1.10E-04	1.80E-05	ND	ND	ND	ND	ND	ND	ND	ND	3.10E-06	ND	ND
ADPF	MJ	ND	ND	ND	2.60E-01	4.30E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.80E-02	ND	ND
GWP	kg CO2 eq	ND	ND	ND	1.30E+02	5.90E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.40E+00	ND	ND
ODP	kg CFC 11 eq	ND	ND	ND	2.90E-06	9.60E-07	ND	ND	ND	ND	ND	ND	ND	ND	2.60E-07	ND	ND
POCP	kg ethene eq	ND	ND	ND	3.60E-02	4.40E-03	ND	ND	ND	ND	ND	ND	ND	ND	1.50E-03	ND	ND
AP	kg SO2 eq	ND	ND	ND	4.20E-01	3.20E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.10E-02	ND	ND
EP	kg (PO4)3- eq	ND	ND	ND	6.20E-02	7.40E-03	ND	ND	ND	ND	ND	ND	ND	ND	2.60E-03	ND	ND
HTP	kg DCB-Eq	ND	ND	ND	1.30E+01	1.70E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.00E+00	ND	ND
FAETP	kg DCB-Eq	ND	ND	ND	4.10E-01	7.30E-02	ND	ND	ND	ND	ND	ND	ND	ND	2.20E-02	ND	ND
MAETP	kg DCB-Eq	ND	ND	ND	2.40E+03	3.00E+02	ND	ND	ND	ND	ND	ND	ND	ND	1.50E+02	ND	ND
TETP	kg DCB-Eq	ND	ND	ND	2.60E-01	1.30E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.50E-02	ND	ND

Mortar: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERT	MJ	ND	ND	ND	1.20E+02	1.20E+00	ND	ND	ND	ND	ND	ND	ND	ND	8.50E-01	ND	ND
PENRE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRT	MJ	ND	ND	ND	1.20E+03	9.40E+01	ND	ND	ND	ND	ND	ND	ND	ND	3.90E+01	ND	ND
SM	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	ND	ND	ND	3.50E+01	7.20E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.60E+00	ND	ND

Mortar : output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	ND	ND	ND	2.90E+01	2.30E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.30E+00	ND	ND
NHWD	kg	ND	ND	ND	2.60E+00	1.30E+00	ND	ND	ND	ND	ND	ND	ND	ND	3.90E+01	ND	ND
RWD	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 3: EPD Mortar [45kg]

Mortar [45 kg]

Mortar: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	ND	ND	ND	5.72E-06	9.36E-07	ND	ND	ND	ND	ND	ND	ND	ND	1.61E-07	ND	ND
ADPF	MJ	ND	ND	ND	1.35E-02	2.24E-03	ND	ND	ND	ND	ND	ND	ND	ND	9.36E-04	ND	ND
GWP	kg CO2 eq	ND	ND	ND	6.76E+00	3.07E-01	ND	ND	ND	ND	ND	ND	ND	ND	1.25E-01	ND	ND
ODP	kg CFC 11 eq	ND	ND	ND	1.51E-07	4.99E-08	ND	ND	ND	ND	ND	ND	ND	ND	1.35E-08	ND	ND
POCP	kg ethene eq	ND	ND	ND	1.87E-03	2.29E-04	ND	ND	ND	ND	ND	ND	ND	ND	7.80E-05	ND	ND
AP	kg SO2 eq	ND	ND	ND	2.18E-02	1.66E-03	ND	ND	ND	ND	ND	ND	ND	ND	5.72E-04	ND	ND
EP	kg (PO4)3- eq	ND	ND	ND	3.22E-03	3.85E-04	ND	ND	ND	ND	ND	ND	ND	ND	1.35E-04	ND	ND
HTP	kg DCB-Eq	ND	ND	ND	6.76E-01	8.84E-02	ND	ND	ND	ND	ND	ND	ND	ND	5.20E-02	ND	ND
FAETP	kg DCB-Eq	ND	ND	ND	2.13E-02	3.80E-03	ND	ND	ND	ND	ND	ND	ND	ND	1.14E-03	ND	ND
MAETP	kg DCB-Eq	ND	ND	ND	1.25E+02	1.56E+01	ND	ND	ND	ND	ND	ND	ND	ND	7.80E+00	ND	ND
TETP	kg DCB-Eq	ND	ND	ND	1.35E-02	6.76E-04	ND	ND	ND	ND	ND	ND	ND	ND	7.80E-04	ND	ND

