Material Flows and Circular Options for Residential Buildings in the Netherlands

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Summary

Residential buildings have become a priority product category for the circular economy agenda in the Netherlands due the large amount of materials that their construction requires, the environmental impact of this demand, and the fact that increasingly more houses are needing to be built in response to the housing crisis. To guide and monitor the circularity transition for housing, a quantitative understanding of material stocks and flows is needed, together with insight into the potential impact that different circular options could have. This study begins by quantifying the material stocks and flows for residential buildings in the Netherlands in 2019, including material origins and waste treatment flows, by combining data from past studies into an accounting material flow analysis (MFA) model. The environmental impact of the 2019 material demand is also calculated. This quantification of the current state creates a baseline from which circularity and environmental performance for housing can be improved. Desk research is used to create an inventory of options for increasing circularity in the Dutch housing sector, including estimates of the potential and environmental impact of each as can be found in the literature. Modular construction is often mentioned as a circular option for housing due to its industrialized and demountable construction method, which allows for module, component, and material reuse and facilitates building repair, adaptability, and recycling. However, the impact that more modular construction would have on national material flows and circularity has not yet been quantified. Therefore, this study performs a dynamic MFA to investigate how the large-scale adoption of modular construction could influence the material flows for residential buildings in the Netherlands towards 2100. Primary data from two Dutch modular building companies was used as input for the model. The results illustrate that modular construction is an effective narrowing the loop strategy, capable of reducing material demand by 33% in 2030, 40% in 2050, and 60% in 2100, though its reusability benefits remain limited toward 2100 due to the long lifespan of buildings. Ultimately, this study concludes that modular construction, house splitting, transforming existing non-residential buildings into housing, and adding floors on top of existing buildings appear to be the most impactful options for reducing the material input required for residential buildings in the Netherlands and the associated environmental impact.

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1 Introduction

In the Netherlands, the construction sector (buildings and infrastructure) is responsible for 50% of resource use, 40% of energy consumption, 40% of waste generation, and 35% of CO_2 emissions (Circulaire Bouweconomie, 2018; Conde et al., 2022). Although 88% of demolition waste is recycled, this mainly consists of downcycling, where materials are used to form low-quality aggregates for use in, for example, roads. For the construction of buildings, only 8% of the material input is derived from secondary sources, meaning the sector is still largely dependent on primary raw materials and follows a linear take-make-dispose model, which puts significant pressure on the environment (Conde et al., 2022). In addition, the Netherlands currently faces a housing crisis and there are plans to build 900,000 homes between 2022 and 2030, requiring increasingly more materials and energy (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022).

The circular economy presents a solution for the material demand and environmental impact of the housing sector, proposing a system in which materials rarely become waste since they are continuously used and reused or returned to biological cycles. In this way, the circular economy reduces the need for virgin raw materials and minimizes pollution and the degradation of the environment. At the same time, new business and job opportunities are created, and greater supply security for resources can be achieved, further contributing to sustainable development (Ellen MacArthur Foundation, 2013; Kirchherr et al., 2017).

The Netherlands aims to have a fully circular economy by 2050 (Hanemaaijer et al., 2021). To achieve this goal, the government has developed the Circular Economy Implementation Program, outlining various policy instruments to facilitate the circular economy as well as plans for projects in five key product domains (Ministry of Infrastructure and Water Management, 2021). However, a comprehensive set of quantitative information about material stocks and flows in the Netherlands is still under development, together with insight into the actual environmental and economic impacts that increased circularity would have (Hanemaaijer et al., 2021). This quantitative basis is important for understanding the materials available for recirculation, identifying any trade-offs or undesired impacts, and for informing Dutch policy. To contribute to this knowledge base, the Netherlands Environmental Assessment Agency (PBL) is working together with the research organization TNO, the National Institute for Public Health and the Environment (RIVM), and three Dutch universities to develop the Circular Options Inventory Network (COIN). COIN aims to develop a concrete set of data on all product categories, quantifying the product stocks and flows, identifying relevant circular options, and calculating the environmental impacts. The information will be made publicly available and become a shared knowledge source to guide the circularity transition in the Netherlands (van Dril, 2022). This thesis aims to contribute to the COIN project by focusing on residential buildings as a product category. Housing has become one of the focus product categories of the Dutch circular economy agenda due to its societal importance and large environmental impact.

