Msc Industrial Ecology (joint degree TU Delft & Leiden University)

Reuse Possibilities within (De-)Construction in The Netherlands

Multi-Methods Material Flow Analysis

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Acknowledgments

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Dedication

I want to dedicate my Master's thesis to my mom, Gertie Janssen, whose love and strength carries me from the other side.

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Executive Summary

This thesis examines how reusing components from demolished buildings can contribute to a circular and low carbon built environment. The construction sector globally accounts for nearly half of material consumption and 39% of greenhouse gas emissions (Mollaei et al., 2023). Simultaneously, the Netherlands has committed to reducing the CO2 emissions, lowering primary material consumption and becoming circular.

In the field of industrial ecology extensive research has been done on the potential of urban mining to lower raw material demand, CO_2 emissions and to strive for a circular economy. However, these studies concentrate on recycling, as opposed to reuse. Whereas, emissions, raw material input and foreign processing can further be lowered through reuse instead of recycling. This thesis contributes to the urban mining field by investigating: "To what extent can material reuse meet the demand by synchronising material flows in the built environment of The Netherlands from 2018 to 2023?". It aims to answer this by using a mixed-methods approach. By combining quantitative methods (spatial modelling using GIS and Material Flow Analysis) and qualitative methods (stakeholder interviews), this thesis develops a framework for analysing the reuse potential of material outflows from demolition combined with construction inflows.

It quantifies and spatialises material stocks, inflows, and outflows across national, provincial and municipal scale in the Netherlands through a bottom-up-approach. Furthermore, it analyses a specific Reuse scenario for bricks, comparing it with Recycling and Business-as-Usual scenarios. It combines historical GIS data (BAG 2018–2023), using the new Multi-Temporal Building Stock Analysis, to identify demolished and newly built structures. Furthermore, interviews were held with three demolition companies and one architectural firm. Insights into current reuse practices fed back into the analysis of the material flows and enabled a quantified national Reuse scenario for bricks.

The results show that bricks exhibit substantial reuse potential: under the Reuse scenario, an estimated 26% of the brick demand could be met with reclaimed bricks, leading to about 58% CO_2-eq. reduction compared to the Business-as-Usual scenario. Although data limitations prevented similar quantification for steel and concrete, qualitative findings suggest that heavy structural components could be reused effectively between similar building types. Demolition companies' views on reuse potential of components vary per reuse chain, with those involved in construction projects more successfully reusing larger steel and concrete components. Significant reuse potential seems to exist for industrial and office buildings, especially for steel and concrete, based on flow ratios and interview insights. Office buildings in particular show strong potential in substituting demand through reuse, as material supply and demand are nearly balanced. Cross-regional exchange could further align supply and demand, which vary by region. In contrast, residential buildings show lower potential in substituting material demand through reuse due to lower outflow-to-inflow ratios and fewer reuse initiatives.

Furthermore, this thesis emphasizes the need to shift analytical focus from materials to components recognizing their diversity, condition, and physicality.

Keywords: Urban mining, Reuse, Circular economy, GIS, MFA, Bottom-up approach, Mixed-Methods

1. Introduction

The building and construction sector is accountable for around half of the material usage worldwide and is a significant contributor to global greenhouse gas emissions, accounting for approximately 39% of worldwide emissions (Mollaei et al., 2023).

Zooming in on the Netherlands, Dutch building projects are expected to produce a total of 113 Mton of CO_2 emissions by 2030 (Copper8, 2024). Simultaneously, the Netherlands has committed to reducing the CO_2 emissions, compared to 1990, with at least 55% by 2030 and with 95% in 2050 (MEZK, 2020). Furthermore, The Netherlands aims to decrease the use of primary raw materials by 50% in 2030, with the ultimate goal of achieving a fully circular economy by 2050 (MAZ, 2023). Furthermore, the Netherlands aims to reduce raw material input by 15% in 2035 compared to 2016. (Rijksoverheid, 2025). Achieving these aims requires innovative approaches to increase regional circularity and reduce both emissions and raw material consumption in the construction sector.

In the field of industrial ecology (IE) extensive research has been done on the potential of 'mining' the already existing material stocks of cities and countries (Urban Mining) to lower raw material demand and strive for a circular economy (Verhagen et al., 2021; Yang, D. et al., 2022; Yang, X. 2022; van Oorschot et al., 2023). Urban mining can supply construction inputs, helping close material loops, reduce carbon emissions and raw material use. (Arora et al., 2021). However, these studies concentrate on the recycling, as opposed to reuse, of existing materials.

Recycling, is understood in this study as processing and converting a material (concrete blocks, scrap metal etc.) to new products (recycled concrete aggregate, new steel beams etc.) (Rakhshan et al., 2020). In this study, reuse is understood as building component reuse (CR), referring to the reintroduction of discarded building components (e.g. beams, columns, bricks) into their original or similar function with minimal or no treatment (Rakhshan et al., 2020).

Recycling, it should be noted, still emits significant amounts of CO_2 and often requires additional raw material input as well (van Oorschot et al., 2023). Emissions and the need for raw material input can be lowered through reuse instead of recycling (Gobbo et al., 2024). This is also in line with achieving a circular economy where recycling is only to be considered if reuse is not possible (Nilsen, 2019).

Bearing the above in mind, in this thesis I aim to contribute to the research in the field of IE on urban mining and circular regions by exploring the potential reuse components in

The Dutch built environment. The research has an innovative approach in the use of spatial modelling and material flow analysis (MFA) for analysing and synchronising material reuse flows on national, provincial and municipal scale. Specifically, it investigates the potential for material reuse to meet material demand for the Dutch construction sector between 2018 and 2023. It will do so by focusing on synchronizing material flows through both quantitative, the usage of GIS in combination with MFA, and qualitative methods, stakeholder interviews, in order to ground it in regional reality. This research aims to offer insights for society on the potential of reusing construction material for ensuring a more sustainable, circular and self-sufficient future of the Netherlands.

2. Literature review

The following sub-chapters will discuss the academic context of MFA and reuse in the built environment and will illustrate the knowledge gap.

2.1 Material Flow Analysis

MFA is widely used in IE to assess material stocks and flows in the built environment (Yang, 2022; Fishman et al., 2014). Bottom-up approaches, often using GIS, provide more detailed spatial insights and are commonly applied to assess urban mining potential (Verhagen et al., 2021). The material stocks of nations or cities can be calculated, and future material flows predicted. Two main approaches are commonly applied: top-down and bottom-up (Mohammadiziazi et al., 2023).

The top-down approach uses large-scale, aggregated data such as population statistics, floor area per capita, and economic flows. It is efficient and useful for broad projections and policy planning. For example, Müller (2006) estimated concrete stocks in Dutch residential buildings.

The bottom-up approach, on the other hand, uses building-specific data, combining physical attributes (floor area, building type) with material intensity (MI) coefficients (Mohammadiziazi et al., 2023). Buildings' physical characteristics can be found using GIS or accessible inventories in towns and nations. This, the bottom-up approach, provides more detailed insights into material types and spatial distributions. Bottom-up studies are often done in order to look into the potential of urban mining. In urban mining the current material stock is used as a ‘mine’ outflow of which can potentially be used as an input for construction in order to close the material loops of the built environment (Verhagen et al., 2021).

At the national scale in the Netherlands, Van der Voet et al. (2025) analysed urban mines across sectors, including buildings, infrastructure, and vehicles. Van Oorschot et al. (2023) and Yang (2022) combined spatial modelling, GIS, and MFA to assess material

stocks and future urban mining potential. Van Oorschot et al. (2023) further modelled three future building scenarios (conventional, circular and biobased) for 2018–2050. Also non-academic research on national construction material flows has been done including Economisch Instituut voor de Bouw (EIB) et al., 2026, monitoring construction flows for the year 2023.

At the provincial level, research remains limited, although commissioned studies for example conducted by Metabolic (2024) for South Holland indicate interest. This study analysed material flows in the built environment and explored future reuse potential of materials such as brick, wood, and concrete (Metabolic, 2024).

At the municipal scale, several studies further illustrate the application of MFA. Verhagen et al. (2021) analysed the matching of future construction and demolition material flows in Leiden, similar to Kootstra et al. (2019) focusing on Amsterdam. Additionally, Van den Berghe and Verhagen (2021) studied future material flows in The Hague (2020–2025), combining MFA and GIS to assess the impact of the spatial distribution of concrete recycling facilities. These studies are future-oriented, with limited retrospective analysis. Van der Voet et al. (2025) therefore recommends retrospective research on material flows as well.

2.2 Material Intensities

Material intensity (MI) measures the mass of construction materials per unit of floor area (kg/m^2), reflecting material efficiency and serving as a proxy for building function (Fishman et al., 2024). Several country-specific MI datasets exist, including Canada, China, Germany and the Netherlands (Fishman et al., 2024; Sprecher et al., 2021). Fishman et al. (2024) developed a consistent global dataset covering 32 regions.

However, many material intensity studies, including on the Netherlands (Sprecher et al., 2021), focus on materials such as concrete rather than building components (e.g., beams, slabs), despite growing recognition that component-level modelling is essential for circular resource management by enabling more detailed insights into material stocks and recovery potentials (Dai et al., 2025; Tirado et al., 2021).

Recent studies begin to address this gap: Dai et al. (2025) applied machine learning to estimate component stocks in the UK, Tirado et al. (2021) analysed component-level intensities in France, and Alaux et al. (2024) integrated component data with LCA and MFA in Austria. Nevertheless, to the best of my knowledge a comprehensive component-level MI database for the Netherlands is not available.

2.3 Recycling or Reuse

Most urban mining research focuses on recycling materials from demolished buildings as a substitute for primary inflows (Verhagen et al., 2021; Van den Berghe & Verhagen,

2021; van Oorschot et al., 2023; van der Voet et al., 2025). In contrast, the reuse of building components from existing stock is rarely considered as a scenario in MFA. This is clearly shown by van Oorschot et al. (2023). They argue that materials from buildings not designed with circular construction principles, essentially the current building stock, are considered to be unsuitable for reuse, even under a circular scenario. Similarly, although van der Voet et al. (2025) mention reuse as a potential urban mining strategy, it is not further developed into scenarios.

However within the circular economy framework of so called R-principles, that are based on the Ladder of Lansink, reuse is prioritized over recycling. R-strategies typically range from 3 to 9 levels, aligned with Reduce, Reuse, and Recycle, where reduction is most preferred and recycling the least. (Zhang et al., 2021). These principles form a part of circular economy thinking, which aims to close and slow resource loops to reduce environmental impacts.

Reusing components can significantly reduce both emissions and resource consumption (Rakhshan et al., 2020). In contrast, recycling, particularly of materials such as concrete, often involves high energy use, additional emissions, and the need for supplementary raw materials (van Oorschot et al., 2023).

2.4 Reuse in practice

In addition, material reuse is already demonstrated at smaller scale in practice. Projects such as Kantoor vol Afval (reused brick panels, steel beams, and building systems) and Biopartner 5 (reused steel structure and partition walls) show feasibility within Dutch construction (PtSA, 2021; Rijksvastgoedbedrijf, 2024). Similar reuse potential has been explored in case studies, mainly in Scandinavia (Bellini, 2024; Glarborg et al., 2023). Different reuse supply chain models have been also described by Icibaci (2018).

For concrete, prefabricated elements (e.g. hollow-core slabs and wall panels) show the highest reuse potential due to standardisation, though in-situ elements can also be reused through cutting and reprocessing (Suchorzewski et al., 2023; Huuhka et al., 2015; Küpfer et al., 2022; Önalan et al., 2024). Benefits include reduced CO_2 emissions and land use (Küpfer et al., 2022). Dutch examples include Prinsenhof (up to 90% structural reuse) and Meijs Beton's concrete "transplantation" projects (Province Gelderland, 2026; Meijs Ingenieurs, 2025).

Steel reuse shows strong environmental and economic benefits, with up to 87% CO_2 reduction compared to recycling and 96% compared to new production (Bartsch, 2025; Selvaraj & Chan, 2024). Steel reuse is particularly promising for utility buildings (Kanyilmaz et al., 2023), as also demonstrated by the reused steel frame in Biopartner 5 (PtSA, 2021).

For wood, components such as beams, doors, and window frames are widely identified as suitable for reuse in the Netherlands (Icibaci, 2018). Timber reuse provides significant emission reductions and is already applied in several projects in the Netherlands, such as the reuse of timber frames in *KEVN* (Pronk et al., 2022).

For bricks, reuse potential is particularly high due to their durability, modularity, and widespread presence in the Dutch building stock. Bricks are well suited for reuse because of their long lifespan and "architectural flexibility" (Devos et al., 2024). They can be reused either as individual units or as larger sawn elements (brick panels). Recent literature shows that bricks bonded with cement-based mortars, commonly used in modern construction, can be recovered for reuse, further enhancing their circular potential (Salmio & Huuhka, 2026).

Circular building initiatives are increasingly driven by both policy and industry, including collaborations between governments and market parties. The *Transitieteam Circulaire Bouweconomie* brings together public and private stakeholders such as demolition companies and housing corporations to promote circular construction (CBE, 2026). In parallel, material marketplaces like New Horizon (2026), circular demolition practices by Meijs Ingenieurs & Uitvoering, 2025, and design-driven firms such as Superuse Studios (2026), put reuse into practice. Material passports are being developed for new buildings through platforms such as Madaster (2026), with plans to extend this to existing buildings (van der Voet et al., 2025). At the municipal level, Leiden has also introduced circular demolition policies (Gemeente Leiden, 2021).

Barriers to reuse have been examined in a systematic literature review on component reuse (Rakhshan et al., 2020), identifying technical, social, market, and legal challenges, including the lack of standardised deconstruction methods and inconsistent material quality. Similar issues, particularly the mismatch between supply and demand, are observed for concrete (Küpfer et al., 2022) and steel (Selvaraj & Chan, 2024).

2.5 Knowledge gap

There appears to be a significant need for reusing materials from buildings, including from buildings that were not originally designed with circularity in mind, from both a material usage and greenhouse gas (GHG) emissions perspective. Despite this importance, the urban mining possibilities and quantifications of component reuse of construction material flows have rarely been explored in literature.

At the municipal scale in Singapore, non-structural elements have been identified as recoverable urban resources with strong reuse potential when supported by appropriate policy and demolition practices (Arora et al., 2021). More recent MFA–LCA studies show that component reuse could reduce embodied GHG emissions by 5–8% by 2050 in Austria (Alaux et al., 2025) and highlight significant national reuse potential in Denmark, while

also emphasizing that implementation is constrained by spatial mismatches between demolition supply and construction demand (Hoxha & Birgisdottir, 2025).

To the best of my knowledge no scientific research has incorporated reuse in assessing and quantifying construction material flows in The Netherlands, despite the relative extensive research on urban mining. Integrating reuse into MFA in the Dutch context therefore forms the main knowledge gap of this thesis.

3. Research objective and research questions

In this thesis I aim to give insights into the material and component stocks of the Netherlands on national provincial and municipal scale, and their flows and reuse possibilities. The study aims to assess the reuse potential of materials of past demolition activities and match them with construction inflows for the years 2018–2023. So, it can be evaluated how the material demand, the inflow into in-use stock, could be met with reused materials, from the outflow from the in-use stock. For bricks this will be analysed in hypothetical retrospective scenarios alongside their environmental impacts.

3.1 Research aims

This research has five main goals:

1. Calculating the material stock of the Netherlands and the inflow, and outflow of materials between 2018-2023, focusing on concrete, steel, wood and bricks.
2. Identifying the reuse potential of building materials in the Netherlands.
3. Developing a framework that links MFA with reuse of building materials and components.
4. Evaluating potential synchronisation of material flows through reuse in the Netherlands, focusing on concrete, steel, wood and bricks.
5. Quantifying the environmental impact of reuse scenario for bricks.

3.2 Research questions

“To what extent can material reuse meet the demand by synchronising material flows in the built environment of The Netherlands from 2018 to 2023?”

The sub-research questions that will enable answering the research question are the following:

1. What is the material stock of The Netherlands in 2018 and 2023?
2. What quantities of materials become available, and where do they become available?
3. What quantities of materials are required, and where are they needed?
4. What is the reuse potential of materials and building types?
5. Can the material outflow be synchronised with the inflow considering reuse?
6. What insights can be derived from mapping and visualising spatial patterns of material flows?
7. To what extent can the material inflows be substituted by the material outflows?
8. What is the environmental impact of integrating material outflows into inflows through reuse?

For bricks, research questions seven and eight will be quantified through a scenario-based approach, enabled by available data on material intensities and reuse rates. For other materials this is not possible due to a lack of component-level data (see methodology).

4. Methodology

4.1. Research approach

The Mixed-Methods research approach of this thesis, visualised in Figure 1, is an embedded research design, that relies both on quantitative parts, including spatial modelling in GIS and a Material Flow analysis, as well as on a qualitative part, including stakeholder interviews. Combining qualitative and quantitative methods offers deeper insights than using either alone (Creswell & Plano Clark, 2017). In this case the input of local stakeholder knowledge allows for quantifications and analyses that are more grounded in the reality of the Dutch construction sector.

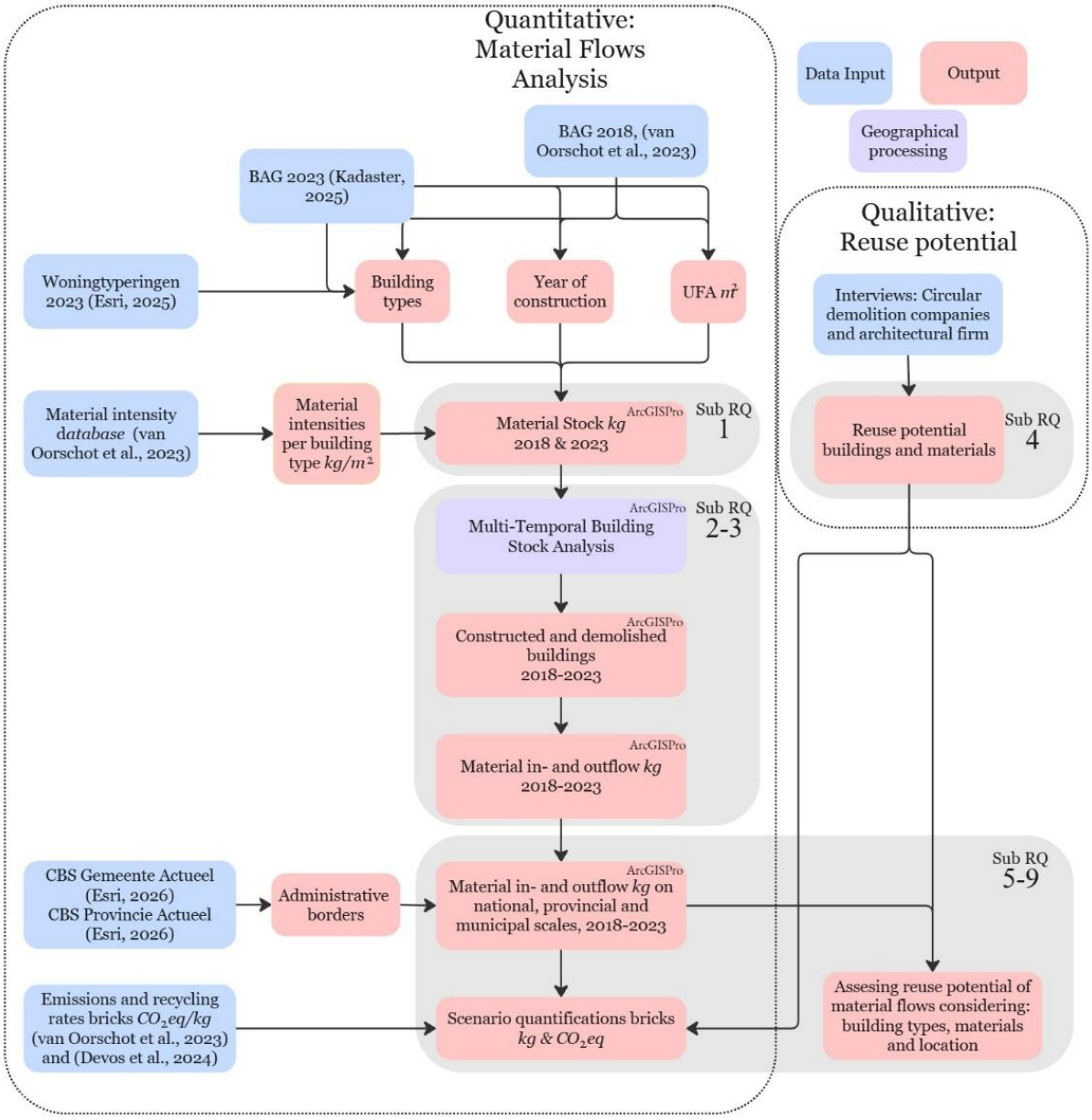


Figure 1:Research diagram

4.2. Qualitative; Expert interviews

In order to gain information on the reuse potential of buildings and components (sub research question 4), four exploratory expert interviews were conducted with demolition companies and architects, each lasting approximately 50 minutes. One participant provided additional information on brick reuse rates via post-interview correspondence.