Mortar: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERT	MJ	ND	ND	ND	6.24E+00	6.24E-02	ND	ND	ND	ND	ND	ND	ND	ND	4.42E-02	ND	ND
PENRE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRT	MJ	ND	ND	ND	6.24E+01	4.89E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.03E+00	ND	ND
SM	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	ND	ND	ND	1.82E+00	3.74E-01	ND	ND	ND	ND	ND	ND	ND	ND	8.32E-02	ND	ND

Mortar: output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	ND	ND	ND	1.51E+03	1.20E+02	ND	ND	ND	ND	ND	ND	ND	ND	1.20E+02	ND	ND
NHWD	kg	ND	ND	ND	1.35E+02	6.76E+01	ND	ND	ND	ND	ND	ND	ND	ND	2.03E+03	ND	ND
RWD	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 4: EPD Joint Mortar [tonnes]

Joint mortar [1tonnes]

Joint mortar: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	ND	ND	ND	1.60E-04	1.90E-05	ND	ND	ND	ND	ND	ND	ND	ND	3.10E-06	ND	ND
ADPF	MJ	ND	ND	ND	3.50E-01	4.60E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.80E-02	ND	ND
GWP	kg CO2 eq	ND	ND	ND	1.50E+02	6.40E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.40E+00	ND	ND
ODP	kg CFC 11 eq	ND	ND	ND	4.20E-06	1.00E-06	ND	ND	ND	ND	ND	ND	ND	ND	2.60E-07	ND	ND
POCP	kg ethene eq	ND	ND	ND	4.40E-02	4.70E-03	ND	ND	ND	ND	ND	ND	ND	ND	1.50E-03	ND	ND
AP	kg SO2 eq	ND	ND	ND	1.90E-01	3.50E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.10E-02	ND	ND
EP	kg (PO4)3- eq	ND	ND	ND	7.40E-02	8.00E-03	ND	ND	ND	ND	ND	ND	ND	ND	2.60E-03	ND	ND
HTP	kg DCB-Eq	ND	ND	ND	1.60E+01	1.80E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.00E+00	ND	ND
FAETP	kg DCB-Eq	ND	ND	ND	3.10E+01	7.90E-02	ND	ND	ND	ND	ND	ND	ND	ND	2.20E-02	ND	ND
MAETP	kg DCB-Eq	ND	ND	ND	3.20E+03	3.30E+02	ND	ND	ND	ND	ND	ND	ND	ND	1.50E+02	ND	ND
TETP	kg DCB-Eq	ND	ND	ND	2.20E-01	1.40E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.50E-02	ND	ND

Joint mortar: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERT	MJ	ND	ND	ND	1.40E+02	1.30E+00	ND	ND	ND	ND	ND	ND	ND	ND	8.50E-01	ND	ND
PENRE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRT	MJ	ND	ND	ND	1.50E+03	1.00E+02	ND	ND	ND	ND	ND	ND	ND	ND	3.80E+01	ND	ND
SM	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	ND	ND	ND	4.60E+01	7.80E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.60E+00	ND	ND

Joint mortar: output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	ND	ND	ND	3.20E+01	2.50E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.30E+00	ND	ND
NHWD	kg	ND	ND	ND	3.90E+00	1.40E+00	ND	ND	ND	ND	ND	ND	ND	ND	3.80E+01	ND	ND
RWD	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 5: EPD Joint Mortar [7kg]

Joint mortar [7kg]

Joint mortar: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	ND	ND	ND	1.12E-06	1.33E-07	ND	ND	ND	ND	ND	ND	ND	ND	4.43E-10	ND	ND
ADPF	MJ	ND	ND	ND	2.45E-03	3.22E-04	ND	ND	ND	ND	ND	ND	ND	ND	2.57E-06	ND	ND
GWP	kg CO2 eq	ND	ND	ND	1.05E+00	4.48E-02	ND	ND	ND	ND	ND	ND	ND	ND	3.43E-04	ND	ND
ODP	kg CFC 11 eq	ND	ND	ND	2.94E-08	7.00E-09	ND	ND	ND	ND	ND	ND	ND	ND	3.71E-11	ND	ND
POCP	kg ethene eq	ND	ND	ND	3.08E-04	3.29E-05	ND	ND	ND	ND	ND	ND	ND	ND	2.14E-07	ND	ND
AP	kg SO2 eq	ND	ND	ND	1.33E-03	2.45E-04	ND	ND	ND	ND	ND	ND	ND	ND	1.57E-06	ND	ND
EP	kg (PO4)3- eq	ND	ND	ND	5.18E-04	5.60E-05	ND	ND	ND	ND	ND	ND	ND	ND	3.71E-07	ND	ND
HTP	kg DCB-Eq	ND	ND	ND	1.12E-01	1.26E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.43E-04	ND	ND
FAETP	kg DCB-Eq	ND	ND	ND	2.17E-01	5.53E-04	ND	ND	ND	ND	ND	ND	ND	ND	3.14E-06	ND	ND
MAETP	kg DCB-Eq	ND	ND	ND	2.24E+01	2.31E+00	ND	ND	ND	ND	ND	ND	ND	ND	2.14E-02	ND	ND
TETP	kg DCB-Eq	ND	ND	ND	1.54E-03	9.80E-05	ND	ND	ND	ND	ND	ND	ND	ND	2.14E-06	ND	ND