Chapter 2 provides a brief overview of existing literature on circularity in the Dutch housing sector and defines key terms. This leads to the main research question, together with four sub-questions to structure the research. Chapter 3 explains the methods used to answer each sub-question, and Chapter 4 presents the results, including a quantification of the material stocks and flows for Dutch housing in 2019, an estimation of the material related environmental impacts, an inventory of different circular options, and a more detailed look at the impacts of modular construction. Chapter 5 discusses the limitations of the methods used to answer each sub-question and proposes directions for future research. Chapter 6 concludes by summarizing the main findings and discussing their implications.

2 Literature review and research questions

2.1 Quantifications of material stocks and flows

Given the large quantities of materials consumed by construction and the need to monitor material streams in order to guide the circularity transition, several studies have been performed which map the material stocks and flows associated with residential buildings in the Netherlands. Arnoldussen et al. (2022) quantified the material inflows and outflows for the construction sector in the Netherlands in 2019, differentiating between four different types of residential buildings and 20 types of materials. The study also quantified the amount of secondary and renewable material inputs, indicated the environmental impact of the different building elements in terms of an aggregated monetary indicator, and projected the material inflows and outflows for housing in 2030 and 2050 assuming a business-as-usual scenario. Van Oorschot et al. (2020) builds on the report by Arnoldussen et al. (2022) by combining the material intensities of different buildings with the national cadaster database to quantify the stocks of materials in residential buildings in the Netherlands. Yang et al. (2022) also quantifies the material stocks and flows for housing in the Netherlands using a dynamic stock model approach. Lastly, Conde et al. (2022) quantifies the material inflows and outflows for Dutch housing but differs from the other studies in that it indicates the destination of material outflows, quantifying the amount that is incinerated, landfilled, or recycled. While several studies have quantified the material stocks and flows for residential buildings in the Netherlands, none include the origin of the materials and products: whether they are domestically produced or imported. This distinction is useful for insight into where decisions about material production are made and the extent to which Dutch policy could have an influence. It is also useful for determining the potential impact of circularity on Dutch imports.

2.2 Circular economy terms

Several strategies can be used to increase the efficiency of material use and achieve a circular economy. These so-called circularity strategies are categorized differently throughout the literature, but this study will adopt the definitions and groupings used by PBL. PBL distinguishes between six circularity strategies called R-strategies, which are illustrated in Figure 2.1. In general, the strategies that are higher on the list are thought to cause less environmental impact and are therefore preferred, but in reality, a combination of these strategies is necessary (Hanemaaijer et al., 2021).

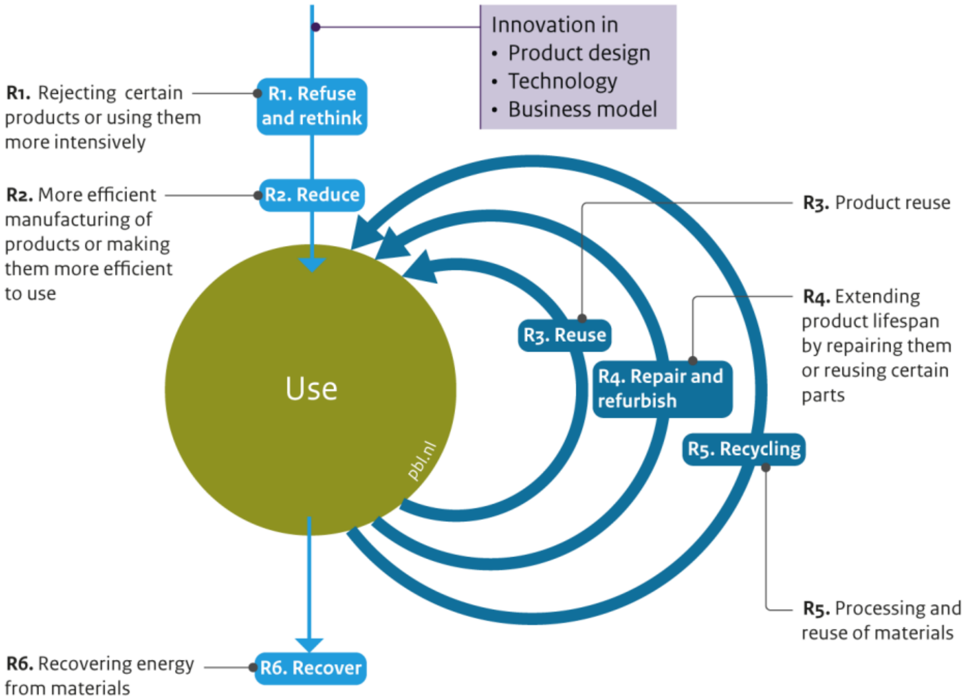

Figure 2.1 R-strategies (Hanemaaijer et al., 2021).