Participants were selected using purposive sampling, meaning they were intentionally chosen based on their relevance to circular demolition and reuse in the Netherlands. They were identified through documented reuse case studies. The sample consisted of participants from three circular demolition companies and one architectural firm specialised in reused components, ensuring coverage of both supply (demolition) and demand (design) perspectives, see Table 1.

Table 1: Role and experience interview participants

Participant	Company	Role and experience
CDP 1	Circular demolition company	CDP 1 is the director of CDC 1, where they are responsible for demolition activities, inner-city projects, and innovation. CDP 1 has been with the company for around fifty years and is also online platform for selling used construction materials.
CDP 2	Circular demolition company	CDP2 is a program manager for circularity at CDC2, since 2018. With former experience in the IT sector.
CDP 3	Circular demolition company	CDP 3 works within the demolition company (10 years experience) on establishing collaborations and finding partners for the uptake of materials, ensures material inventories are carried.
CAP 4	Circular architecture firm	The interviewee (CA 1) is an architect who has been specifically designing for reuse since 2012, 13 years.

In total, seven organisations were approached, and data collection stopped after four interviews due to time constraints and because the sample already covered a substantial share of relevant circular demolition and reuse initiatives in the Netherlands.

The interviews were initially designed to collect data on component intensities and reuse rates. The original semi-structured interview protocol is provided in Appendix A.4.1. However, no quantitative component-level data was obtained due to limited availability and commercial sensitivity (Appendix A.4.2). Consequently, the interviews became more exploratory, focusing on reuse practices across components and building types.

The interview transcripts were analysed by reviewing and identifying text fragments relevant to reuse, which were then grouped into recurring themes. The analysis resulted

in several themes: reuse chains; material- and component-specific reuse practices; reuse of building types; and material and component inventory data. Technical summaries of the interviews can be found in Appendix A.4.

4.3 Quantitative

I performed an MFA to calculate the material stock and flows of the demolition and construction in The Netherlands (sub-research question 2-3) and to form a quantitative based analysis of reuse potential of the flows (sub-research question 5-9), see Figure 1.

4.3.1. Geographical and temporal scope

This research compares spatial data sets containing buildings as vector-based polygons in the Netherlands from 2018 and 2023. The spatial data layers have a high geometric resolution of 0.0001 meters, ensuring detailed representation of building. The years were selected both for their data availability and because a five-year interval allows for a more comprehensive capture of demolition and construction activities than a single year. This interval also helps to reduce the influence of outliers and provides a more representative picture of actual developments.

4.3.2. Material and components

Ideally, this research would have been conducted at the component level rather than the material level. Materials such as concrete can take many physical forms, including poured concrete, precast elements, concrete tiles, or hollow-core slabs, and are often combined with other materials, for example steel reinforcement in precast concrete beams, to form structural components.

Since reuse concerns the recovery of components rather than the reprocessing of raw materials, the relevant question is not how many kilograms of concrete are available, but how many specific components (e.g. hollow-core slabs) can be reused. A component-based approach would therefore better capture reuse potential, as also suggested by emerging work such as Alaux et al. (2025), who link component flows to reuse rates in Austria. Although this study was not yet available during the methodological design phase and is not fully transferable to the Dutch context, it provides useful direction for future research.

However, component-level data was not available in literature or interviews. Therefore, a material-based MFA approach was used as the most feasible method. While more aggregated, it still captures inflows and outflows and provides an initial estimate of reuse potential, serving as a framework that could be refined when more detailed data becomes available.

4.3.3. Material stocks

A bottom-up approach was used to calculate the material stocks, enabling stock estimation at the individual building-level, and aggregation flexibility across scales. A dynamic stock model, was considered but has limitations in the Dutch context. It does not

accurately reflect real-world construction and demolition patterns since buildings are often demolished before their technical end-of-life, while demolitions are rare in historic centres.

The spatial data processing and modelling were conducted in ArcGIS Pro 3.1.2. This software was used for spatial data cleaning, layer merging, spatial joins, multi-temporal building stock analysis, and aggregation of material flows across scales.

Figure 2 represents the steps to calculate the material stocks.

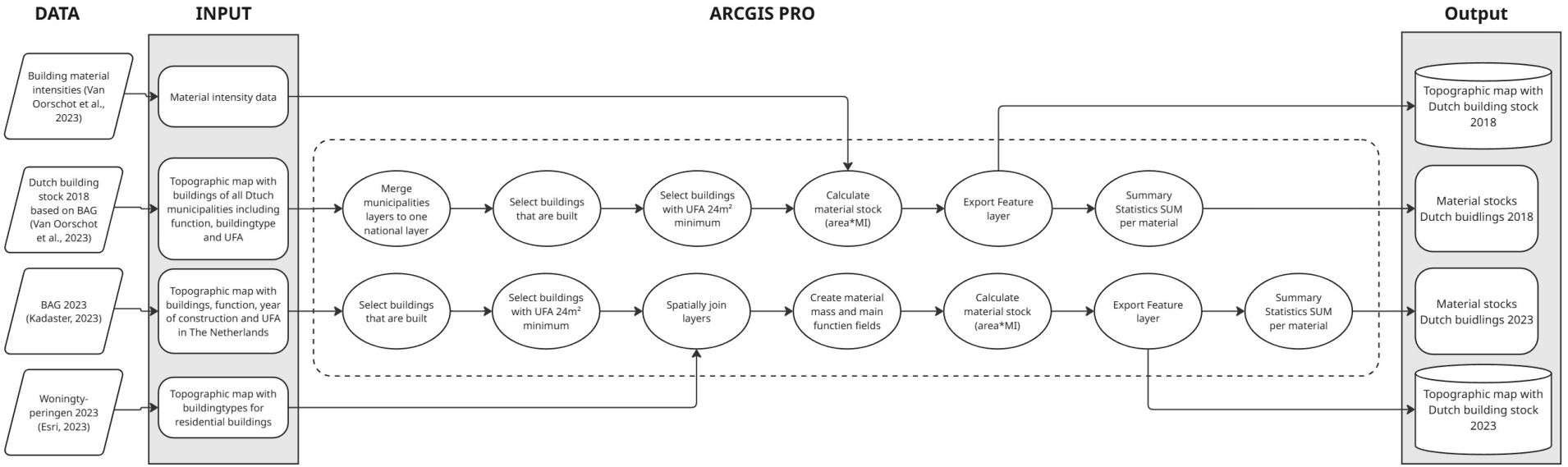


Figure 2 : Flowchart ArcGISpro material stocks

The calculation of the Dutch building stock of 2018 is based on the spatial datasets "voorraden_BAG_gem" from van Oorschot et al. (2023), that is derived from the BAG 2018 from *kadaster* and UFA from *kadaster.* These contained Usable Floor Area (UFA), function (e.g. office, industrial, retail), building type (e.g. apartment, row-house) and the construction year per municipality. The municipal layers were merged to one national layer. This data set also included material stocks, however to keep consistency with the 2023 data this was calculated using self-written code.

For the 2023 data BAG 2023 was used, this spatial dataset includes the usable floor area per building, its function, and the building year (kadaster, 2024). This dataset was spatially joined with the 'woningtyperingen_2023' to allow for building types for residential buildings (Esri, 2025).

This research differentiates between the building types: row house, detached house, apartment, retail, industry, office and services. Buildings smaller than 24 m^2 were excluded from the analysis since these mostly included sheds, lacking material intensity data and often leading to misclassifications of demolished buildings see Appendix A.1.3. Additionally, buildings with the status 'under construction' or 'permit applied' were excluded from the analysis since UFA data for these buildings were deemed unreliable.

Material stocks for both 2018 and 2023 were calculated using building material intensity values per building type from van Oorschot et al. (2023) according to the following equation:

$$M_{i,j,k,l}(kg) = MI_{j,k,l}(kg/m^2) \times UFA_i(m^2)$$

The material intensity $MI_{j,k,l}$ for each material j is determined as a function of building type k, construction year l, and UFA_i represents the usable floor area (m^2) of building i. The $M_{i,j,k,l}$ expresses the total mass (kg) of material j in building i, distinguished by building type and construction period. Python scripts were integrated within the ArcGIS Pro environment to perform the material stock calculations.

More information regarding modelling assumptions and codes can be found in Appendix.1.1.

4.3.4. Multi-temporal building stock analysis

To identify which buildings were constructed and demolished, this study developed a Multi-Temporal Building Stock Analysis (MTBSA), building on the approaches of Van Oorschot et al. (2023) and Van den Berghe & Verhagen (2021).

Various methods exist to detect demolition using spatial datasets over time. Miatto et al. (2018) use temporal layers but estimate outflows from lifetime assumptions rather than observed change. Guo et al. (2020) compare maps across time, but their GIS approach to identifying disappeared or replaced buildings is not clearly specified.

The MTBSA adopts the spatial comparison logic from Van Oorschot et al. (2023) and Van den Berghe & Verhagen (2021), where buildings are considered demolished if they

spatially overlap with newly constructed ones, but applies this to observed data rather than modelled or projected changes. In addition, MTBSA extends this approach by identifying buildings that have disappeared without being replaced.

4.3.4.1. Constructed buildings

To identify constructed buildings, buildings built after 2018 were selected in the 2023 layer through select by attribute 'year of construction'. A new layer "construction 2018-2023" was made from this selection, including its earlier calculated material stock.

4.3.4.2. Demolished buildings

To determine the demolished buildings, the MTBSA uses a combination of two spatial analysis procedures.

1. Type A buildings: Present in the earlier dataset but absent in the later dataset. A 'Select by Location'-operation was applied to the 2018 layer using the 2023 layer as spatial reference. The spatial relationship 'Intersect' was inverted, selecting features that no longer intersect. These features were classified as demolished without replacement.
2. Type B buildings: Demolished and replaced by new construction. Buildings from the 2018 layer that spatially intersect with the 'construction 2018–2023' layer were selected with the 'Select by Location'-tool.

The second selection was added to the first selection and made into a new layer, 'demolished buildings 2018-2023', which also includes its earlier calculated material stock.

UFA attributes were screened for anomalies, revealing one extreme outlier (UFA = 999999) in both datasets, these records were excluded. Additionally, a region with exceptionally high demolition density was identified and cross-verified using Google Maps and Google Earth imagery. The buildings were found not to be demolished and were excluded from analysis, see Limitations 7.1.2. for further explanation. Finally, building typologies were verified through random cross-checks of approximately twenty buildings, using Google Maps and Google Earth to confirm building type and function.

4.3.5. Material in- and outflow

The material inflow is defined as the material required for new construction during the study period, 2028 to 2023. This inflow is represented by the material stock in the layer 'construction 2018–2023'.

The material outflow is defined as material released through building demolitions during the same period. This outflow is represented by the layer 'demolished buildings 2018–2023'. A new field, mass total, was created to summarise material mass per building.

4.3.6. Provincial and municipal scales

To analyse the potential reuse (mis-)matches of the material in- and outflows on different geographical and governmental scales, I added provincial and municipal border layers to the spatial data sets.

1. The layer added for provincial borders and names is CBS Provincie Actueel (Esri, 2026).
2. The layer added for municipal borders and names is CBS Gemeente Actueel (Esri, 2026).
3. I summarized the material flows within both province layer and municipality layer, using the Summarize Within tool.
4. For municipalities I calculated the ratio of outflow to inflow by adding another field: $Percentage = outflow/inflow \times 100$

To capture regional and scale variations, the analysis focuses on two provinces (South Holland and Gelderland) and one municipality (The Hague). These were selected based on prior studies, including Van den Berghe & Verhagen (2021) and a study commissioned by the Province of South Holland (Metabolic, 2024), as well as their circular ambitions in construction, such as South Holland's focus on construction materials (Province of South Holland, 2024), The Hague's goal to be climate neutral by 2030 (Gemeente Den Haag, 2024), and Gelderland's support for circular construction projects (Province Gelderland, 2026). Additionally, the provinces represent contrasting contexts, with South Holland being more urbanised and Gelderland more agriculture-dominated.

I performed the following procedure to analyse the chosen regions:

1. Select by Attribute to select the province of Gelderland from the CBS Provincie Actueel layer.
2. Make a new layer from the selected features.
3. Perform a Pairwise Clip using the new layer.
4. Repeat the same procedure for the province of South Holland, and for the municipality of The Hague, using the CBS Gemeente Actueel layer.
5. I summarized the material fields using Summary Statistics and adding building type as a statistics field to get the kg material per building type. These outcomes were copied into Excel.

At the municipal scale, visual validation compared building footprints with mapped material mass distributions. Discrepancies were checked using Google Earth and Google Maps, revealing one retail building that could not be identified in satellite imagery, likely due to a registration error; it was therefore excluded from further analysis.

4.3.7. Material flows for reuse

An important insight from the interviews is that reuse mainly occurs between similar building types, as they require comparable components. This informed the analysis of

material flows by building typology and spatial scale, providing an indicative framework for assessing circular potential in the absence of component-level data.

While reuse construction research often focuses on office, utility buildings, this study also includes residential types due to the Dutch housing shortage. Material flows are therefore analysed across multiple scales for four categories: houses, apartments, offices, and industrial buildings.

4.3.8. Brick scenarios

Since bricks as a material closely correspond to the component level, and reuse data was available from interviews and literature, reuse could be quantified based on calculated material flows. Therefore, three hypothetical retrospective scenarios were developed. These are counterfactual scenarios representing alternative histories for 2018–2023 under different policy and practice conditions. The business-as-usual scenario serves as a baseline reflecting conventional construction and demolition practices in the Netherlands, while the recycling and reuse scenarios illustrate what could have been achieved if circular strategies had been more strongly implemented in the past.

The purpose of these scenarios is to show, on a national and quantitative level, the potential impact of circular strategies on brick flows. By applying "what-if" scenarios to historical material flows, the analysis makes it possible to estimate the effects of interventions that did not actually occur. This is useful for informing current policy, as it provides insight into the likely impact of similar measures in the future, assuming broadly similar construction and demolition patterns.

4.3.8.1. Scenarios

Business-as-Usual (BAU) scenario

In the Business-as-Usual scenario, bricks are recycled according to the conventional scenario found in van Oorschot (2023): recycling rate 1% and waste 99%.

$$Recycled\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 0.01$$

$$Waste\ (kg) = Outflow\ bricks\ (kg) \times 0.99$$

$$Inflow\ virgin\ produced\ \ bricks\ (kg) = inlow\ bricks\ (kg)$$

Recycling scenario

In the recycling scenario the outflow of bricks is recycled according to the recycling best practice rate from Oorschot et al. (2023): recycling rate 95% and waste 5%.

$$Recycled\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 095$$

$$Waste\ (kg) = Outflow\ bricks\ (kg) \times 0.05$$

$$Inflow\ virgin\ produced\ \ bricks\ (kg) = inlow\ bricks\ (kg) - recycled\ bricks\ (kg)$$

Reuse scenario

A reuse scenario, using the reusable brick material outflow for substituting the material inflow, is designed. Based on information provided by the interviewees the reuse rate of bricks in The Netherlands was assumed to be 80% for bricks from buildings before 1970 (category A) and 40% for buildings after 1970 (category B), see appendix A.1.5. for modelling details.

$$Cat\ A_{<1970}: reusable\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 0.8$$

$$Cat\ B_{>1970}: reusable\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 0.4$$

The leftover outflow is treated as the recycling scenario, so at the best practice recycling rate. (Oorschot, 2023)

$$Cat\ A_{<1970}: recycled\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 0.8 \times 0.2 \times 0.95$$

$$Cat\ B_{>1970}: recycled\ bricks\ (kg) = Outflow\ bricks\ (kg) \times 0.6 \times 0.95$$

$$Cat\ A_{<1970}: waste\ (kg) = Outflow\ bricks\ (kg) \times 0.2 \times 0.05$$

$$Cat\ B_{>1970}: waste\ (kg) = Outflow\ bricks\ (kg) \times 0.6 \times 0.05$$

$$Inflow\ virgin\ produced\ \ bricks\ (kg) = inflow\ bricks\ (kg) - recycled\ bricks\ (kg) - reused\ bricks$$

4.3.8.2 Environmental impact

The environmental impact of the brick scenarios was calculated based on CO_2-eq. emissions of recycling, primary production and waste disposal by Oorschot et al. (2023) by conducting a Life Cycle Assessment (LCA), see Appendix.1.2. According to a LCA conducted by Devos et al. (2024) reusing bricks reduces emissions by about 88–89% (kg CO_2-eq.) compared to new production, depending on brick type, mortar, and whether processing is manual or mechanical. Based on this an overall reduction of 88% on CO_2-eq. emissions for reuse of bricks is assumed in this research.

Per scenario the following calculations were made in Excel:

$$E_{scenario} = m_{reuse}\, e_{reuse} + m_{recycle}\, e_{recycle} + m_{waste}\, e_{waste} + m_{virgin}\, e_{virgin}$$

Where $E_{scenario}$ is the total greenhouse gas emissions per scenario (kg CO_2-eq.), m_i the mass flow (kg), and e_i the emission factor (kg CO_2-eq./kg) for the brick pathways $i \in$ {reuse, recycle, waste, virgin}.

5. Results

5.1. Qualitative Reuse in practice

An overview of the interviewees of their respective roles within reuse chains and relevant information on component and building reuse potential is provided below.