Joint mortar: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERT	MJ	ND	ND	ND	9.80E-01	9.10E-03	ND	ND	ND	ND	ND	ND	ND	ND	5.95E-03	ND	ND
PENRE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRM	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRT	MJ	ND	ND	ND	1.05E+01	7.00E-01	ND	ND	ND	ND	ND	ND	ND	ND	2.66E-01	ND	ND
SM	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	ND	ND	ND	3.22E-01	5.46E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.12E-02	ND	ND

Joint mortar: output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	ND	ND	ND	2.24E-01	1.75E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.61E-02	ND	ND
NHWD	kg	ND	ND	ND	2.73E-02	9.80E-03	ND	ND	ND	ND	ND	ND	ND	ND	2.66E-01	ND	ND
RWD	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 6: Result EPD masonry – mortar and joint mortar

Bricks [127.5kg]

Bricks: Enviromental impact per functional unit

1	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
ADPE	kg Sb eq	ND	3.81E-07	ND	1.29E-06	9.83E-06	ND	ND	ND	ND	ND	ND	ND	ND	1.24E-08	ND	ND
ADPF	MJ	ND	1.18E-03	ND	1.34E-01	2.56E-02	ND	ND	ND	ND	ND	ND	ND	ND	1.22E-03	ND	ND
GWP	kg CO2 eq	ND	1.66E-01	ND	1.20E+01	3.48E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.61E-01	ND	ND
ODP	kg CFC 11 eq	ND	2.91E-08	ND	1.56E-06	6.48E-07	ND	ND	ND	ND	ND	ND	ND	ND	1.97E-08	ND	ND
POCP	kg ethene eq	ND	9.73E-05	ND	3.52E-03	2.00E-03	ND	ND	ND	ND	ND	ND	ND	ND	8.18E-05	ND	ND
AP	kg SO2 eq	ND	8.31E-04	ND	1.32E-02	1.47E-02	ND	ND	ND	ND	ND	ND	ND	ND	7.46E-04	ND	ND
EP	kg (PO4)3- eq	ND	1.72E-04	ND	1.71E-03	2.87E-03	ND	ND	ND	ND	ND	ND	ND	ND	1.61E-04	ND	ND
HTP	kg DCB-Eq	ND	5.92E-02	ND	3.59E+00	1.43E+00	ND	ND	ND	ND	ND	ND	ND	ND	1.05E-02	ND	ND
FAETP	kg DCB-Eq	ND	1.70E-03	ND	-2.15E-01	4.06E-02	ND	ND	ND	ND	ND	ND	ND	ND	-9.71E-05	ND	ND
MAETP	kg DCB-Eq	ND	6.04E+00	ND	4.26E+02	4.44E+02	ND	ND	ND	ND	ND	ND	ND	ND	-3.81E+00	ND	ND
TETP	kg DCB-Eq	ND	2.24E-04	ND	-4.27E-03	8.87E-03	ND	ND	ND	ND	ND	ND	ND	ND	6.29E-05	ND	ND

Bricks: Resource use per functional unit

2	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
PERE	MJ	ND	3.76E-02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERM	MJ	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PERT	MJ	ND	3.76E-02	ND	8.3229	5.37E-01	ND	ND	ND	ND	ND	ND	ND	ND	1.82E-01	ND	ND
PENRE	MJ	ND	2.63E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRM	MJ	ND	0.00E+00	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PENRT	MJ	ND	2.63E+00	ND	2.48E+02	3.15E+02	ND	ND	ND	ND	ND	ND	ND	ND	2.23E+00	ND	ND
SM	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
RSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NRSF	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
FW	m2	ND	1.81E-05	ND	-2.14E+00	-4.29E-01	ND	ND	ND	ND	ND	ND	ND	ND	-9.44E-02	ND	ND

Bricks: output flow and waste categories

3	Unit	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
HWD	kg	ND	1.81E-05	ND	-1.51E+03	-1.20E+02	ND	ND	ND	ND	ND	ND	ND	ND	-1.20E+02	ND	ND
NHWD	kg	ND	1.21E-01	ND	-1.35E+02	-6.40E+01	ND	ND	ND	ND	ND	ND	ND	ND	-2.03E+03	ND	ND
RWD	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CRU	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MFR	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MER	kg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EEE	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
EET	MJ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table D 7: Scenario Traditional building A1-A5