Of these circularity strategies, refuse, rethink and reduce contribute to "narrowing the loop", which refers to decreasing the amount of material used. Reuse, repair, refurbish, and remanufacture contribute to "slowing the sloop", which ensures materials are used to their full potential and postpones the need for new inputs. Recycling contributes to "closing the loop", ensuring materials are reused and do not become waste (Bocken et al., 2016; Hanemaaijer et al., 2021). "Substitution" is also considered a circularity strategy and refers to replacing primary materials with more sustainable alternatives, making it a refuse strategy (Ministry of Infrastructure and Water Management, 2023).

Table 2.1 R-strategies mapped to the strategies of substitution, narrowing the loop, slowing the loop, and closing the loop.

	R-strategies
Substitution	Refuse and rethink
Narrowing the loop	Refuse and rethink Reduce
Slowing the loop	Reuse Repair, refurbish, and remanufacture
Closing the loop	Recycling

To clarify the differences between repair, refurbishment, and remanufacturing, the definitions from Bakker et al. (2019) are used. When a product is repaired, it is brought back to its original functional state and remains in use by the same user. Refurbishment is similar to repair but typically involves larger adjustments, often making the product not only functional but also improving its aesthetic. A refurbished product is not necessarily returned to the same user. Lastly, when a product is remanufactured, it is fully disassembled, cleaned, fitted with new components where necessary, etc., in order to deliver a product that is good as new.

Within this framework of circularity strategies, the COIN project uses the term "circular options" to refer to the specific options to improve circularity relevant to a particular product category.

2.3 Circular economy for buildings

Several studies outline the circular options for buildings, with most referring to the environmental impact reductions that can be achieved at the building and component level (Gallego-Schmid et al., 2020; van Stijn & Gruis, 2019). However, in order to work towards a circular economy in the Netherlands, understanding the implications of different circular options on a national level is crucial.

Conde et al. (2022) takes a national perspective. The authors present a variety of circular options and estimate the extent to which the total material input for buildings in the Netherlands could decrease with each. For example, the study states that repairing the structures of existing buildings could reduce the need for new construction and thereby reduce the volume of material inputs by 2%. In addition, the authors estimate that reusing existing buildings by transforming them into housing could prevent 7% of new residential construction each year. Although not all are quantified, other options that are addressed include the use of biobased materials, secondary materials, design for disassembly, co-living spaces, repair and maintenance, and advanced demolition. While Conde et al. (2022) does take a national perspective, it does not analyze how the different options would influence specific material flows nor does it calculate the associated changes in environmental impact.

Van Oorschot et al. (2022) quantifies how the widespread adoption of two circular options, namely biobased construction and construction with detachable and reusable components, could influence the specific material flows required by residential buildings in the Netherlands. Both options are found to reduce the mass of material needed for new construction between 2018 and 2050 by almost half. The results distinguish between the impacts on individual material flows (e.g. changes in concrete, wood, and steel consumption). Van Oorschot et al. (2023) then elaborates on the previous study by calculating the change in greenhouse gas emissions and land use impacts that are associated with the changes in material use.

Similarly, Yang et al. (2022) quantifies how increasing the closed loop recycling of materials from the urban mine could influence the material flows and material related greenhouse gas emissions of the Dutch residential building sector.

Additionally, a recent study by Bosch et al. (2023) analyzed the impacts of six different circularity options for housing in the Netherlands towards 2030. The strategies include house sharing, the vertical extension and transformation of existing buildings, building smaller, high value reuse, biobased construction, and industrialized construction. For each option, the potential reduction in material use, CO_2 emissions, and overall environmental impact are calculated. The environmental impact is calculated using the Environmental Performance of Buildings (MPG) assessment method, which combines the results from life cycle assessments of different construction products across 11 impact categories into one environmental impact score in monetary terms (Bosch et al., 2023; RVO, 2017).

2.4 Modular construction

The literature on circular options for housing in the Netherlands is extensive, with several studies also going a step further and quantifying the potential impacts. However, little research has been done about modular construction. Modular construction presents an interesting circular option since it enables many of the circularity strategies: reduce, reuse, repair, refurbish, remanufacture, and recycle. In addition, modular construction is industrialized construction, and is therefore in line with the Dutch government's goal of increasing the amount of industrialized and digitally produced housing such that it meets half of the new construction demand by 2030 (Ministry of Infrastructure and Water Management, 2023).