Table 2:Main findings interviews

Main findings	Sources (Interviews)	Notes
Bricks are highly reusable, have established reuse chains, financially viable, and are interchangeable between building types. The required deconstruction takes more time than conventional demolition.	CDC 1-3, CAF 1	Bricks are highly reusable CDC 1-3, CAF1; supported by established reuse chains CDC 1-3; financially viable explicitly mentioned in CDC 1-2; interchangeable between building types mentioned in CDC 1-2; time requirements mentioned in CDC 3.
Concrete and steel components can be reused between similar utility buildings, such as offices, beyond pilot scale.	CDC 2, CAF 1	Concrete and steel components have been reused in (pilot) projects of CDC 1-3 and CAF 1; CDC 2 and CAF 1 mention the reuse of concrete and steel components in similar utility buildings as part of their (beyond pilot scale) work activities
Reuse potential varies more by component than by material; for example, in-situ cast concrete has a different reuse potential compared to hollow-core slabs.	CDC 1-3, CAF 1	Reuse potential varies more by component than by material CDC 1-3, CAF 1; in-situ cast concrete has a different reuse potential compared to hollow-core slabs, example mentioned by CAF 1.
Reuse chains and reused materials differ in between companies	CDC 1-3, CAF 1	This is elaborated on per interview in the section below
Work activities differ in between circular demolition companies	CDC 1-3	This is elaborated on per interview in the section below

1. *Circular Demolition Company 1 (CDC1) Reuse chain*

   CDC 1 operates nationally and occasionally in Germany, focusing on demolition projects without linked new construction. As shown in Figure 3, the process starts with a demolition request, after which selected components (including hardwood doors and bricks) are recovered, processed, and reintroduced to the market. A pilot involving reuse of larger structural components (e.g. steel and hollow-core slabs) proved economically unviable due to issues like dimensional mismatches and certification requirements. The company therefore focuses on making specific building material streams circular, such as hardwood, bricks, and sees potential in solutions like national brick reuse hubs.

2. *Circular Demolition Company 2 (CDC2) Reuse chain*

   CDC 2 operates nationally and often works with property owners planning demolition or redevelopment. By anticipating future demolitions, they can strategically match components, such as steel and concrete to new building projects. As shown in Figure 3, the process starts from a construction request.

They identify similar buildings scheduled for demolition as donor buildings and model them in 3D to assess available components. This approach is only applied when a matching project is secured, ensuring financial viability. Collaborations with universities for testing and certifying of the components also keep the costs down. Unused components are recycled or disposed of. CDC 2 mainly reuses steel and concrete in utility buildings, while brick reuse can occur across different building types.

3. *Circular Demolition Company 3 (CDC3) Reuse chain*

CDC 3 operates nationally and begins with a demolition request (Figure 3). It facilitates reuse by connecting parties, rather than investing in its own processing hubs, relying instead on specialized partners. For CDC 3 reuse depends on finding partners willing to take responsibility for materials, which is often difficult due to limited timelines (typically four weeks for pricing and eight weeks before construction). In a pilot with a one-year preparation period, up to 90% of materials were reused. However, for many components, such as hollow-core slabs, reuse pathways are lacking. For bricks, established partners (ReBrick and Klinkhistorica) enable reuse when sufficient time is available for required deconstruction.

4. *Circular Architectural Firm 1 (CAF 1) Reuse chain*

The architecture firm starts with a project request, Figure 3, and then sources matching components from buildings scheduled for demolition through its network. These components are integrated into the new design. This approach is viable; in one case, an entire steel structure was reused at no extra cost. They primarily reuse steel, concrete, and brick components between utility buildings. Reuse is very much component-specific e.g., concrete elements differ by type, and brick reuse depends on the mortar: cement-bonded bricks are reused as slabs, while lime-mortar bricks are reused individually.

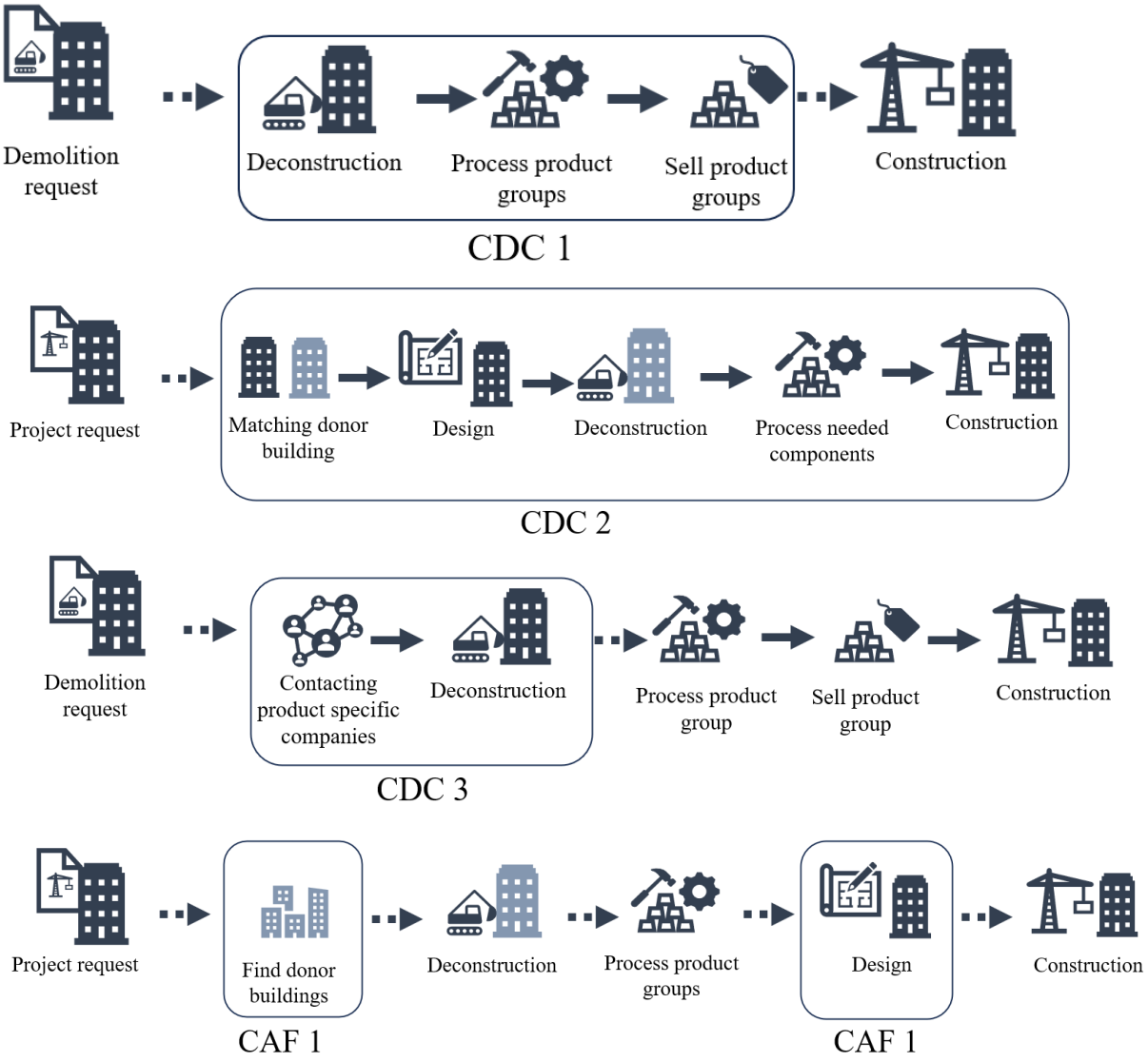


Figure 3: Reuse chain of Circular Demolition Company 1-3 and Circular Architectural Firm 1

5.2. Quantitative

5.2.1. Stocks

The material stock of buildings in The Netherlands in 2018 and 2023, as seen in Figure 4, was calculated based on the spatial data and material intensities. The material stock in 2018 is 2.65 Mega tonnes. For 2023, the calculated material stock is 2.90 Mega tonnes.

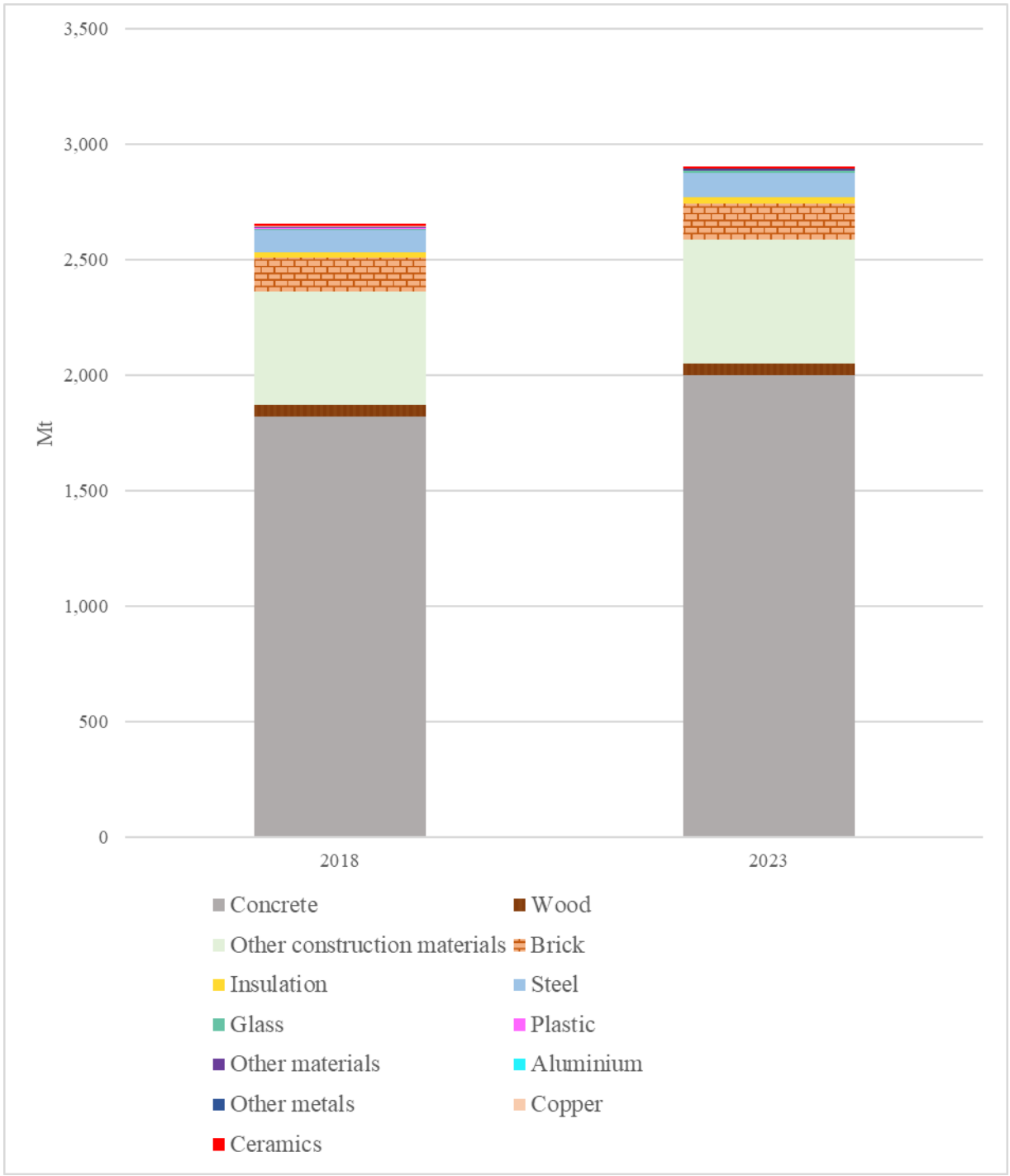


Figure 4 Material stock buildings The Netherlands 2018 & 2023

The stocks appear to consist largely of the same material shares, Table 3, with slight differences, including an increase in concrete, steel, and insulation, and a decrease in ceramics and bricks. Concrete, other construction materials, brick, steel, and wood make up most of the Dutch building stock and will be elaborated on in the results.

Table 3: Percentages materials in Dutch building stocks

Material	% of stock 2018	% of stock 2023
Concrete	68.61%	68.78%
Wood	1.79%	1.80%
Other construction materials	18.50%	18.38%
Brick	5.55%	5.46%
Insulation	0.88%	0.89%
Steel	3.67%	3.71%
Glass	0.21%	0.21%
Plastic	0.09%	0.09%
Other materials	0.12%	0.12%
Aluminium	0.09%	0.09%
Other metals	0.07%	0.07%
Copper	0.02%	0.02%
Ceramics	0.40%	0.38%

5.2.2. Demolition and construction

The maps shown in Figures 5 and 6 showcase the location of buildings that were demolished and constructed between 2018 and 2023 with dots sized accordingly to the total mass of materials in tonnes of the buildings.



Figure 5 : Map with the demolished buildings in The Netherlands between 2018-2023, dots scaled to mass of demolished buildings



Figure 6 : Map with the constructed buildings in The Netherlands between 2018-2023, dots scaled to mass of constructed buildings

The map in Figure 7 illustrates the percentage ratio of material outflow (total material mass in kilograms from demolished buildings) to material inflow (total material mass in kilograms for newly constructed buildings). The observed values range from 0–10% to 120–160%, with a substantial part around 20–40%, including the municipality of The Hague (21%).

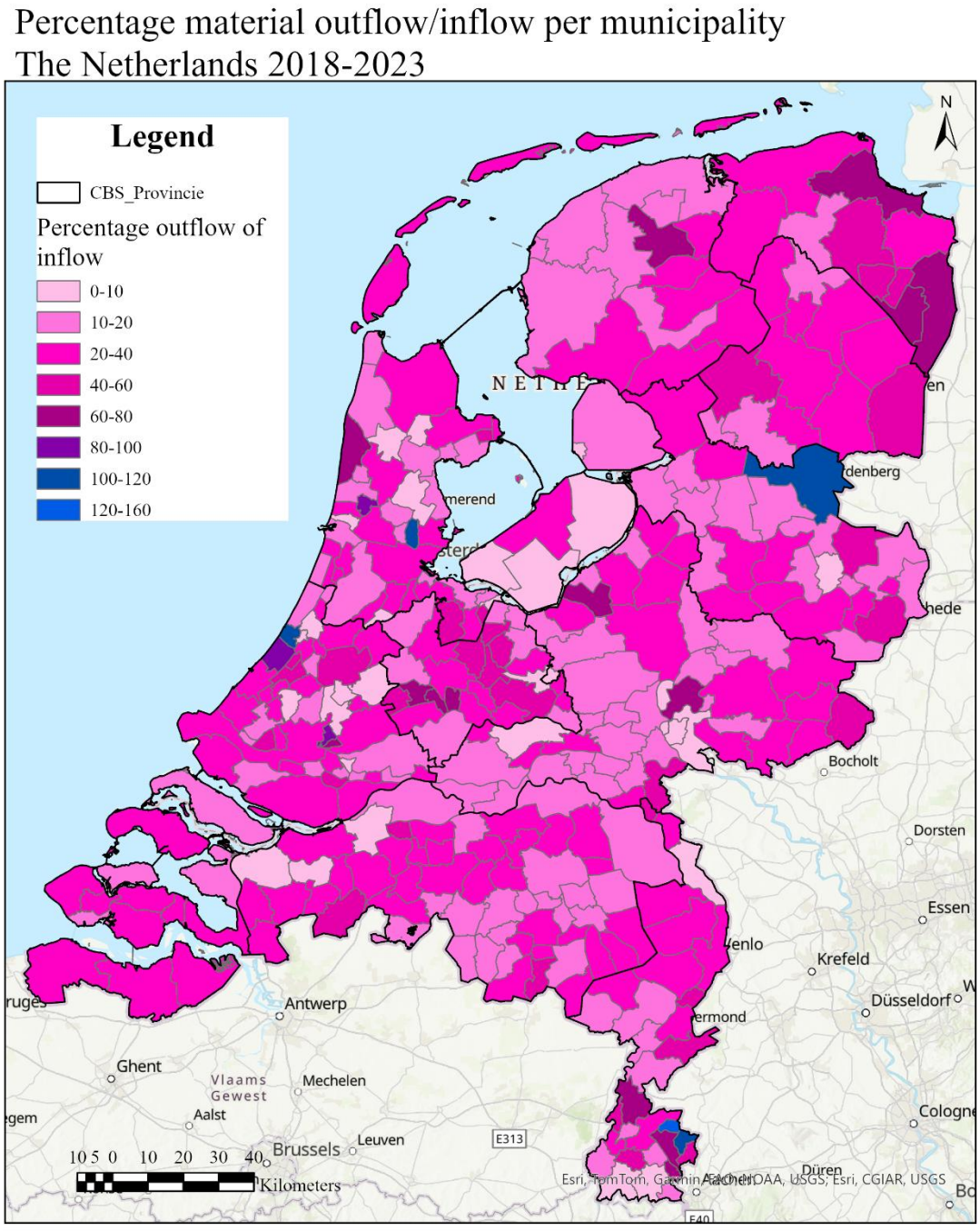


Figure 7 : Map of The Netherlands presenting the percentage of released material from demolished buildings of the demand of material for constructed buildings (outflow/inflow) per municipality 2018-2023

5.2.2. Structural material flows

Figures 8-11 present the quantities of concrete, steel, wood and bricks that became available through demolition of buildings and the quantities required for new construction between 2018 and 2023 in The Netherlands. The results are disaggregated by building type, based on the information gathered from the interviews that component reuse for concrete and steel containing components is most likely to occur within similar buildings and building types.

5.2.2.1. National scale

At the national level, a substantial higher inflow (the demand needed for construction) than outflow (materials released through demolition) can be observed for concrete, steel in both industrial and residential buildings. For offices, on the other hand, the in- and outflow of concrete and steel are more similar.