1	Unit	A1	A2	A3	A4	A5	Total
ADPE	kg Sb eq	5.71E-06	5.36E-07	1.88E-06	1.09E-05	6.48E-06	2.55E-05
ADPF	MJ	1.20E-02	1.66E-03	1.36E-01	2.82E-02	1.57E-02	1.94E-01
GWP	kg CO2 eq	1.66E+00	2.33E-01	1.79E+01	3.83E+00	6.78E+00	3.04E+01
ODP	kg CFC 11 eq	2.43E-07	4.09E-08	1.46E-06	7.05E-07	1.83E-07	2.63E-06
POCP	kg ethene eq	1.30E-03	1.37E-04	4.26E-03	2.26E-03	1.97E-03	9.93E-03
AP	kg SO2 eq	1.08E-02	1.17E-03	2.44E-02	1.66E-02	2.23E-02	7.53E-02
EP	kg (PO4)3- eq	2.24E-03	2.42E-04	2.97E-03	3.31E-03	3.40E-03	1.22E-02
HTP	kg DCB-Eq	5.36E-01	8.33E-02	3.76E+00	1.53E+00	7.47E-01	6.66E+00
FAETP	kg DCB-Eq	7.79E-03	2.40E-03	1.35E-02	4.49E-02	1.37E-02	8.23E-02
MAETP	kg DCB-Eq	2.95E+01	8.50E+00	5.35E+02	4.62E+02	1.40E+02	1.18E+03
TETP	kg DCB-Eq	1.51E-03	3.15E-04	8.97E-03	9.64E-03	9.64E-03	3.01E-02

2	Unit	A1	A2	A3	A4	A5	Total
PERT	MJ	8.90E-01	5.29E-02	1.46E+01	6.08E-01	6.08E-01	1.68E+01
PENRT	MJ	2.67E+01	3.70E+00	2.90E+02	3.21E+02	6.66E+01	7.08E+02
FW	m2	6.55E-04	2.55E-05	4.47E-04	4.35E-04	1.53E+00	1.53E+00

3	Unit	A1	A2	A3	A4	A5	Total
HWD	kg	6.55E-04	2.55E-05	4.47E-04	4.35E-04	1.53E+00	1.53E+00
NHWD	kg	1.26E-01	1.70E-01	1.97E-01	3.62E+00	3.69E-01	4.48E+00

Table D 8: Scenario Traditional building A1-A5 MKI value

MKI Weight factor (€/unit) Old
0.16
0.16
0.05
30
2
4
9
0.09
0.03
0.0001
0.06

1	Unit	A1	A2	A3	A4	A5	Total
ADPE	kg Sb eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
ADPF	MJ	€ 0.00	€ 0.00	€ 0.02	€ 0.00	€ 0.00	€ 0.03
GWP	kg CO2 eq	€ 0.08	€ 0.01	€ 0.90	€ 0.19	€ 0.34	€ 1.52
ODP	kg CFC 11 eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
POCP	kg C2H4 eq	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.02
AP	kg SO2 eq	€ 0.04	€ 0.00	€ 0.10	€ 0.07	€ 0.09	€ 0.30
EP	kg (PO4)3- eq	€ 0.02	€ 0.00	€ 0.03	€ 0.03	€ 0.03	€ 0.11
HTP	kg DCB-Eq	€ 0.05	€ 0.01	€ 0.34	€ 0.14	€ 0.07	€ 0.60
FAETP	kg DCB-Eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
MAETP	kg DCB-Eq	€ 0.00	€ 0.00	€ 0.05	€ 0.05	€ 0.01	€ 0.12
TETP	kg DCB-Eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total		€ 0.20	€ 0.03	€ 1.44	€ 0.48	€ 0.55	€ 2.70