Industrialized construction goes beyond the prefabrication of building components and refers to the off-site prefabrication of houses in a factory. Entire 3D volumetric units or 2D panelized elements are manufactured, often already integrating the necessary wiring and plumbing, and these are then transported to the construction site for final assembly into a complete building (de Ruiter & Koning, 2023; Kedir & Hall, 2021; Ministry of the Interior and Kingdom Relations, 2021). Although the primary purpose of industrialized construction has thus far been to increase construction productivity, it also has the potential to reduce material use, minimize waste, and facilitate a circular economy (Kedir & Hall, 2021). Within industrialized construction, modular construction uses standard connections and building systems, allowing the modules and components to be easily disassembled for reuse or reconfiguration (Bertram et al., 2019; Ministry of the Interior and Kingdom Relations, 2021). Industrialized, modular construction can yield environmental benefits since the manufacturing process is optimized and controlled, and the modules can be disassembled, facilitating reuse, repair, remanufacturing, and recycling.

Bosch et al. (2023) quantifies the impact of increased industrialized construction towards 2030 and compares the material composition and embodied CO_2 impacts of a modular and traditional terraced house. However, since the temporal scope only extends to 2030, the study does not take into account the benefit of module, component, or material reuse.

2.5 Research questions and approach

While modular construction is often mentioned as an option for improving the circularity of housing, the impact that it would have on national material flows, taking into account the potential for module/component/material reuse, has not been analyzed. To address this knowledge gap and meet the goals of the COIN project, this thesis aims to answer the following research question:

How can different circular options, specifically modular construction, influence the material flows and material related environmental impacts of residential buildings in the Netherlands?

The first step in answering this question is to quantify the current state of material stocks and flows for housing, in order to establish a baseline from which circularity can be improved. While several studies have made similar quantifications, this research aims to include the additional information of material origins. Therefore, the first sub-question is:

1. What is the current state of material stocks and flows for residential buildings in the Netherlands, including whether materials are imported or domestically produced?

To continue quantifying and describing the baseline state, the environmental impact of the current material demand is calculated through the second sub-question:

2. What is the current environmental impact of the material inflows required for residential buildings?

After gaining an understanding of the current state, options for increasing circularity are inventoried, including impact estimates to the extent that other studies have determined them. This phase is also descriptive and combines both quantitative and qualitative information to create an overview of circular options. Hence, the third sub-question is:

3. Which circular options can be applied to residential buildings in the Netherlands and what is the estimated potential and impact?

Since the impact of more modular construction has not yet been analyzed in detail, the final phase of the research is exploratory and takes a quantitative approach to answer the fourth sub-question:

4. How would increasing the amount of modular construction in the Netherlands influence the material flows for residential buildings between 2019 and 2100?

3 Methods

The methods used to answer each sub-question are described below.

3.1 Quantifying current material stocks and flows

Material flow analysis (MFA) is a method used for quantifying the material stocks and flows within a system and has been used to understand the stocks and flows of materials for buildings in the Netherlands (Arnoldussen et al., 2022; Conde et al., 2022). The result makes it possible to visualize the magnitude of stocks and flows, identify main contributors, and observe any existing circular flows. While several such visualizations have been made for buildings in the Netherlands, the first stage of this research combined the different quantifications into an accounting MFA model in order to create a holistic picture of the current state, including material origins, inflows, stocks, outflows, and waste treatment streams, and focus specifically on residential buildings. Another reason for reconstructing such an accounting MFA model was to compile and derive the background data on e.g. material compositions, house surface areas, and construction and demolition numbers, such that the data is usable by COIN and can be used as input for the dynamic MFA model made later in the study.

The accounting MFA model was made for the year 2019, since most data is available for this year. The model distinguishes between three residential building types and thirteen material categories, in line with the study by van Oorschot et al. (2020), which provides the most detailed data on building material intensities and stocks that is publicly available. Van Oorschot et al. (2020) uses the material intensities from Arnoldussen et al. (2020). Van Oorschot et al. (2020) then combines these with the BAG dataset (Kadaster, n.d.), which shows the building type, location, surface area, height, and year of construction for all buildings in the Netherlands. The combination of BAG and the material intensities allows van Oorschot et al. (2020) to calculate the stocks of materials in residential buildings in 2018. This stock quantification was taken as the starting point for quantifying the 2019 values.