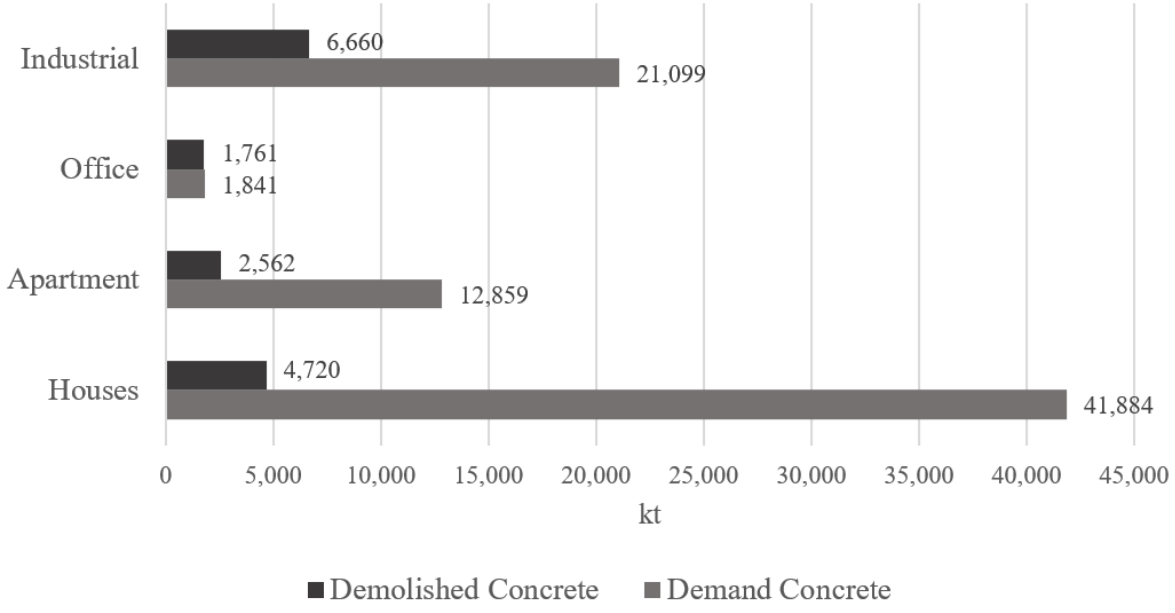


Figure 8 Concrete Flows from demolished and constructed buildings in The Netherlands 2018-2023

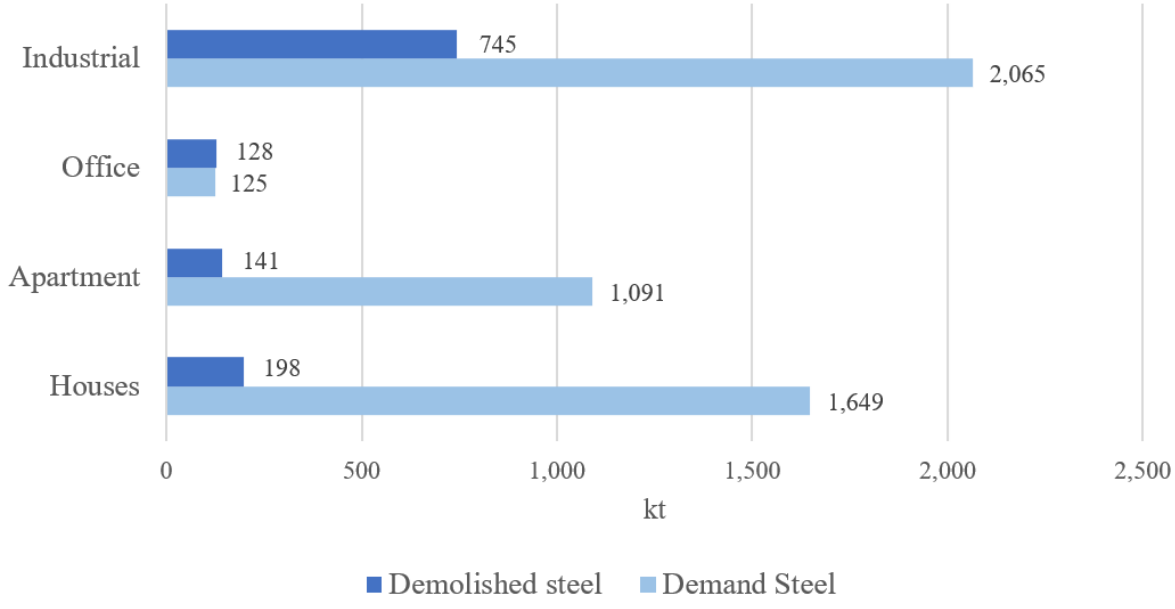


Figure 9 Steel Flows from demolished and constructed buildings in The Netherlands 2018-2023

Looking at, wood and brick (Figures 10, 11) the inflow is significantly larger than the outflow for residential buildings. For industrial and office buildings the wood inflow is smaller than the outflow. For offices this is also the case for brick in- and outflow. On the contrary, for industrial buildings the brick inflow (demand) is larger than the outflow (demolition).

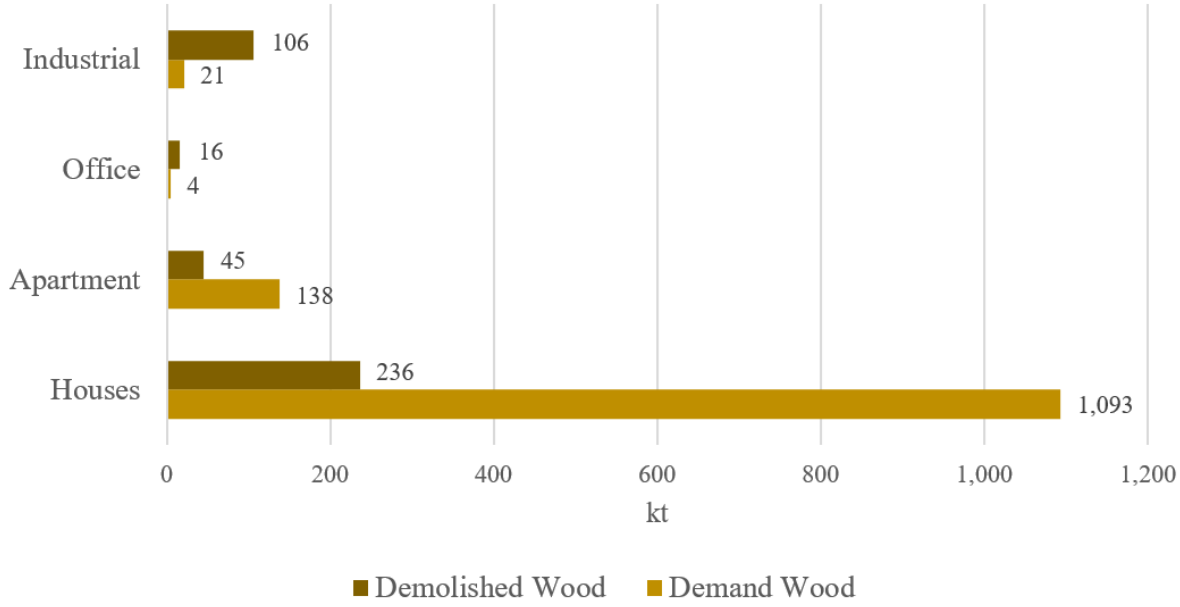


Figure 10 Wood Flows from demolished and constructed buildings in The Netherlands 2018-2023

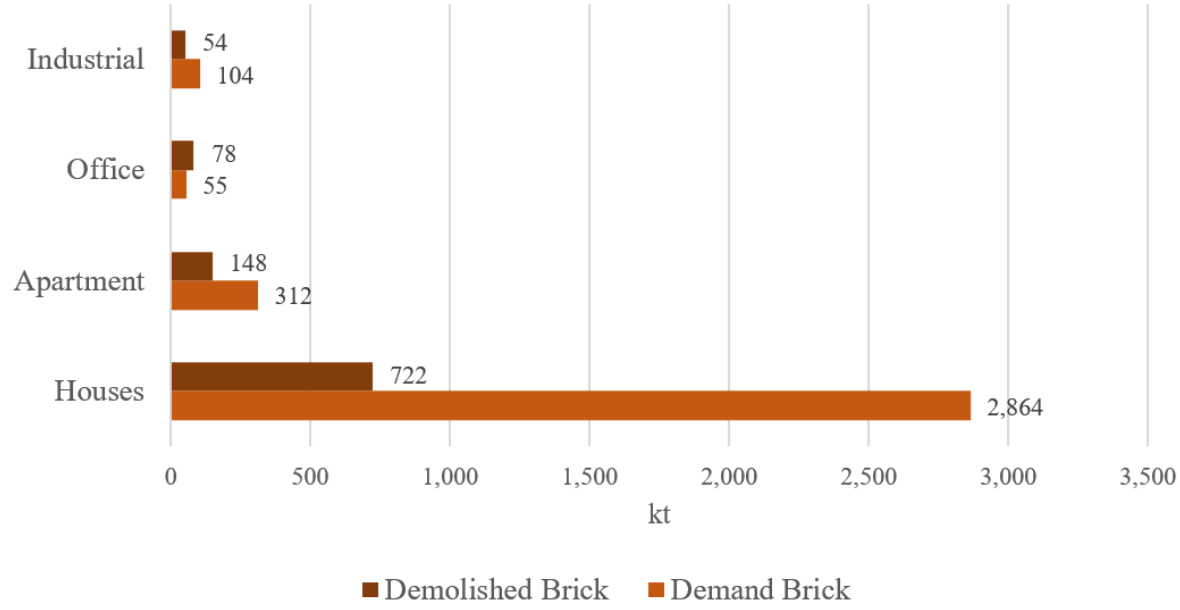


Figure 11 Brick Flows from demolished and constructed buildings in The Netherlands 2018-2023

5.2.2.2. Provincial scale

At the provincial scale (South Holland and Gelderland), Figures 12–15 show similar patterns to the national level. For concrete and steel, residential and industrial buildings have lower inflows than outflows, while office buildings show more balanced flows. For wood, residential inflows exceed outflows, whereas industrial and office buildings show lower inflows than outflows. For brick, residential inflows are higher than outflows; office buildings show lower inflows than outflows, while industrial buildings show the opposite pattern with higher inflows than outflows.

Material in- and outflows for all four materials are higher in South Holland than in Gelderland. For residential buildings, the balance differs: South Holland shows higher material demand than demolition supply.

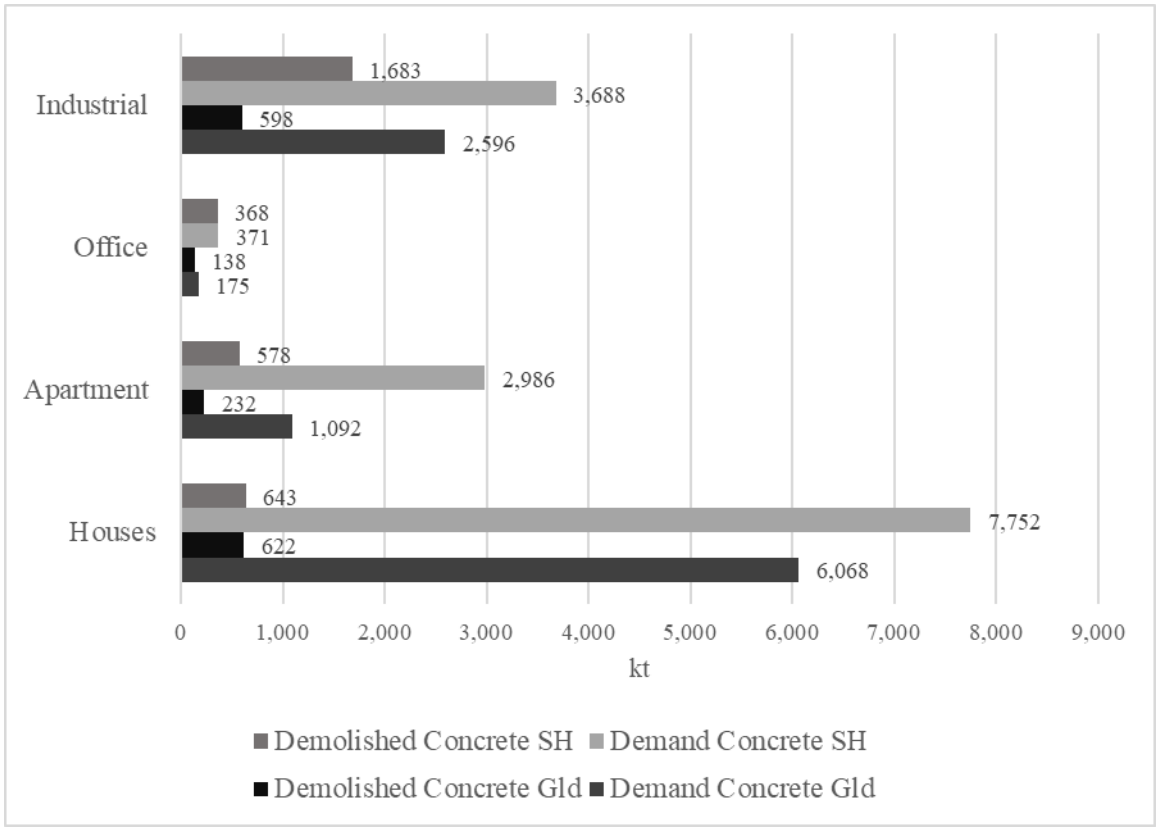


Figure 12 Concrete Flows from demolished and constructed buildings in Gelderland and South Holland 2018-2023

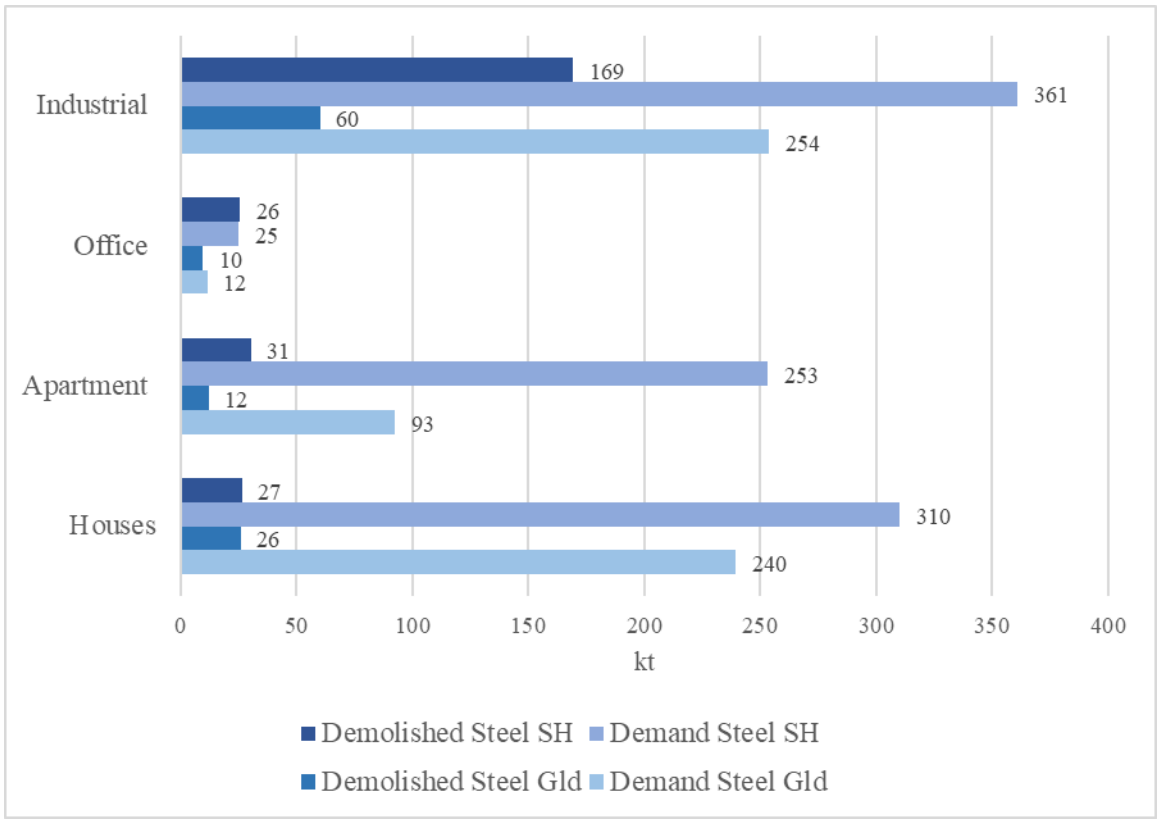


Figure 13 Steel Flows from demolished and constructed buildings in Gelderland and South Holland 2018-2023

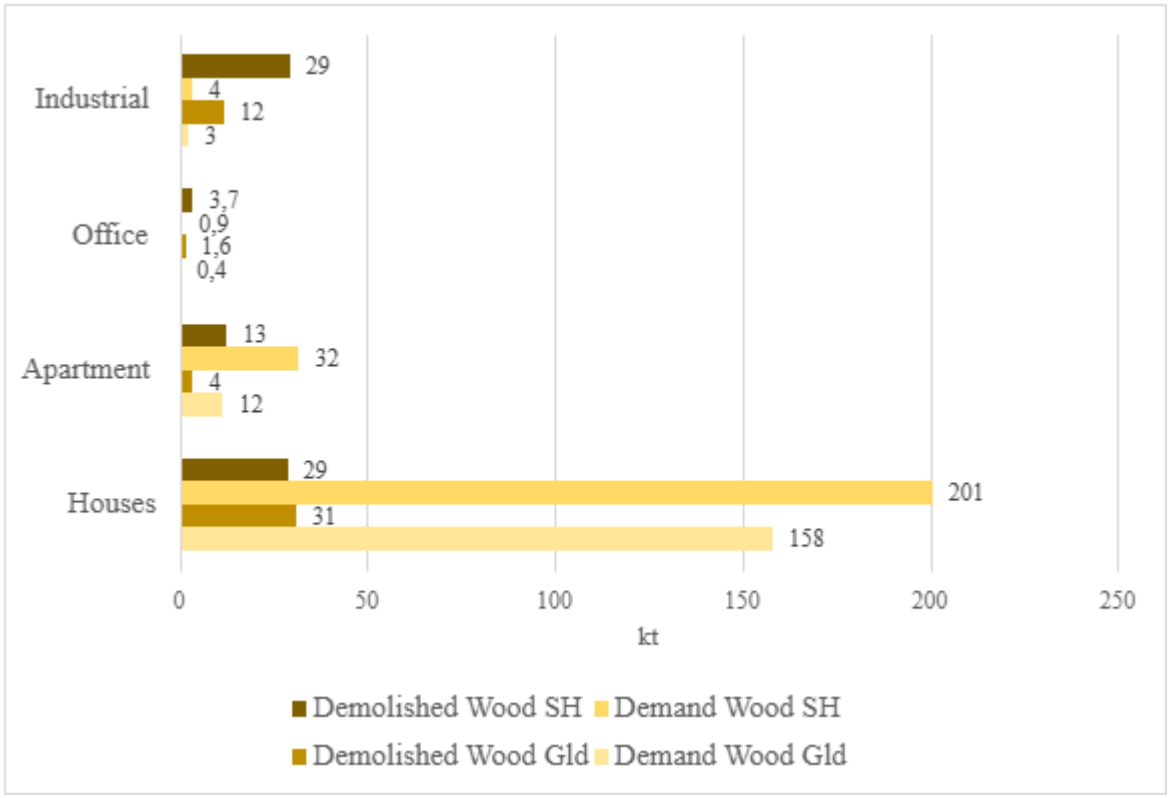


Figure 14 Wood Flows from demolished and constructed buildings in Gelderland and South Holland 2018-2023