Table D 9: Scenario Traditional building division mortar and brick

1	Unit	A1-3 masonry	A1-A3 mortar	A1-A3 Brick	A4 masonry	A4 mortar	A4 Brick	A5	Total
ADPE	kg Sb eq	8.13E-06	6.84E-06	1.29E-06	1.09E-05	1.07E-06	9.83E-06	6.48E-06	2.55E-05
ADPF	MJ	1.50E-01	1.60E-02	1.34E-01	2.82E-02	2.56E-03	2.56E-02	1.57E-02	1.94E-01
GWP	kg CO2 eq	1.98E+01	7.81E+00	1.20E+01	3.83E+00	3.52E-01	3.48E+00	6.78E+00	3.04E+01
ODP	kg CFC 11 eq	1.74E-06	1.80E-07	1.56E-06	7.05E-07	5.69E-08	6.48E-07	1.83E-07	2.63E-06
POCP	kg ethene eq	5.70E-03	2.18E-03	3.52E-03	2.26E-03	2.62E-04	2.00E-03	1.97E-03	9.93E-03
AP	kg SO2 eq	3.64E-02	2.32E-02	1.32E-02	1.66E-02	1.91E-03	1.47E-02	2.23E-02	7.53E-02
EP	kg (PO4)3- eq	5.45E-03	3.74E-03	1.71E-03	3.31E-03	4.41E-04	2.87E-03	3.40E-03	1.22E-02
HTP	kg DCB-Eq	4.38E+00	7.88E-01	3.59E+00	1.53E+00	1.01E-01	1.43E+00	7.47E-01	6.66E+00
FAETP	kg DCB-Eq	2.37E-02	2.38E-01	-2.15E-01	4.49E-02	4.35E-03	4.06E-02	1.37E-02	8.23E-02
MAETP	kg DCB-Eq	5.73E+02	1.47E+02	4.26E+02	4.62E+02	1.79E+01	4.44E+02	1.40E+02	1.18E+03
TETP	kg DCB-Eq	1.08E-02	1.51E-02	-4.27E-03	9.64E-03	7.74E-04	8.87E-03	9.64E-03	3.01E-02

Table D 10: Scenario Traditional building division mortar and brick MKI value

MKI Weight factor (€/unit) Old	1	Unit	A1-3 masonry	A1-A3 mortar	A1-A3 Brick	A4 masonry	A4 mortar	A4 Brick	A5	Total
0.16	ADPE	kg Sb eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
0.16	ADPF	MJ	€ 0.02	€ 0.00	€ 0.02	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.03
0.05	GWP	kg CO2 eq	€ 0.99	€ 0.39	€ 0.60	€ 0.19	€ 0.02	€ 0.17	€ 0.34	€ 1.52
30	ODP	kg CFC 11 eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
2	POCP	kg ethene eq	€ 0.01	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.02
4	AP	kg SO2 eq	€ 0.15	€ 0.09	€ 0.05	€ 0.07	€ 0.01	€ 0.06	€ 0.09	€ 0.30
9	EP	kg (PO4)3- eq	€ 0.05	€ 0.03	€ 0.02	€ 0.03	€ 0.00	€ 0.03	€ 0.03	€ 0.11
0.09	HTP	kg DCB-Eq	€ 0.39	€ 0.07	€ 0.32	€ 0.14	€ 0.01	€ 0.13	€ 0.07	€ 0.60
0.03	FAETP	kg DCB-Eq	€ 0.00	€ 0.01	€ -0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
0.0001	MAETP	kg DCB-Eq	€ 0.06	€ 0.01	€ 0.04	€ 0.05	€ 0.00	€ 0.04	€ 0.01	€ 0.12
0.06	TETP	kg DCB-Eq	€ 0.00	€ 0.00	€ -0.0003	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Total		€ 1.67	€ 0.62	€ 1.05	€ 0.48	€ 0.04	€ 0.44	€ 0.55	€ 2.70

Table D 11: Scenario reuse masonry brick

1	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 bricks	A1-A3 morter 45kg	A4 morter 45kg	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
ADPE	kg Sb eq	4.02E-06	5.28E-06	9.37E-08	5.87E-09	9.83E-06	5.72E-06	9.36E-07	1.12E-06	1.33E-07	6.48E-06	3.36E-05
ADPF	MJ	2.22E-02	1.37E-02	1.16E-03	7.00E-05	2.56E-02	1.35E-02	2.24E-03	2.45E-03	3.22E-04	1.57E-02	9.69E-02
GWP	kg CO2 eq	3.14E+00	1.86E+00	1.54E-01	5.16E-03	3.48E+00	6.76E+00	3.07E-01	1.05E+00	4.48E-02	6.78E+00	2.36E+01
ODP	kg CFC 11 eq	5.69E-07	3.42E-07	1.79E-08	1.71E-09	6.48E-07	1.51E-07	4.99E-08	2.94E-08	7.00E-09	1.83E-07	2.00E-06
POCP	kg ethene eq	2.66E-03	1.10E-03	8.62E-05	5.49E-06	2.00E-03	1.87E-03	2.29E-04	3.08E-04	3.29E-05	1.97E-03	1.03E-02
AP	kg SO2 eq	1.98E-02	8.05E-03	7.11E-04	3.82E-05	1.47E-02	2.18E-02	1.66E-03	1.33E-03	2.45E-04	2.23E-02	9.07E-02
EP	kg (PO4)3- eq	4.32E-03	1.60E-03	1.60E-04	7.16E-06	2.87E-03	3.22E-03	3.85E-04	5.18E-04	5.60E-05	3.40E-03	1.65E-02
HTP	kg DCB-Eq	1.16E+00	7.42E-01	3.37E-02	2.11E-05	1.43E+00	6.76E-01	8.84E-02	1.12E-01	1.26E-02	7.47E-01	5.00E+00
FAETP	kg DCB-Eq	2.35E-02	2.17E-02	5.65E-04	5.23E-05	4.06E-02	2.13E-02	3.80E-03	2.17E-01	5.53E-04	1.37E-02	3.43E-01
MAETP	kg DCB-Eq	8.28E+01	7.86E+01	2.16E+00	1.80E-01	4.44E+02	1.25E+02	1.56E+01	2.24E+01	2.31E+00	1.40E+02	9.13E+02
TETP	kg DCB-Eq	2.83E-03	2.63E-03	4.55E-04	6.25E-06	8.87E-03	1.35E-02	6.76E-04	1.54E-03	9.80E-05	9.64E-03	4.03E-02