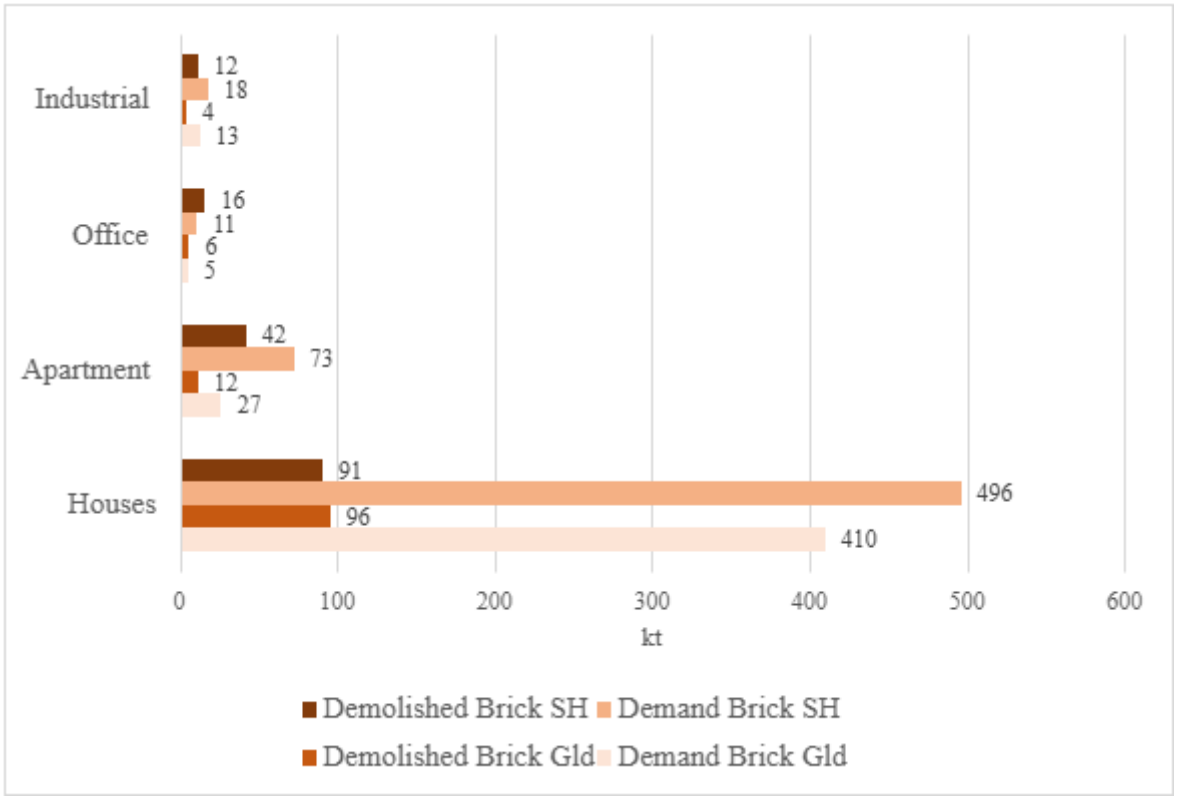


Figure 15 Brick Flows from demolished and constructed buildings in Gelderland and South Holland 2018-2023

5.2.2.3. Municipal scale

At the municipal scale, focusing on the Municipality of The Hague, somewhat different trends can be noted in the material flows seen in Figures 16-19. Industrial buildings show more equal in- and outflows than on the national and provincial scale, while office buildings show relatively higher material outflows than the inflows required for new construction. Additionally, residential buildings demonstrate comparatively higher demand, inflows, alongside lower outflows.

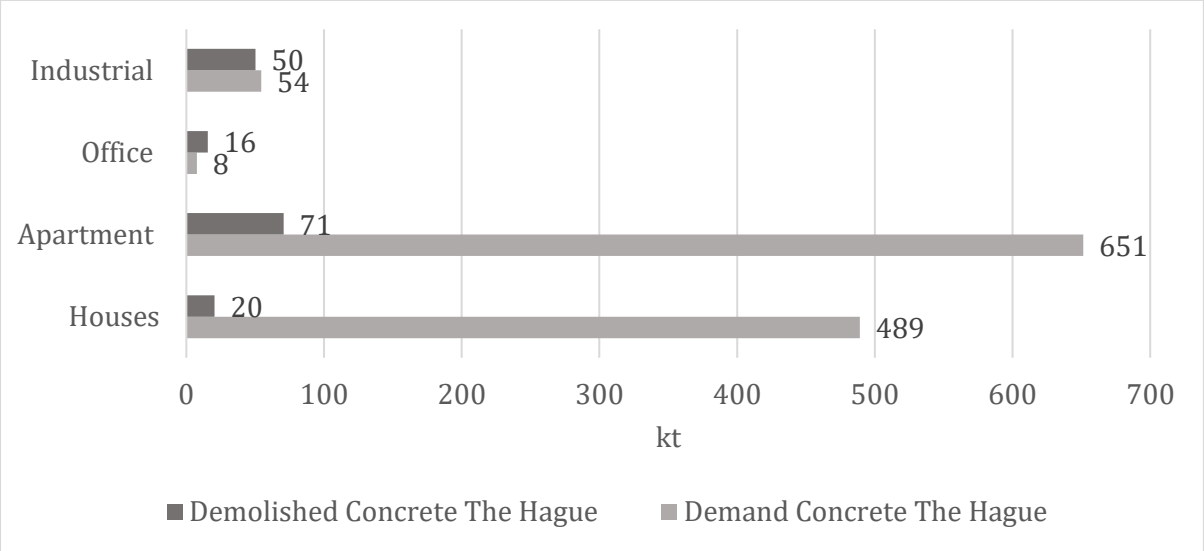


Figure 16 Concrete Flows from demolished and constructed buildings in The Hague 2018-2023

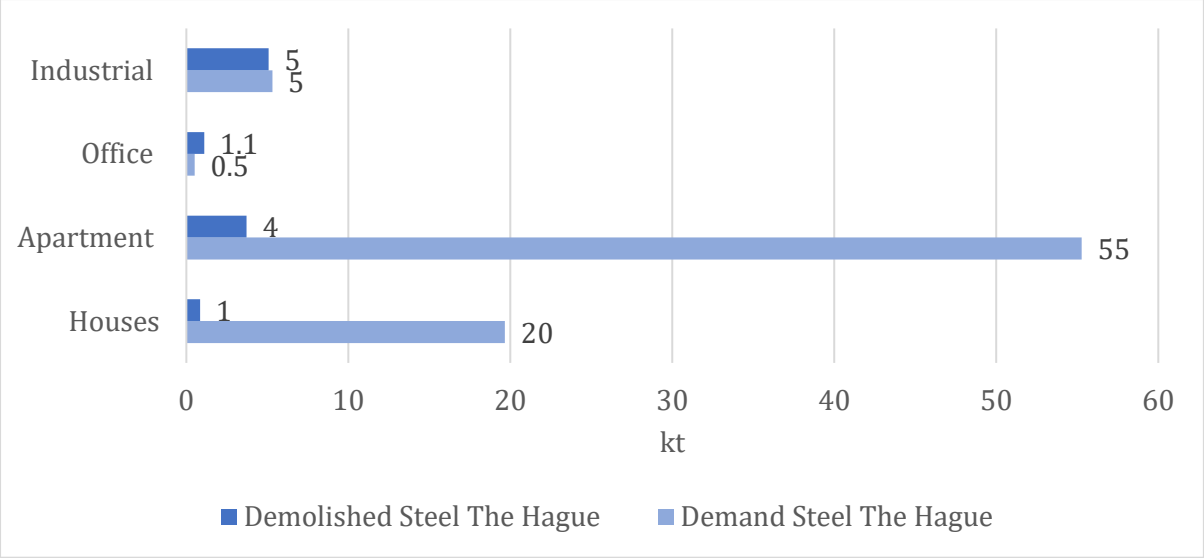


Figure 17 Steel Flows from demolished and constructed buildings in The Hague 2018-2023

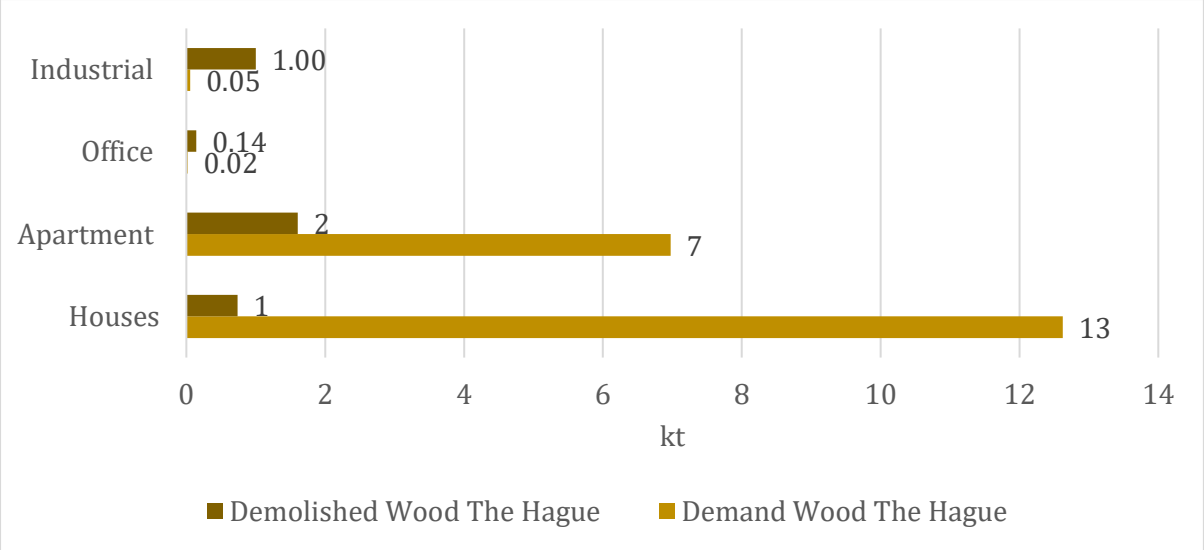


Figure 18 Wood Flows from demolished and constructed buildings in The Hague 2018-2023

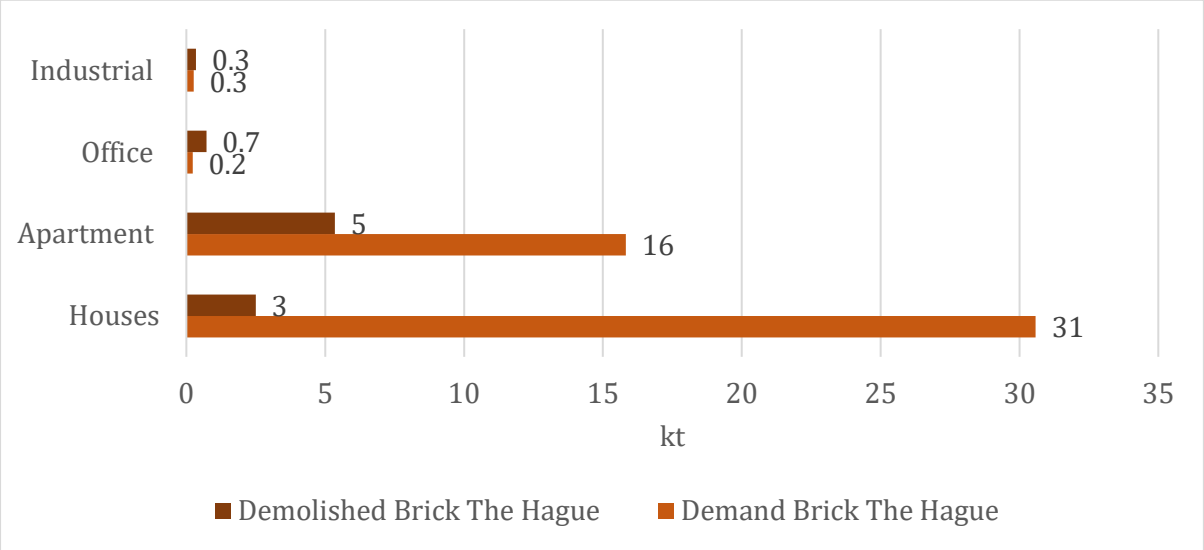


Figure 19 Brick Flows from demolished and constructed buildings in The Hague 2018-2023

5.2.2. Bricks scenarios

Based on the national material in- and outflows the brick flows for three hypothetical scenarios are calculated: Business-as-Usual, Recycling and Reuse. Sanky-diagrams of the scenarios are presented in the following. As explained in the methodology, the scenarios account for varying brick material intensities by building type and combine recycling, reuse, and waste in the outflow. The reuse scenario applies different reuse rates for pre- and post-1970 buildings due to mortar changes and assumes bricks can be reused across building types based on interview insights.

5.2.2.1. Scenario Business-as-Usual

Figure 20 shows the Sanky diagram of the BAU scenario in kt. This scenario aims to model the material flows of bricks from 2018-2023 based on current recycling and production practices in The Netherlands. Approximately 15 kt brick outflow is recycled back into construction. The construction of new buildings relies for 99,9% on primary production of bricks, ~4000 kt.

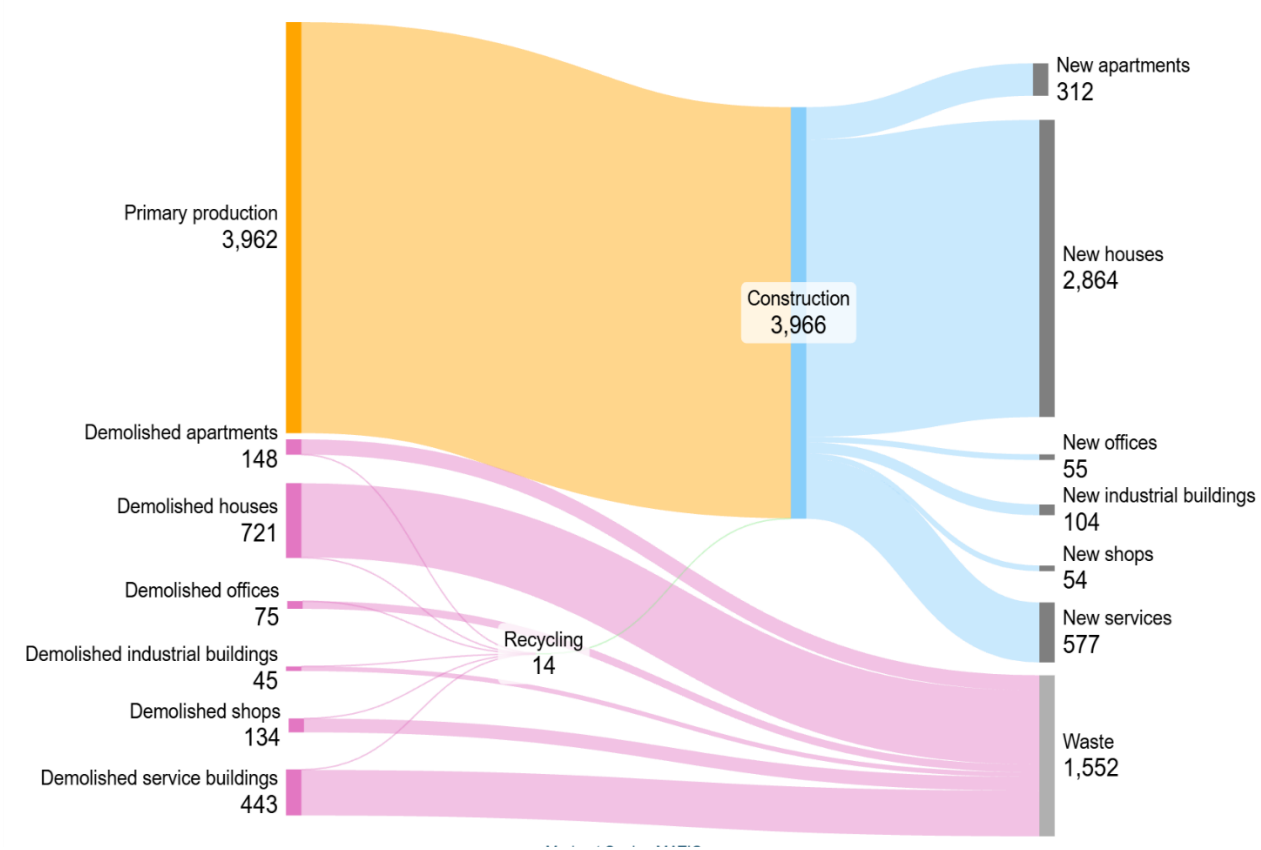


Figure 20 : Brick flows in kt The Netherlands 2018-2023 Business-as-Usual scenario

5.2.2.2. Scenario Recycling

Figure 21 seen below visualizes the Recycling scenario in kt, showcasing how the outflow of bricks in The Netherlands from 2018-2023 could possibly have been synchronized with the inflow on a national scale based on best practice recycling rates. In total 38% of the amount of bricks needed in construction would be made from recycled bricks, this is equal to 1490 kt. The needed primary production in this scenario is ~2500 kt.

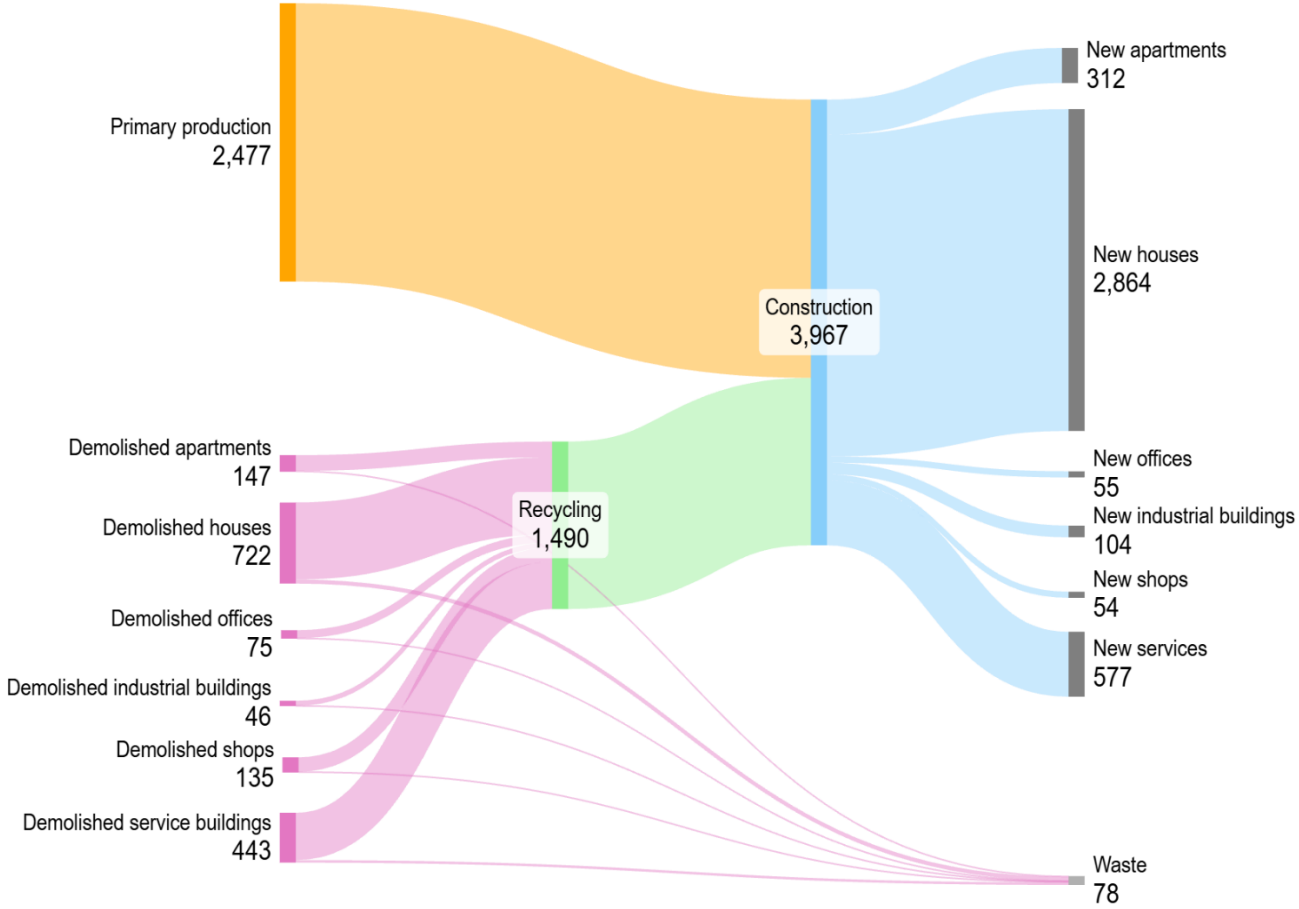


Figure 21 : Brick flows in kt The Netherlands 2018-2023 Recycling scenario

5.2.2.3. Scenario Reuse

Figure 22, below, visualizes the Reuse scenario in kt, showcasing how the outflow of bricks in The Netherlands from 2018-2023 could possibly have been synchronized with the inflow on a national scale by implementing a both the reusing and recycling of bricks. In total 26% of the bricks needed in construction would be reused bricks, this is equal to 1038 kt. The associated primary production is ~2400 kt.

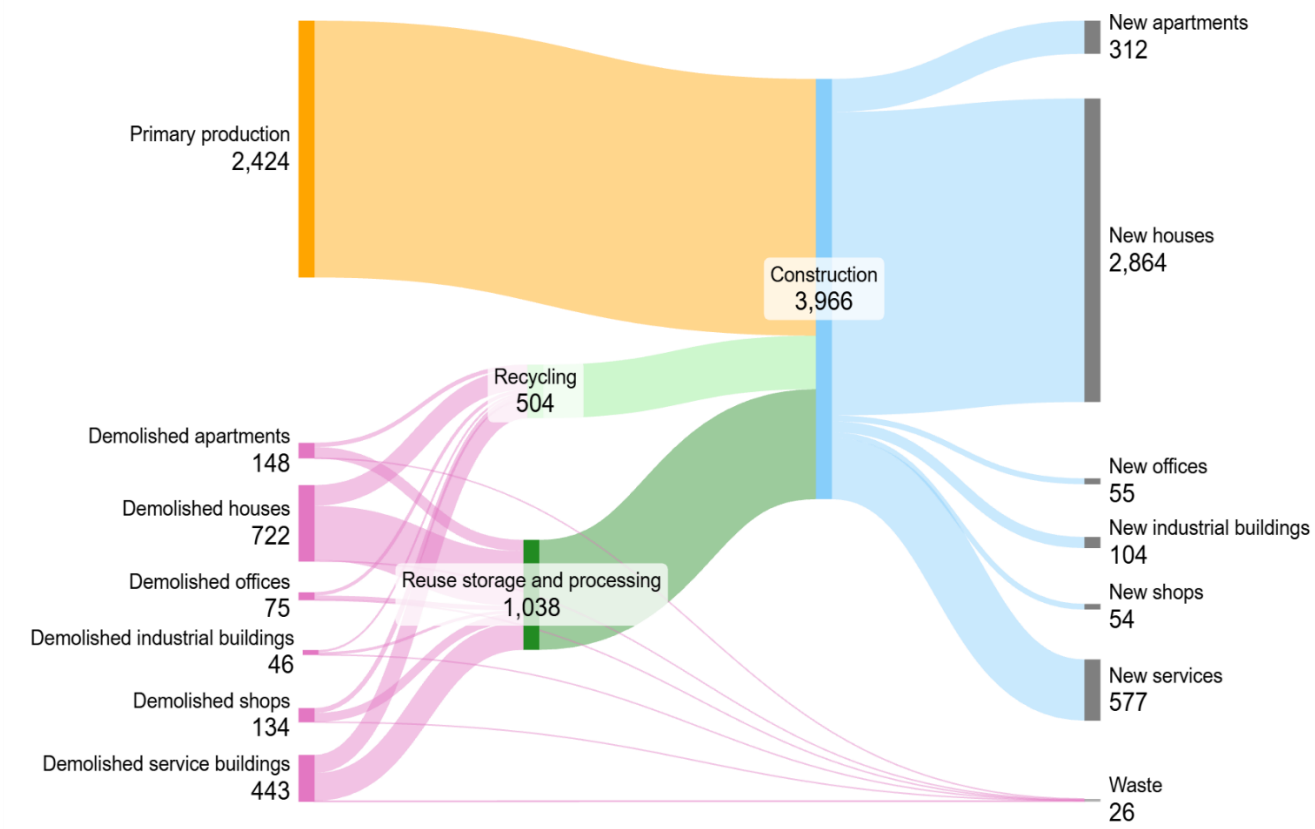


Figure 22: Brick flows in kt The Netherlands 2018-2023 Reuse scenario

5.2.3. Emissions scenarios

The corresponding emissions of the production and waste associated with the scenarios were calculated, see Figure 23 below. The BAU scenario has the highest emission with 1,270 kt CO_2-eq. The Recycling scenario has a lower emission with 936 kt CO_2-eq. The Reuse scenario, 732 kt CO_2-eq., has 538 kt CO_2-eq. less compared to the BAU scenario.

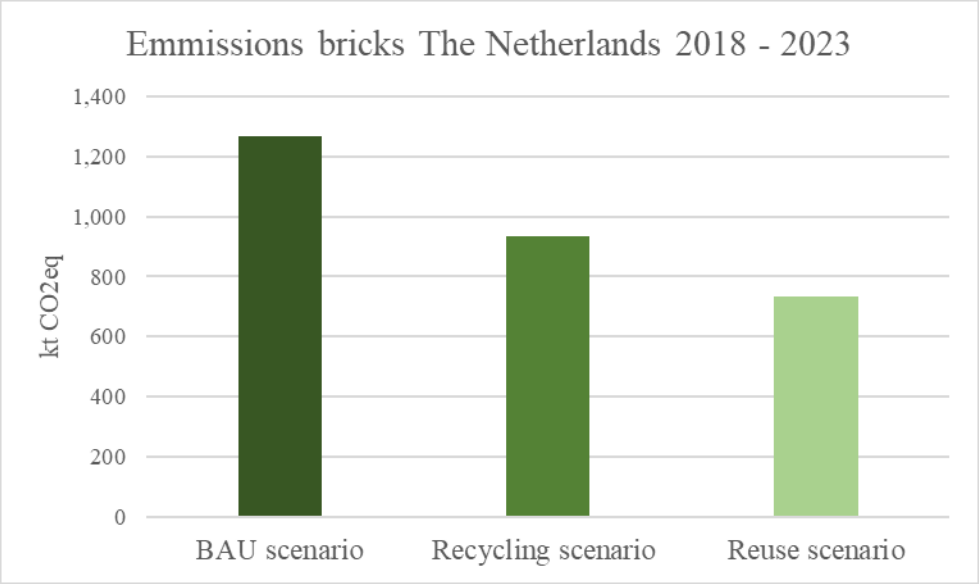


Figure 23 : Emissions associated with the three brick material flow scenarios 2018-2023

6. Discussion

6.1. Reuse of material flows

Sub-RQs 1–3 (material stock, outflows, and inflows) have been addressed through the quantitative MFA results, and Sub-RQ 4 (reuse potential of materials and building types) through the presented qualitative findings. Below these will be discussed to answer Sub-RQs 5, 6 and 7 (flow synchronisation, spatial insights and substitution potential), and for bricks Sub-RQs 7 and 8 (substitution potential and environmental impact) are answered through the scenario analysis for bricks.

6.1.1. Brick Reuse

Scenarios

Trough the scenarios this study contributes to the academic discourse on urban mining and responds to the call by Van der Voet et al. (2025) for the development of scenario-based approaches to explore the potential of the urban mine in the Netherlands.

Under the reuse scenario, salvaged bricks could meet ~26% of Dutch brick demand (2018–2023), equivalent to 0.8% of total material inflow. Compared to BAU, this reduces primary production by ~1.54 Mt and emissions by ~42% (538 kt CO_2-eq.). Given that based on the conventional scenario from van Oorschot et al. (2023) bricks account for ~11% of cumulative construction-related emissions for 2018–2050 (Appendix A.5), this indicates substantial national mitigation potential.

The gap between reuse and BAU is larger than between reuse and recycling, highlighting recycling as a complementary strategy.

These results are based on two key assumptions:

1. Bricks are transferable across building types due to standardisation, enabling redistribution of surpluses (e.g., offices or housing).
2. Reuse rates differ by construction period: 80% for pre-1970 chalk-bound masonry and 40% for post-1970 cement-bound masonry. These rates are based on stakeholder interviews and in line with by literature (Devos et al., 2024; Salmio & Huuhka 2026). Cement-based recovery rates align with findings by Salmio & Huuhka (2026), who report reclamation rates of 24–38% depending on processing methods.

   However, these studies were conducted in Belgium (Devos et al., 2024) and Finland (Salmio & Huuhka, 2026), not in the Netherlands. Differences in brick types, mortar, and construction practices may therefore affect applicability, although the Belgian context is likely comparable. Further

research on brick harvesting in the Netherlands, particularly in combination with LCA, is recommended.

Brick reuse in practice

Large-scale reuse remains hypothetical. Deconstruction is not yet standard practice and is time intensive. However, reuse chains are emerging (e.g., ReBrick, Klinker Historika), and brick-reuse is considered financially viable and value-retaining, also based on the interviews. Their modularity and uniformity make them particularly suitable for cross-building-type reuse. For example, surplus outflow bricks from offices, as shown in the Sankey diagrams, could help meet demand in residential construction.

6.1.2. Concrete & Steel Reuse

Reuse potential concrete & steel components

Interviews confirm reuse of steel and concrete components in between similar utility buildings beyond pilot scale. Interview findings suggest that current reuse practices for these materials are primarily concentrated in utility and non-residential buildings, rather than in housing. This is partly explained by the relatively low presence of structural steel in residential construction in the Netherlands according to the interviews, as also noted by Icibaci (2018).

Concrete & steel material flows

MFA results show national outflow–inflow alignment for offices (~100%) and partial alignment for industry (~34%). In contrast for residential buildings the demand far exceeds outflows, particularly in single-family housing.

Synchronising concrete & steel flows reuse substitution demand

These results suggest that outflows and inflows can be, in principle, synchronised through reuse within similar office and industrial building types. However, the extent to which this occurs in practice depends on both actor perspective and spatial scale. While some interviewees actively reuse components beyond pilot projects, others do not (see Section 6.3). In addition, outflow–inflow ratios vary significantly across regions, particularly at the municipal level, indicating local mismatches despite more favourable national patterns.

Based on the available data, it is not possible to precisely estimate how much material inflow can be substituted through reuse of steel and concrete components, mainly due to limited insight into component intensities and reusable shares within total flows.

However, opportunities appear greater in office and industrial buildings than in residential ones, given their higher reuse potential and more balanced inflow–outflow ratios. Future research into component-level data is therefore welcomed.

6.1.3. Wood Reuse

Reuse potential wooden components

Interviews identify timber beams, window frames, and hardwood doors as reusable, but their cross-building applicability remains uncertain.

Wood material flows

Demolition outflows of wood substantially exceed construction demand across all analysed at spatial scales, also likely due to higher timber intensity in older buildings. However, increasing interest in biobased construction arising for example through national policy initiatives including *Nationale Aanpak Biobased Bouwen* (Rijksoverheid, 2023), may alter future demand and reuse dynamics.

In contrast, residential buildings show a different pattern. At the Hague municipal level, there are relatively low outflows compared to demand. At provincial and national scales, the balance improves slightly.

Synchronising wood flows and reuse substitution demand

Wood flows could be partially synchronised, depending on scale and cross-building reuse feasibility. Surpluses in utility buildings suggest opportunities to supply residential demand, but a lack of data on component intensities and reuse possibilities firm conclusions. Further research is needed, particularly on cross-sector reuse potential and component intensities.

6. 2. Cross-regional material flow synchronisation

Figure 7 further reveals strong municipal variation in the alignment of material inflows and outflows, highlighting spatial heterogeneity. Although combined with Figures 5–6, it becomes clear that match percentages must be interpreted alongside absolute volumes: high matches can reflect small flows, while lower percentages may still represent large material quantities. Figures 8–19 show higher residential construction in urban regions such as South Holland and The Hague, while industrial and office functions are more often demolished, indicating industrial relocation and office decentralisation.

Overall, the insights from the spatial analysis underscore the potential for cross-regional component exchange. For instance, surplus steel from office buildings in The Hague could support demand elsewhere. Larger spatial scales generally improve matching potential due to more diverse building stocks, consistent with Hoxha & Birgisdottir (2025). Interviews reinforce this, emphasising cross-regional and even cross-border exchange (e.g. Germany) to maximise reuse and CO_2 reduction.

At the same time, provincial and municipal levels remain important, as they can play a key coordinating role in facilitating such exchanges, as illustrated by initiatives such as

the partial reuse of an office building coordinated by the Province of Gelderland (Province Gelderland, 2026).

6.3. Reuse chains and potential

6.3.1. Reuse chain roles

I expected circular demolition companies to have similar business models, but results show diverse roles, reflected in their positions along the supply–demand and construction–demolition axes (Figure 24). They seem to be taking on new and hybrid roles. For example, CDC1 operates as demolisher and a supplier of reclaimed components, while another (CDC2) combines demolition and construction activities, both generating and demanding components.

Demand is linked to construction activities, while supply originates from demolition. This helps explain why certain quadrants (i.e. supply–construction and demand–demolition) are unoccupied.

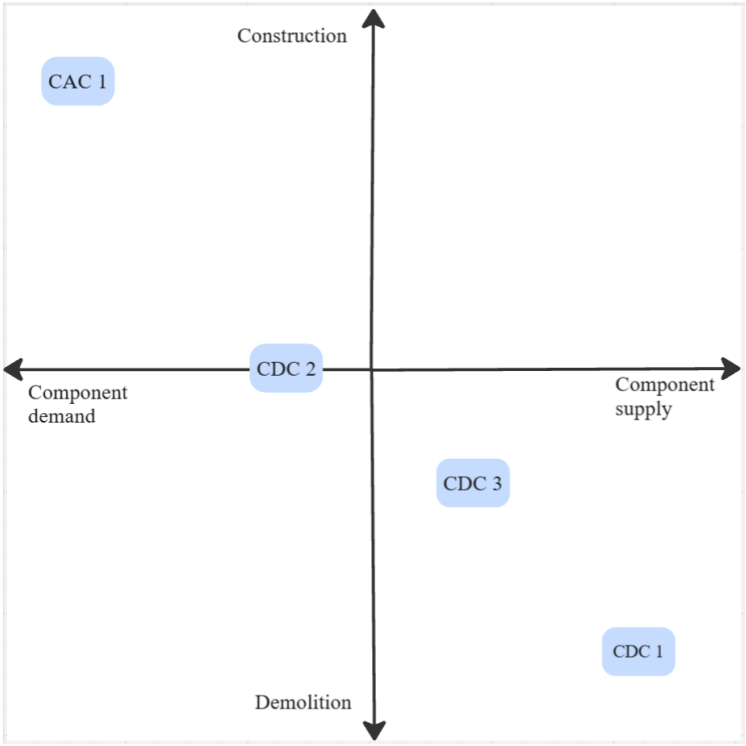


Figure 24 : Stakeholder map showcasing the position of the interviewed companies

6.3.2. Reuse potential chain dependency

An important insight from the interviews is the distinction between two categories of building components in terms of handling and perceived reuse potential:

1. Standardised, non-massive components (e.g. bricks and wooden beams), and

2. Massive, less standardised components (e.g. slabs, and complete steel structures).

For category 1 components, such as bricks, reuse chains are already relatively well-developed. These components are generally considered easier to recover, process, and match on both the supply and demand side. In contrast, the reuse potential of larger and more unique components (category 2) is perceived more variably.

Interviewees positioned on the demand or construction side tend to view the reuse of large structural components more positively, whereas those on the supply or demolition side often consider such components difficult to process, match, and scale beyond pilot projects. This demonstrates that perceived reuse potential is closely related to how inflows and outflows are synchronised through reuse chains.

Demand-driven approaches, in which a receiving party is identified early in the process, reduce uncertainty by ensuring a guaranteed application for recovered components. This allows for selective "cherry-picking" of suitable elements and helps to cover the higher initial costs of reuse.

The absence of a guaranteed recipient is widely recognised in the literature as a key barrier to the reuse of structural components, particularly precast concrete (Icibaci, 2018; Rakhshan et al., 2020). The findings of this study suggest that demand-driven approaches may help overcome these barriers, although such strategies are not yet widely emphasised in existing literature, which tends to focus on supply-driven reuse chains originating from demolition activities (Icibaci, 2018). Such approaches could enhance the effective synchronisation of material flows observed in the MFA.

6.5. Societal relevance and recommendations

6.5.1. Bricks as a circular building product

The results identify bricks as a highly promising circular building product, with strong potential to contribute to national circularity targets, including lowering CO_2-emissions and reducing raw material input (EZK, 2020; MAZ, 2023). However, this study shows barriers remain, including longer deconstruction times and costs. Stakeholder recommendations from this study to improve brick reuse are provided in Table 4.

Table 4: Stakeholder recommendations brick reuse

Category	Recommendation
Policy (national/provincial/municipal)	Support the development of regional or national reuse hubs in collaboration with demolition companies (e.g. CDC1).
	Introduce financial incentives (e.g. subsidies, tax benefits) to offset higher deconstruction costs.
Demolition companies	Further develop harvesting, sorting, and processing capabilities for bricks.
	Explore partnerships with public actors for centralised collection and redistribution.
Architects and designers	Incorporate reused bricks from already established reuse chains.
Portfolio holders / clients	Account for longer deconstruction timelines in project planning.
	Consider total value (including environmental benefits) rather than lowest upfront cost.

6.5.2. Reuse of steel and concrete components within utility

For steel and concrete, reuse potential and the ability to substitute material demand are most evident in utility buildings and depend strongly on demand-driven approaches that link demolition to new construction. This is particularly relevant given the relatively high emissions associated with steel and concrete in the construction sector (Van Oorschot et al., 2023), which can be significantly reduced through the reuse of structural components (Kanyilmaz et al., 2023; Küpfer et al., 2023). Stakeholder recommendations are provided in Table 5:

Table 5: Stakeholder recommendations concrete and steel reuse

Category	Recommendation
Policy (national/provincial/municipal)	Facilitate early-stage coordination between demolition and construction projects to ensure uptake for steel and concrete components, e.g. making planned demolition and construction early known to stakeholders.
	Use provincial-level coordination of reuse initiatives to balance material availability and transport distances.
	Actively support and promote demand-driven reuse chains among demolition companies and construction firms.
Demolition companies	Collaborate with contractors and portfolio holders to secure outlets for recovered components.
Architects and designers	Network with demolition companies to create reuse collaborations.
Portfolio holders / clients	Ensure early alignment between demolition and construction within portfolio.