2	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 bricks	A1-A3 morter 45kg	A4 morter 45kg	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
PERT	MJ	2.67E-01	2.54E-01	8.12E-02	2.45E-03	5.37E-01	6.24E+00	6.24E-02	9.80E-01	9.10E-03	6.08E+00	1.39E+01
PENRT	MJ	3.23E+01	1.98E+01	1.58E+00	1.02E-01	3.15E+02	6.24E+01	4.89E+00	1.05E+01	7.00E-01	6.66E+01	4.61E+02
FW	m2	2.23E-04	1.37E-04	9.17E-06	6.93E-07	-4.29E-01	1.82E+00	3.74E-01	3.22E-01	5.46E-02	1.53E+00	3.67E+00

3	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 bricks	A1-A3 morter 45kg	A4 morter 45kg	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
HWD	kg	2.23E-04	1.37E-04	9.17E-06	6.93E-07	-1.20E+02	1.51E+03	1.20E+02	2.24E-01	1.75E-02	1.53E+00	1.51E+03
NHWD	kg	7.47E-01	1.14E+00	1.91E-01	6.27E-01	FALSE	1.35E+02	6.76E+01	2.73E-02	9.80E-03	3.69E-01	2.03E+02

Table D 12: Scenario reuse masonry brick MKI value

MKI Weight factor (€/unit)	1	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 bricks	A1-A3 morter 45kg	A4 morter 45kg	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
0.16	ADPE	kg Sb eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
0.16	ADPF	MJ	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.02
0.05	GWP	kg CO2 eq	€ 0.16	€ 0.09	€ 0.01	€ 0.00	€ 0.17	€ 0.34	€ 0.02	€ 0.05	€ 0.00	€ 0.34	€ 1.18
30	ODP	g CFC 11 e	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
2	POCP	kg C2H4 e	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.02
4	AP	kg SO2 eq	€ 0.08	€ 0.03	€ 0.00	€ 0.00	€ 0.06	€ 0.09	€ 0.01	€ 0.01	€ 0.00	€ 0.09	€ 0.36
9	EP	g (PO4)3- e	€ 0.04	€ 0.01	€ 0.00	€ 0.00	€ 0.03	€ 0.03	€ 0.00	€ 0.00	€ 0.00	€ 0.03	€ 0.15
0.09	HTP	kg DCB-Ec	€ 0.10	€ 0.07	€ 0.00	€ 0.00	€ 0.13	€ 0.06	€ 0.01	€ 0.01	€ 0.00	€ 0.07	€ 0.45
0.03	FAETP	kg DCB-Ec	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.01
0.0001	MAETP	kg DCB-Ec	€ 0.01	€ 0.01	€ 0.00	€ 0.00	€ 0.04	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.09
0.06	TETP	kg DCB-Ec	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Total		€ 0.40	€ 0.22	€ 0.02	€ 0.00	€ 0.44	€ 0.54	€ 0.04	€ 0.08	€ 0.01	€ 0.55	€ 2.28