6.5.3. Usage of MFA framework

This research demonstrates usage of the MTBSA for MFA for analysing circular construction strategies. At the policy level, the framework can be used to evaluate past construction and demolition activities, support future scenario planning. It is recommended to improve data standardisation on building components for more detailed material flow analyses. For portfolio holders, including municipalities, MFA insights can help optimise synchronisation of demolition and construction at the portfolio level.

7. Limitations and representation

7.1. Limitations and data uncertainty

7.1.1. BAG Data sets and processing

Several limitations relate to the underlying spatial datasets (BAG). Inconsistencies in usable floor area (UFA), occasional misclassification of building functions, and missing residential typologies introduce uncertainty in material stock calculations. In addition, temporal inconsistencies, such as buildings with zero UFA while still present, or slight differences in building footprints, may lead to misclassification of demolition events in the MTBSA (see Appendix A.1.4.).

Despite these limitations, BAG is widely recognised as one of the most reliable and comprehensive building datasets available in the Netherlands and is frequently used in recent MFA studies (Van Oorschot et al., 2023; Van der Voet et al., 2025; Van Den Berghe & Verhagen, 2021). Its bottom-up structure also provides high spatial explicitness, which is identified as a key limitation in other reuse-oriented MFA studies (Alaux et al., 2025).

The impact of these uncertainties varies by scale: at smaller spatial scales results are more sensitive to data errors, while at larger scales effects tend to average out. However, smaller scales allow for more detailed validation, for example by verifying individual demolition events at municipal level, which is not possible at national scale.

7.1.2. Modelling assumptions

Material intensity values are based on generalized estimates and do not fully reflect real-world variation. Future research could improve accuracy by integrating higher-resolution datasets when they become available. This is particularly relevant for service-oriented building functions (e.g. assembly or detention), where specific material intensity data is lacking despite likely differences in material composition. As a result, the analysis focuses primarily on residential, office, and industrial buildings, where data reliability is higher.

Furthermore, mixed-use buildings had to be assigned a single dominant function, introducing classification uncertainty (see Appendix A.1.1. for decision rules). While absolute material quantities are therefore uncertain, aggregated results can be considered robust, especially at larger spatial scales.

7.1.3. Exclusion of renovations and extensions

Renovations and extensions were excluded due to methodological and data limitations, leading to an underestimation of total construction-related material flows. However, the study focuses consistently on full construction and demolition, providing a coherent view of structural stock dynamics in line with existing MFA literature (e.g. Van Oorschot et al.,

2023 & Van Den Berghe & Verhagen, 2021). Including renovation flows is recommended for future research.

7.1.4. Temporal boundary

The five-year period (2018–2023) masks year-to-year variation in construction and demolition activity. Administrative delays and registration timing also introduce uncertainty in exact temporal classification. This limits annual-level interpretation but not overall trend analysis.

7.1.5. Interviews

Four interviews limit representativeness across the sector, although they provided valuable exploratory insights into reuse practices. Future research should include a larger and more targeted sample focused on reuse chains and component-specific processes.

7.2. Representation and scientific context

7.2.1. Mixed-Methods for material flows

The Mixed-Methods approach underscores that material flow synchronisation is not purely a quantitative or spatial issue. While previous MFA studies often apply generalised reuse rates (Hoxha & Birgisdottir, 2025; Alaux et al., 2025), this study shows that reuse rates are also depends on reuse chains. This strengthens the IE perspective by incorporating socio-technical dynamics alongside material flows.

The qualitative input also enriched the material flow analyses by highlighting the need to differentiate by component and context. For bricks, two reuse rates are defined based on mortar type. This contrasts with Hoxha & Birgisdottir (2025), who apply one rate per material group, and complements Alaux et al. (2025), who differentiate by component but do not include bricks in reuse scenario.

7.2.1. The Hague as case municipal study

The Hague as a highly urbanised municipality, is characterised by relatively high industrial and office outflows and comparatively higher residential material demand. The Hague is likely to a more accurate representation of other urban municipalities that fall around the 20% overall match range than municipalities that differ from these characteristics.

Van den Berghe & Verhagen (2021) estimate annual construction and demolition flows in The Hague (2020–2023). Inflows are similar to this study, but demolition outflows differ substantially (3.95×10^{8} kg vs. 0.65×10^{8} kg), likely due to methodological differences. Their reliance on projected demolition data introduces uncertainty (see Appendix Research Progress).

Whereas this study uses observed stock changes from spatial datasets (MTBSA), making it independent of forecasts. This highlights the added value of MTBS methodology and suggests future research could perhaps improve demolition estimates using historical demolition patterns.

7.2.2. Gelderland and South Holland as case provincial case studies

The chosen provinces provide a representative ratio of in- and outflows compared to the other provinces, see Appendix A.2.1.

At the provincial level, no comparable scientific studies on material stocks and flows were found, making this research a valuable starting point. However, Metabolic (2024) analysed construction material flows in South Holland (2024–2030), focusing on similar materials (wood, concrete, bricks) and reuse. Results are of a similar magnitude, indicating general consistency despite differences in scope, methods, and assumptions.

As discussed in Section 6.2 on cross-regional component exchange, provinces may play an important coordinating and governing role in facilitating reuse, making this scale particularly relevant for future research.

7.2.3. National stocks and flows

Compared to the material flow study by the EIB et al. (2026), both inflow and outflow estimates are of a similar order of magnitude.

Material stock increased by ~0.25 billion kg (2018–2023), while construction inflow accounts for only ~0.13 billion kg, even without subtracting demolition. This indicates additional contributing factors (see Appendix A.2.2) and highlights that estimating inflow from stock differences is unreliable.

The 2018 material stock aligns with van Oorschot et al., reflecting similar methods with minor coding differences (2023). However, their 2050 projections differ: This study finds an inflow of ~0.13 billion kg over 2018–2023, while van Oorschot et al. estimate ~4.8 billion kg growth over 32 years (~0.07 billion kg per five years). This indicates substantially higher recent construction activity than long-term projections.

8. Future research

Materials to components: from recycling to reuse

Reuse requires both a methodological shift from material flow to component-based analysis and a conceptual shift towards the physical reality of building components rather than abstract material categories.

Future research should develop component-level data and methods, supported by emerging studies (e.g. Dai et al., 2025; Arabi et al., 2021). Developing data on (Dutch) component intensities would enable future analyses to move beyond material-level

estimates and provide more accurate assessments of reuse potential, particularly for concrete, steel, and timber components.

Reuse potential

This research indicates that reuse potential is closely linked to the organisation of reuse chains. However, this relationship is not yet well captured in existing studies. For example, research on reuse in the Netherlands (Icibaci, 2018) does not explicitly account for how different chain configurations influence reuse outcomes. Similarly, MFA-based reuse studies (Alaux et al., 2024; Hoxha & Birgisdottir, 2025) largely overlook the implications of different supply chain structures for material, or rather component, flows.

Future research could therefore explore how different reuse chain configurations (e.g. demand-driven versus supply-driven) affect the actual realisation of reuse potential, and how these translate into measurable impacts on material flows.

Reuse?

In addition, from an IE perspective, it is important to critically assess how in the Netherlands reuse compares to recycling or renovating in terms of environmental impact, possibly by combining MFA with LCA. While this study explored such an approach for bricks, extending it to other components, such as hollow-core slabs, would provide valuable insights into which strategies are most effective, rather than assuming reuse is always preferable.

Scales

Building on Van den Berghe & Verhagen (2021), this study links reuse to material flows, policies, and networks across scales. Future research should further examine which spatial scales best facilitate reuse and how governance can coordinate across them. The provincial scale is a promising option: large enough to balance component inflows and outflows, yet small enough to limit transport distances, with an existing governing body for coordination.

9. Conclusion

This study addressed the question: To what extent can material reuse meet demand by synchronising material flows in the Dutch built environment between 2018 and 2023?

The results show that reused bricks could meet 26% of demand, equivalent to 0.8% of total material inflow. Bricks present strong opportunities as a circular building product due to existing reuse chains, which could be further scaled through policy support. For other concrete, steel and wood, precise estimates could not be determined and require further research, particularly on component intensities, reuse chains, and spatial scales. Overall, the results point to significant potential for the reuse of structural components, especially in utility buildings. Furthermore, demand-driven reuse chains appear capable of improving synchronisation for steel and concrete component, suggesting opportunities for demolition companies and policymakers.

By combining spatial analysis, MFA, and qualitative research, this study introduces a novel approach to assessing reuse across national, provincial, and municipal scales in the Netherlands. It demonstrates the potential of existing spatial datasets through the new MTBSA methodology and develops a framework linking MFA to component reuse.

The study identifies reuse opportunities and provides recommendations towards a more resource-independent and circular Netherlands, lowering the demand for raw materials, energy usage and emissions, highly relevant in light of national climate goals, climate crisis and geopolitical turmoil.

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Appendix

A.1. Modelling

A.1.1. Functions and building types

A.1.1. Codes

Use function

In the BAG 2023 no gebruiks1 (main use function) was available. The use functions were presented as field with a number corresponding with if that function is in that building. In order to determine the main function on which the material intensity was based the code below was used. This code determines which use functions has the highest number per building and chooses that as the main function. If in the rare case two functions are equally present then the first function is chosen, for example if woonfunctie = 1 and bijeenkomstfunctie = 1 it is ascribed woonfunctie as gebruiks1.

```
def bepaal_gebruiksdoel1(
    gebr_woonfunctie, gebr_bijeenkomstfunctie, gebr_celfunctie, gebr_gezondheidszorgfunctie,
    gebr_industriefunctie, gebr_kantoorfunctie, gebr_logiesfunctie, gebr_onderwijsfunctie,
    gebr_sportfunctie, gebr_winkelfunctie, gebr_overige_gebruiksfunctie
):
    functies = {
        'woonfunctie': gebr_woonfunctie,
        'bijeenkomstfunctie': gebr_bijeenkomstfunctie,
        'celfunctie': gebr_celfunctie,
        'gezondheidszorgfunctie': gebr_gezondheidszorgfunctie,
        'industriefunctie': gebr_industriefunctie,
        'kantoorfunctie': gebr_kantoorfunctie,
        'logiesfunctie': gebr_logiesfunctie,
        'onderwijsfunctie': gebr_onderwijsfunctie,
        'sportfunctie': gebr_sportfunctie,
        'winkelfunctie': gebr_winkelfunctie,
        'overige gebruiksfunctie': gebr_overige_gebruiksfunctie
```

```
    }


    if all(v == 0 or v is None for v in functies.values()):
            return ""
    return max(functies.items(), key=lambda x: x[1])[0]
```

Material stock calculations

The material masses per building were calculated using the same code for BAG 2018 as for 2023. The material intensity (mi) data is retrieved from van Oorschot et al., 2023. Below is an example code used for the calculation of the steel mass, the same code is used for other materials with their corresponding mi.

```
def steel_mass(gebruiks1, bouwjaar, oppervlakte, woningtypering):
    functies_services = {
        'onderwijsfunctie', 'sportfunctie', 'overige gebruiksfunctie',
        'logiesfunctie', 'bijeenkomstfunctie', 'gezondheidszorgfunctie',
        'celfunctie'
    }

    steel_mi = 0

    if gebruiks1 == 'kantoorfunctie':
        if bouwjaar < 1945:
            steel_mi = 73.96
        elif bouwjaar < 1971:
            steel_mi = 74.04
        elif bouwjaar < 2001:
            steel_mi = 88.38
        else:
            steel_mi = 88.36

    elif gebruiks1 == 'winkelfunctie':
        if bouwjaar < 1945:
            steel_mi = 46.47
        elif bouwjaar < 1971:
            steel_mi = 46.57
        elif bouwjaar < 2001:
            steel_mi = 48.05
        else:
            steel_mi = 48.03

    elif gebruiks1 == 'industriefunctie':
        if bouwjaar < 1945:
            steel_mi = 92.11
        elif bouwjaar < 1971:
            steel_mi = 85.93
```

```
    elif bouwjaar < 2001:
        steel_mi = 80.17
    else:
        steel_mi = 80.17

elif gebruiks1 in functies_services:
    if bouwjaar < 1945:
        steel_mi = 76.37
    elif bouwjaar < 1971:
        steel_mi = 75.80
    elif bouwjaar < 2001:
        steel_mi = 77.42
    else:
        steel_mi = 77.42

elif gebruiks1 == 'woonfunctie' and woningtypering:
    woningtypering = woningtypering.lower()
    if woningtypering == 'appartement':
        if bouwjaar < 1945:
            steel_mi = 63.25
        elif bouwjaar < 1971:
            steel_mi = 63.18
        elif bouwjaar < 2001:
            steel_mi = 78.15
        else:
            steel_mi = 78.13

    elif woningtypering in {'vrijstaande woning', 'twee-onder-een-kap'}:
        if bouwjaar < 1945:
            steel_mi = 64.54
        elif bouwjaar < 1971:
            steel_mi = 59.08
        elif bouwjaar < 2001:
            steel_mi = 53.76
        else:
            steel_mi = 53.75

    elif woningtypering in {'hoekwoning', 'tussenwoning/geschakeld'}:
        if bouwjaar < 1945:
            steel_mi = 51.24
        elif bouwjaar < 1971:
            steel_mi = 53.19
        elif bouwjaar < 2001:
            steel_mi = 54.83
        else:
            steel_mi = 54.81

if oppervlakte is None or steel_mi == 0:
    return 0
```

return oppervlakte * steel_mi

A.1.2. Emissions Bricks

Below in Table 7 are the associated emissions from brick production, recycling and waste derived from van Oorschot et al. 2023.

Table 6: Brick emissions from van Oorschot et al., 2023

Primary production in CO_2-eq./kg	**Recycling in CO_2-eq./kg**	**Waste in CO_2-eq./kg**
0,242537431	0,224687016	0,008231

A.1.3. Assumptions

Buildings smaller than 24 m^2 were excluded from the analysis, as these typically represent sheds that often spatially intersect with main buildings. This threshold reduces spatial misclassification and improves the reliability of demolition detection in multi-temporal analyses. Sheds also tend to have relatively short lifespans which is less appropriate for the five-year time span between the data sets, and they lack material intensity data

A.1.4. MTBSA demolition detection

On the demolition map see Figure 25 a region with exceptionally high demolition density was identified, red square, and cross-verified using Google Maps and Google Earth imagery. The buildings were found not to be demolished and were excluded from analysis.



Figure 25: Demolished buildings The Netherlands 2018-2023 showcasing anomaly in red square

During data cleaning, all polygons with UFA smaller than 24m² were removed. When applying the MTBSA, these buildings therefore appeared to exist in 2018 but not in 2023, leading to false demolition detection. This issue highlights a limitation of both the dataset and the MTBSA method when attribute completeness changes between time steps.

Upon inspection using Google maps, I concluded that the affected buildings belonged to Tata Steel. A possible explanation is that building information was withdrawn from public registration. Similar issues may exist elsewhere in the dataset but remained undetected. All affected buildings were removed from the demolished buildings layer and excluded from subsequent analyses.

A.1.5. Reuse scenario

I added a new field in GIS to the 'demolished buildings 2018-2023' layers. In the new field the demolished buildings were categorized into two categories based on the field ‘building year’, category A: built before 1970 and category B built after 1970, based on the building's year of construction provided in the 2018 spatial data set. I summarised the kg brick using Summary Statistics and adding ‘building type’ as a statistics field the ‘category’ field as a statistics field. The following calculations were made per building type in Excel.

A.2. Results and discussion

A.2.1. Material Flows Provinces

	Mass constructed (kg)	**Mass demolished (kg)**	**Difference (=inflow-outflow) (kg)**	**Percentage outflow/inflow (%)**
Groningen	4087630967	1341655933	2745975033	32,8223351
Fryslân	4115653325	919314798,9	3196338526	22,33703197
Drenthe	3107419493	872213035,5	2235206458	28,06872511
Overijssel	9101813189	2550583260	6551229929	28,02280388
Flevoland	5113479846	694866041,5	4418613804	13,58890741
Gelderland	17445087767	3347082374	14098005393	19,18638885
Utrecht	8769424495	2382928098	6386496396	27,17314118
Noord-Holland	19905713153	5265585651	14640127502	26,45263503
Zuid-Holland	25328690557	6752725120	18575965437	26,66037988
Zeeland	3934696364	889152906	3045543458	22,59775148
Noord-Brabant	24654830531	5969742288	18685088243	24,2132765
Limburg	7541372643	2185478314	5355894328	28,97984781

A.2.2. Stock growth

The material stock of the Netherlands increased by approximately 0.25 billion kg between 2018 and 2023, according to material stock calculations. This growth is striking, given that the inflow of new materials, even without considering outflows, only adds up to around 0.13 billion kg. Part of this discrepancy might be explained by increased unaccounted floor area (UFA) resulting from building renovations, which are not fully captured in the inflow data. However, the magnitude of the increase appears too large to be attributed solely to remodelling. A closer inspection of the GIS datasets revealed that the same buildings were classified with different user functions or building types in 2018 compared to 2023. These reclassifications affect the assigned material intensities and may partially explain the differences observed. Additionally, adjustments or improvements in recorded UFA values between datasets may have contributed to higher

estimated material stocks. Future research could further investigate this discrepancy in stock calculations.

A.3. Research process

Initially, the research aimed to use future-oriented data with a focus on the municipality of The Hague. However, despite early collaboration with the Municipality of The Hague, the required data, planned construction and demolition activities for the next five years, was not made available in time for this project. Moreover, such data would have involved significant uncertainties and confidentiality issues. It remains unclear whether this type of information could or would have been made available even within a longer timeframe. This challenge, of not knowing which buildings will be demolished and which components will become available, affects not only this research but is a broader struggle across the reuse construction industry. While awareness of the importance of having insight into future construction and demolition is growing, progress remains slow. Even with collaboration from municipalities, such data often remains unavailable due to project confidentiality.

An alternative considered was the use of existing databases from previous studies and earlier future projections (van der Berghe et al., 2021). Yet, these were said by the researcher to be highly speculative due to the absence of reliable municipal data and were ultimately not provided by the researcher.

Since future construction and demolition data was not accessible at the municipal level, the research turned to analysing historical construction and demolition patterns instead. This shift made it possible to broaden the scope to a national level rather than focusing on a single municipality. Interviews further supported this choice, as most companies active in the reuse sector operate across the Netherlands rather than being limited to one city.

A.4. Interviews

A.4.1. Interview questions

Introductie:

Uitleg onderzoek:

Kunt u uzelf kort voorstellen en uw rol bij [naam organisatie] toelichten?

Geschiktheid voor hergebruik

Welke materialen lenen zich goed voor hergebruik?

2. Welke gebouwtypes (bijv. kantoren, woningen, flats) en bouwjaren lenen zich volgens u goed voor materiaalhergebruik?

3. Welke materialen of componenten, geschikt voor hergebruik, zijn doorgaans aanwezig in deze gebouwtypes? Is het mogelijk om een inschatting te geven in hoeveelheid?