Table D 13: Scenario reuse masonry element

1	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 elements 98%	A1-A3 morter 45kg 2%	A4 morter 45kg 2%	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
ADPE	kg Sb eq	2.90E-06	3.81E-06	1.93E-08	1.21E-09	3.36E-06	1.14E-07	1.87E-08	1.12E-06	1.33E-07	3.00E-06	1.45E-05
ADPF	MJ	1.60E-02	9.89E-03	2.40E-04	1.44E-05	8.72E-03	2.70E-04	4.47E-05	2.45E-03	3.22E-04	1.53E-02	5.33E-02
GWP	kg CO2 eq	2.27E+00	1.34E+00	3.18E-02	1.07E-03	1.19E+00	1.35E-01	6.14E-03	1.05E+00	4.48E-02	2.45E+00	8.51E+00
ODP	kg CFC 11 eq	4.11E-07	2.47E-07	3.70E-09	3.52E-10	2.18E-07	3.02E-09	9.98E-10	2.94E-08	7.00E-09	3.81E-07	1.30E-06
POCP	kg C2H4 eq	1.92E-03	7.91E-04	1.78E-05	1.13E-06	6.98E-04	3.74E-05	4.58E-06	3.08E-04	3.29E-05	1.85E-03	5.66E-03
AP	kg SO2 eq	1.43E-02	5.81E-03	1.47E-04	7.88E-06	5.13E-03	4.37E-04	3.33E-05	1.33E-03	2.45E-04	1.42E-02	4.17E-02
EP	kg (PO4)3- eq	3.12E-03	1.16E-03	3.30E-05	1.48E-06	1.02E-03	6.45E-05	7.70E-06	5.18E-04	5.60E-05	3.01E-03	8.99E-03
HTP	kg DCB-Eq	8.41E-01	5.36E-01	6.96E-03	4.34E-06	4.72E-01	1.35E-02	1.77E-03	1.12E-01	1.26E-02	8.02E-01	2.80E+00
FAETP	kg DCB-Eq	1.70E-02	1.57E-02	1.17E-04	1.08E-05	1.38E-02	4.26E-04	7.59E-05	2.17E-01	5.53E-04	1.61E-02	2.81E-01
MAETP	kg DCB-Eq	5.98E+01	5.68E+01	4.46E-01	3.71E-02	5.01E+01	2.50E+00	3.12E-01	2.24E+01	2.31E+00	6.22E+01	2.57E+02
TETP	kg DCB-Eq	2.04E-03	1.90E-03	9.39E-05	1.29E-06	1.68E-03	2.70E-04	1.35E-05	1.54E-03	9.80E-05	2.42E-03	1.01E-02

2	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 elements 98%	A1-A3 morter 45kg 2%	A4 morter 45kg 2%	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
PERT	MJ	2.97E-01	2.82E-01	2.58E-02	7.77E-04	5.18E-02	1.25E-01	1.25E-03	9.80E-01	9.10E-03	2.67E-01	2.04E+00
PENRT	MJ	3.59E+01	2.20E+01	5.02E-01	3.24E-02	3.63E+00	1.25E+00	9.78E-02	1.05E+01	7.00E-01	3.23E+01	1.07E+02
FW	m2	2.48E-04	1.52E-04	2.91E-06	2.20E-07	1.10E-03	3.64E-02	7.49E-03	3.22E-01	5.46E-02	2.23E-04	4.22E-01

3	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 elements 98%	A1-A3 morter 45kg 2%	A4 morter 45kg 2%	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
HWD	kg	2.48E-04	1.52E-04	2.91E-06	2.20E-07	2.50E-05	3.02E+01	2.39E+00	2.24E-01	1.75E-02	2.23E-04	3.28E+01
NHWD	kg	8.30E-01	1.27E+00	6.07E-02	1.99E-01	1.67E-01	2.70E+00	1.35E+00	2.73E-02	9.80E-03	1.14E+00	7.76E+00

Table D 14: Scenario reuse masonry element MKI value

MKI Weight factor (€/unit)	1	Unit	C1 Multiply	C2 Multiply	C3* Multiply	C4* Multiply	A4 elements 98%	A1-A3 morter 45kg 2%	A4 morter 45kg 2%	A1-A3 joint mortar 7kg	A4 joint mortar 7kg	A5	Total
0.16	ADPE	kg Sb eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
0.16	ADPF	MJ	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01
0.05	GWP	kg CO2 eq	€ 0.11	€ 0.07	€ 0.00	€ 0.00	€ 0.06	€ 0.01	€ 0.00	€ 0.05	€ 0.00	€ 0.12	€ 0.43
30	ODP	kg CFC 11 eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
2	POCP	kg C2H4 eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01
4	AP	kg SO2 eq	€ 0.06	€ 0.02	€ 0.00	€ 0.00	€ 0.02	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.06	€ 0.17
9	EP	kg (PO4)3- eq	€ 0.03	€ 0.01	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.03	€ 0.08
0.09	HTP	kg DCB-Eq	€ 0.08	€ 0.05	€ 0.00	€ 0.00	€ 0.04	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.07	€ 0.25
0.03	FAETP	kg DCB-Eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.01
0.0001	MAETP	kg DCB-Eq	€ 0.01	€ 0.01	€ 0.00	€ 0.00	€ 0.01	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.01	€ 0.03
0.06	TETP	kg DCB-Eq	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Total		€ 0.29	€ 0.16	€ 0.00	€ 0.00	€ 0.14	€ 0.01	€ 0.00	€ 0.08	€ 0.01	€ 0.29	€ 0.98