4. Welke gebouwtypes lenen zich minder goed voor hergebruik, en wat zijn hiervoor de belangrijkste redenen?

Beschikbaarheid en inschattingen op schaalniveau

5. Welke inschattingen kunnen volgens u worden gemaakt over de beschikbaarheid van herbruikbare materialen op gemeentelijke schaal, zonder gedetailleerde materiaalinspecties? Op basis waarvan kunnen deze inschattingen worden gedaan?

6. Is het volgens u mogelijk om een betrouwbare inschatting te maken van de hergebruiksmogelijkheden van bijvoorbeeld woningflats uit de jaren 1950?

Match tussen materiaal en toepassing

7. Worden materialen uit het ene gebouwtype (bijv. kantoren) in de praktijk ook toegepast in andere gebouwtypes (bijv. woningen)? Hoe flexibel is die uitwisseling?

8. Waar ziet u kansen voor het koppelen van materiaalstromen op gemeentelijke schaal?

9. Welke belemmeringen ervaart u bij het koppelen van materiaalstromen op gemeentelijke schaal?

Inventarisatie en praktijkervaring

10. Zijn er bestaande materiaalinventarisaties die ik zou mogen inzien voor mijn onderzoek?

11. In mijn onderzoek blijkt een mismatch tussen vraag en aanbod van materialen, vooral voor woningbouw. Herkent u dit beeld in de praktijk? Zo ja, hoe groot is die mismatch volgens uw ervaring (bijv. verhouding 1:2 of 1:10)?

A.4.2. Extra information from the interviews

A.4.2.1. Information regarding material inventories

General component information can be retrieved from technical drawings, which are publicly available in the Netherlands, according to CAF1, and with sufficient training it is possible to identify potentially reusable elements from these drawings within about a day. However, technical drawings do not provide information about the actual condition

of components, their exact dimensions as built, or the way in which elements are connected.

CDC3 explained that they conduct their own material inventories, although these are less extensive than the legolising approach of CDC2. Their inventories do not involve full 3D modelling but remain labour-intensive processes based on on-site assessments. In some cases, an inventory is provided by the building owner. Such inventories are more commonly available for publicly owned buildings than for commercial real estate. Both CDC3 and CAF1 expressed doubts about the practical usefulness of the highly detailed material inventories sometimes commissioned by governmental bodies. They argued that these documents are typically supply-driven, whereas the construction sector largely operates as a demand-driven market. Instead of focusing on highly detailed inventories, they suggested that municipalities could play a more active role in connecting demolition contractors, developers, and architects. Providing higher-level, accessible information about available materials would be more effective than producing exhaustive technical documentation.

They also noted that demolition companies often have limited time to identify reuse opportunities, particularly for large, heavy, or unique components for which no established reuse chains exist. According to CDC3, this process could be significantly facilitated if projects were coordinated within a single portfolio, allowing material flows to be aligned more strategically across multiple developments.

A.4.2.2. Supply chain integration analysis

The interviews highlight emerging supply chain integration, with some companies combining demolition and contractor roles, and others linking demolition with retail functions. While the latter is documented in literature (Icibaci, 2018), the former is less explored. This demand-driven integration may enable reuse of high-impact components such as steel and concrete, which currently face major barriers to large-scale reuse.

A.4.2. Summaries

CDC 1

Introduction

The interviewee (CDP 1) is the director of CDC 1, where they are responsible for demolition activities, inner-city projects, and innovation. CDP 1 has been with the company for around fifty years. In addition, CDP 1 is involved in an online platform for selling used construction materials. CDP 1 is one of the founders of the associated foundation and currently serves as chair of the cooperative, which consists of 13 demolition companies**.**

Working method

CDC 1 operates nationally and occasionally internationally, focusing on demolition projects without linked new construction. The process starts with a demolition request,

after which selected components (including hardwood doors and bricks) are recovered, processed, and reintroduced to the market.

In addition, the interviewee emphasizes that strictly adhering to regional boundaries in circular construction does not always result in the best environmental gains. According to them, the CO_2 argument for transport is often applied too narrowly: in some cases, reuse over longer distances can actually lead to greater CO_2 reduction. “Yes, keeping it within the region, everyone thinks that makes it understandable, and you keep transport low. But ultimately, if I have to drive it to Munich and can save three times more CO_2 there than if I keep it in the region, then you are just sticking your head in the sand. Then you are only doing it for show.”

In response to the question: “Do you have any further comments or anything you would like to add or ask?” they replied: “Make sure that in your thesis you really broaden it, further than a municipality.”

Reuse of materials

As a pilot project, they also reused larger structural components such as steel structures and concrete hollow core slabs between utility buildings. Although this project generated substantial knowledge and experience, the organization concluded that such practices are not economically viable and do not justify repetition or routine implementation. Key challenges included mismatches between expected and actual component dimensions, as well as certification and permitting requirements. As the participant stated when discussing the pilot project: “Is this the future? No, it is not. However, I do believe in what we are doing now, for example with hardwood.”

The interviewee indicates that initiatives such as digital marketplaces for the reuse of construction materials are “sexy showcases,” but in their view they are not the future of circular construction. On such platforms, it is mainly the lower-value materials that remain available, while high-quality residual streams already find a destination early on. They see the future more in organizing closed material loops, completing the circle: collecting, processing, and reintroducing materials as full-fledged products on the market. At present, they already do this with hardwood, bricks, doors, and storage units, and in the future, they also aim to extend this approach to materials such as steel beams but mainly for the construction of bridges.

The interviewee describes brick as a good and beautiful product. They explain that the raw material, clay, is transported via rivers from Germany and is therefore essentially freely and locally available. A well-made and properly laid brick can last up to 500 years and retains or even increases its value over time. Whereas conventional construction materials are typically depreciated, brick value instead increases with inflation

(approximately 2–3% per year). Over a period of around 35 years, the value of a brick can double, which in their view requires a different financial approach to material value in construction.

Their organization is working on techniques to keep bricks intact during demolition and reuse them. Currently, this “harvesting” is still largely manual, but they are collaborating with a manufacturer on a robotic system that can automatically cut bricks out of walls during demolition. The interviewee notes that bricks, with a market value of approximately one euro each, are also economically attractive for reuse.
To organize this at a larger scale, they propose the concept of one or two national brick hubs: central locations where used bricks from across the country are collected, sorted, and resold. According to them, this model could also be applied to other material streams such as wood, doors, and ceiling panels.

In addition, work is being done with collected hardwood that is sawn, laminated, and reused for window frames and doors. Experiments are also underway with the reuse of glass (where double glazing is upgraded to triple glazing) and steel structures from existing buildings.
The interviewee emphasizes that, in their view, a combination of wood and concrete represents the future of construction. They describe concrete as “a beautiful product, with nothing wrong with it.” In their projects, concrete elements are used that consist entirely of material recovered from demolition. The concrete is crushed, after which the gravel and sand are reused. In some cases, it can even be used without cement, although in practice this proves difficult due to regulations, quality assurance (such as KOMO certification), and limited market acceptance.

They note that the cement industry, led by major players such as Heidelberg, is now working on so-called CO_2-neutral cement. In this process, emitted CO_2 is captured and stored underground. Although this is officially labelled as sustainable and receives subsidies, the interviewee questions the actual environmental benefit of this approach.
According to them, priority should be given to reusing concrete in low-grade applications, such as foundations under houses or infrastructure, rather than directly in structural elements like balconies or bridges. They advocate starting with “the low-hanging fruit”, low-risk applications, before deploying circular concrete in more demanding structures.

The interviewee points out that this is difficult to achieve because concrete producers often also own gravel quarries, giving them a financial interest in using virgin materials. According to them, this hinders the transition to large-scale reuse of secondary concrete.

Reuse of building types
The interviewee describes that construction practices changed significantly between the 1970s and around 2015 compared to earlier periods. During this time, many composite

and glued materials were used, which makes separation and reuse more difficult. According to them, this contrasts with construction before the 1960s, when mainly single-material building components such as brick, concrete, steel, and wood were used, materials that are better suited to a circular approach and can be more easily reused. Steel is rarely used in houses.

They give an example of a project, in which their organization was involved in relocating a former hospital building. The building was not demolished but largely reused and rebuilt as a healthcare centre including a pharmacy, physiotherapy services, and a general practitioner's office.

CDC 2

Introduction

CDP2 is a program manager for circularity at CDC2. The goal is for the construction sector to be fully circular by 2050: all materials from buildings should be reused or, if that is not possible, recycled without CO_2 emissions.

CPD 2 has been working on this since 2018, seven years. Early on, they concluded that not everything from a building should automatically be reused. Instead, the focus should be on reusing the "skin and structure" of buildings the envelope and load bearing structure which together account for roughly 80 percent of a building's mass such as concrete, steel, and glass. Since then, they have set up an extensive program around this approach.

CDP2 explains that their company carries out demolition work on all kinds of buildings homes, apartment complexes, and commercial buildings, and sometimes bridges or viaducts. They do not work on vehicles or machinery. The main focus is on commercial real estate and residential areas. Within these projects, they aim to make circularity truly successful and achieve measurable results. According to them, commercial construction between similar building types offers the greatest opportunities for circular material reuse.

Working method

CDC 2 frequently works directly with property owners who state clearly that they want certain buildings demolished, removed, or altered. In such cases, they are able to engage in broader discussions about what is planned for the site afterward and what additional developments may be required. Through this type of dialogue, they often identify opportunities where upcoming construction projects can be connected to other demolition needs. For example, when a new building is planned, they may already know of several other structures scheduled for demolition in the coming years, enabling them to create strategic matches.

Starting from the building that will be built, the to be constructed building, they look for similar buildings that will be torn down, possible donor buildings. When they find a similar to be demolished building. They start as they coined it 'legolising' the building. They investigate the building using laserscanner and drone in order to draw out the building in 3D, this allows them to know exactly which elements there are and their specifics. They can map their buildings completely into a sort of blueprint: a database shows exactly how much concrete or steel is present, what can be reused one-to-one, and what will be “smart crushed.” This allows them to calculate the CO_2 savings.

Despite their collaborations, they sometimes still have to tender to secure a donor building. Tenders require extra effort, but they often win because they can show exactly how materials will be used, including 3D renders of the new design. "Point out a steel beam to me, and then we’ll show where it is in the new design and/or what we’ve done with it." CDC2 They sometimes challenge the tender party to point a component out so they can showcase where that concrete slab or steel beam will go, or explain whether it will be shortened, reused, or scrapped. This means much of the new design is already prepared. This is as one can imagine a time and money intensive operation, however since they perform this rigorous approach only for a building when they know where the components will be used for, not having to buy those materials as new allows for them to make it a financially viable business. "The materials that are not needed in a follow up project are dealt with business as usual. Or how CDC2 put it "Going bankrupt isn't very circular, as I always say" said by CDC2.

Reuse of building types

They mention an example of a building they are planning to reuse, which consists of precast concrete sandwich façade elements and hollow core slab floors. However, these prefabricated components are all cast together with concrete, making them difficult to dismantle. In the 1980s, dry connections were still rarely used.

From that period onwards, more buildings started being constructed with steel load bearing structures. These structures mainly consist of bolted connections, which makes them more suitable for disassembly. The concrete floors in these buildings are often prefabricated but still cast in place, allowing only partial reuse.

According to CDP2, the future of circular construction will mainly lie in steel structures with demountable connections, where companies like CDC2 focus on carefully dismantling and reusing these elements.

Reuse of materials

Bricks

Bricks especially those from 1960s and 1970s housing can be recovered very effectively. According to CDP2, this leads to a 72 percent CO_2 reduction. It also prevents large amounts of waste, since the bricks are not crushed into rubble.

The brick is reused one to one elsewhere, meaning no new clay is needed and no gas is required for firing. The result is a highly circular and sustainable product a brick. However, these bricks have become relatively expensive. A specially produced new brick costs roughly between 0.80 and 1 euro per piece. Reused bricks end up in a similar price range, but they offer a distinctive weathered aesthetic.

Reused construction materials are increasingly used in new buildings as high quality circular solutions. Examples include reused roof tiles and bricks from post war residential areas used in schools and apartment buildings. Direct reuse of bricks prevents waste and avoids emissions from both new material production and the firing process, with reported CO_2 savings of up to 72 percent.

Although reused bricks are more expensive than standard new bricks, their price is comparable to custom or specialty bricks. Due to their aesthetic quality and circular value, they are often used as architectural accents, such as in representative entrances.
They can also be used as structural elements. It is a fully functional brick that is also certified.

Hollow core slabs
CDP2 discusses testing recovered hollow core slabs, which in fact became stronger after testing. Hollow core slabs can be successfully removed from buildings if not damaged, and CDC2 has proven this in practice. They removed 750 slabs from a project without a single one being damaged.

A few years later, a small number did fail, but this was limited in scale and caused by incorrect transport, improper unloading, or destructive testing.

Material inventory data
Historical data on demolition materials such as concrete or insulation are often outdated, unclear, or incorrect. For example, demolition figures from the EIB 2014 only provide a rough indication of material flows and include errors and implicit assumptions.
CDC2 maps donor buildings using laser scans, drones, and 3D models, allowing exact quantities of materials per element to be determined. CDP2 assumes that in the future, AI can help make predictions based on building types, façade characteristics, and Street View imagery, making hotspots of available materials visible. Estimating at element level is complex due to finishes, structural types, and variations in building configurations.
Access to data on building elements is limited; much of the information is held by private parties or municipal archives and is difficult to access. European legislation and standards such as CSRD and the Digital Product Passport may improve future standardisation and data access, according to CDP2.

When asked whether online data is available on the amount of reused material within the company, or whether material inventories can be accessed, the interviewee explains that such information does exist but is typically part of internal tenders and therefore sensitive business information. For that reason, it is not made public.

Follow-up question (email clarification):
Meta Gewald: Is it also possible for you to reuse bricks laid with cement mortar (and if so, how?), or only where softer mortars have been used?
CDP 2: The bricks do not need to be laid exclusively with softer mortars. The result is somewhat more variable, but 40 to 80% is ultimately achievable. There are also many ongoing innovations (machine processing/robotization/artificial intelligence).

CDC 3

Introduction
The interviewee (CDP 3) works within the demolition company (CDC 3) on establishing collaborations and finding partners for the uptake of materials, both for direct one-to-one reuse and for high-quality recycling. The participant has worked with this demolition company for 10 years. CDP 3 ensures that material inventories are carried out in projects, advise during the tender phase, and support the handover to project managers and site supervisors. In addition, they explore opportunities to scale circularity, for example by connecting parties with little experience in reuse to experienced partners or suppliers.

Working method
The company deliberately chooses not to manage its own material hub, but instead acts as an intermediary between producers, suppliers, and buyers, who according to the interviewee have more specialised knowledge and networks. In this way, material reuse is organised more effectively without the company having to manage full supply chains itself.
According to CDP 3 a key part reuse is matching demolition and new-build projects so that materials can be directly reused. Ideally, architects, builders, and developers are involved at an early stage so that reuse can be incorporated into the design. This works particularly well with organisations that manage large real estate portfolios, such as universities or housing associations. For municipalities, this is more difficult due to the smaller number of buildings.

Reuse of materials
For materials such as prefabricated components, hollow core slabs, and steel structures, reuse is considered very feasible, provided they are properly dismantled. For masonry and bricks, the company works with specialised partners such as Klink Historica and ReBrick, who carry out test setups in advance to determine how easily bricks can be removed and what percentage is suitable for reuse. These data are used to include expected yields, savings on disposal costs, and reuse potential in tender proposals.

Wooden beams are already a relatively mature reuse market. There is consistent demand from both private individuals and commercial builders, for example for sheds or small structures. Steel structures are also reusable, although the economic balance between scrap value and dismantling costs is an important factor.

In a pilot project where a one-year preparation period was granted, CDC3 succeeded in reusing 90 percent of the building materials. However, the company typically has only four weeks to prepare a pricing proposal and eight weeks before construction begins, leaving limited time to arrange reuse pathways. For many components, such as hollow-core slabs, there are no set pathways, so they do not get reused. For bricks Klinkhistorica, helping with deconstructing and testing, and ReBrick, as a buyer, function as set pathways for reuse for bricks, if the demolition timeline is not as tight due to the extra time for correctly peeling the bricks.

Material inventory data

Early availability of demolition information is also important according to the interviewee. In practice, demolition contractors often only get a few weeks to prepare a price and start work, which makes it difficult to organise material reuse efficiently. The interviewee emphasises that practical inventory data is more important than detailed BIM models: what matters are the quantities of materials and which partners can take them, so that matches can be made quickly and reuse becomes feasible.

CAF 1

Introduction

The interviewee (CA 1) is an architect who has been specifically designing for reuse since 2012, 13 years.

Working method

The architecture firm A start with a project request. When the project request is in they start looking for components that would match from buildings that will be demolished. Currently they have built up contacts with demolishers who update them. They select components from to be demolished buildings and design them into the requested project. This is a viable business for them, as an example they had a project where they reused the entire steel structure from a previous building was done cost neutral.

Reuse of materials and building types

They reuse steel, concrete and brick components between utility buildings. When talking about the reuse of materials it is necessary one talks about the reuse of different components, according to CAF 1, each having their own properties as: “Concrete is not concrete, but a poured column or a hollow core slab” stated by the participant from CAF 1. So, for example, the participant mentions that the difference in choosing to reuse form

of brick is dependent on its mortar, as they prefer reuse as a slab for cement mortar and brick per brick for chalk mortar.

Material inventory data

Knowledge of the components available in a building can be retrieved in multiple ways. When a building is put up for demolition, demolition companies can do a material inventory themselves, or the owner of a building provides one. This is often not provided for commercial buildings, but it is often provided for state owned buildings. It can be retrieved from technical drawings, which are publicly available in The Netherlands. If trained, one can very easily in one afternoon retrieve information from those drawings to know which of the elements could be used and where they would be placed in the new building according to CAF1.

A.5. Literature review

Below is Table 8 with the kg CO_2-eq. emissions calculated by van Oorschot et al., 2023 and added percentages.

Table 7: GHG emissions for the conventional scenario presenting the climate impact associated with cumulative material production for construction (including secondary materials) between 2018 and 2050 calculated by van Oorschot et al., 2023

GHG emissions **Scenario**	**Unit**	**Conventional**	**Material emissions/total emissions in %**
Concrete	kg CO_2-eq.	44594541523	41,59%
Clay brick	kg CO_2-eq.	12328230474	11,50%
Other construction materials	kg CO_2-eq.	10920190279	10,18%
Steel & iron	kg CO_2-eq.	7683109590	7,16%
Insulation	kg CO_2-eq.	12588903737	11,74%
Ceramics	kg CO_2-eq.	1922933207	1,79%
Glass	kg CO_2-eq.	2181897227	2,03%
Wood	kg CO_2-eq.	2352137213	2,19%
Other*	kg CO_2-eq.	3705616130	3,46%
Plastics	kg CO_2-eq.	1469385332	1,37%
Aluminum	kg CO_2-eq.	6774355988	6,32%
Copper	kg CO_2-eq.	675225768,4	0,63%
Other metals	kg CO_2-eq.	27275570,11	0,03%
Other biobased materials	kg CO_2-eq.	8420429,087	0,01%
Total	kg CO_2-eq.	1,07232E+11	