Table D 15: All scenarios

1	Unit	Scenario 1	Scenario 2	Scenario 3
ADPE	kg Sb eq	0.000026	0.000034	0.000014
ADPF	MJ	0.194	0.097	0.053
GWP	kg CO2 eq	30.40	23.58	8.51
ODP	kg CFC 11 eq	0.0000026	0.0000020	0.0000013
POCP	kg C2H4 eq	0.0099	0.0103	0.0057
AP	kg SO2 eq	0.075	0.091	0.042
EP	kg (PO4)3- eq	0.012	0.017	0.009
HTP	kg DCB-Eq	6.66	5.00	2.80
FAETP	kg DCB-Eq	0.082	0.343	0.281
MAETP	kg DCB-Eq	1175.00	912.92	256.83
TETP	kg DCB-Eq	0.0301	0.0403	0.0101

Table D 16: All scenarios MKI value

MKI (€)	Senario 1	Senario 2	Senario 3
ADPE	0.00	0.00	0.00
ADPF	0.03	0.02	0.01
GWP	1.52	1.18	0.43
ODP	0.00	0.00	0.00
POCP	0.02	0.02	0.01
AP	0.30	0.36	0.17
EP	0.11	0.15	0.08
HTP	0.60	0.45	0.25
FAETP	0.00	0.01	0.01
MAETP	0.12	0.09	0.03
TETP	0.00	0.00	0.00
Total	2.70	2.28	0.98

Table D 17: All scenarios MKI percentage

MKI (€)	Senario 1	Senario 2	Senario 3
ADPE	0%	0%	0%
ADPF	1%	1%	1%
GWP	56%	52%	43%
ODP	0%	0%	0%
POCP	1%	1%	1%
AP	11%	16%	17%
EP	4%	7%	8%
HTP	22%	20%	26%
FAETP	0%	0%	1%
MAETP	4%	4%	3%
TETP	0%	0%	0%
Total	100%	100%	100%

Table D 18: Division of types Scenario 1

Part masonry bricks	Part mortar	Part Shared
€ 0.00	€ 0.00	€ 0.00
€ 0.03	€ 0.00	€ 0.00
€ 0.77	€ 0.41	€ 0.34
€ 0.00	€ 0.00	€ 0.00
€ 0.01	€ 0.00	€ 0.00
€ 0.11	€ 0.10	€ 0.09
€ 0.04	€ 0.04	€ 0.03
€ 0.45	€ 0.08	€ 0.07
-€ 0.01	€ 0.01	€ 0.00
€ 0.09	€ 0.02	€ 0.01
€ 0.00	€ 0.00	€ 0.00
€ 1.50	€ 0.66	€ 0.55
55%	24%	20%

Table D 19: Division of types Scenario 2

Part masonry bricks	Part mortar	Part Shared
€ 0.00	€ 0.00	€ 0.00
€ 0.01	€ 0.00	€ 0.00
€ 0.43	€ 0.41	€ 0.34
€ 0.00	€ 0.00	€ 0.00
€ 0.01	€ 0.00	€ 0.00
€ 0.17	€ 0.10	€ 0.09
€ 0.08	€ 0.04	€ 0.03
€ 0.30	€ 0.08	€ 0.07
€ 0.00	€ 0.01	€ 0.00
€ 0.06	€ 0.02	€ 0.01
€ 0.00	€ 0.00	€ 0.00
€ 1.08	€ 0.66	€ 0.55
47%	29%	24%

Table D 20: Division of types Scenario 3

Part masonry elements	Part mortar	Part Shared
€ 0.00	€ 0.00	€ 0.00
€ 0.01	€ 0.00	€ 0.00
€ 0.24	€ 0.06	€ 0.12
€ 0.00	€ 0.00	€ 0.00
€ 0.01	€ 0.00	€ 0.00
€ 0.10	€ 0.01	€ 0.06
€ 0.05	€ 0.01	€ 0.03
€ 0.17	€ 0.01	€ 0.07
€ 0.00	€ 0.01	€ 0.00
€ 0.02	€ 0.00	€ 0.01
€ 0.00	€ 0.00	€ 0.00
€ 0.59	€ 0.10	€ 0.29
60%	10%	30%