The operational steps for constructing the accounting MFA model can be seen in Figure 3.1. The inflows and outflows of materials for residential buildings were calculated based on the 2019 construction and demolition data from Arnoldussen et al. (2022). The new construction data is given in terms of the number of residential buildings constructed as well as the gross floor area (GFA) constructed per building type. Since the material intensities are defined in kilograms per useful floor area (UFA), the GFA values were converted to UFA using the conversion factors from Arnoldussen et al. (2020). The demolition data is presented in terms of the number of buildings demolished per building type and age. To convert these values into the UFA area demolished, CBS data on the average UFA per building type and year of construction was used (CBS, 2023c). The UFA constructed and demolished per building type was then multiplied by the corresponding building material intensities to determine the inflows and outflows of materials from new construction and demolition in 2019. To include the material inflows and outflows from repair and renovation activities, the total material inflow and outflow from renovation in 2019 was taken from Arnoldussen et al. (2022), and these values were divided between the various material types based on the material flows for renovation in 2014 as presented in Arnoldussen et al. (2020). Lastly, all the material inflow values were added to the 2018 stock values from van Oorschot et al. (2020) and the outflows were subtracted, in order to calculate the stock of materials in 2019 and construct a balanced model.

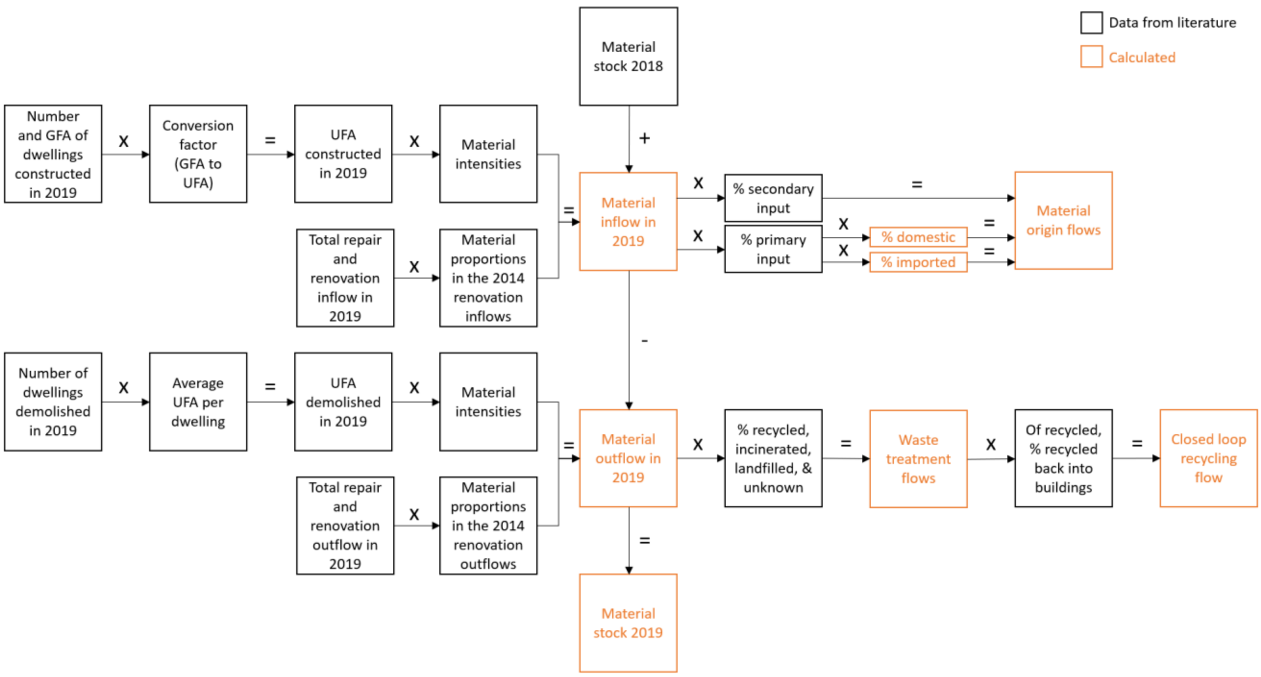

Figure 3.1 Operational steps for quantifying the material stocks and flows for 2019.

The next step of mapping the current state was to investigate the origin of the different construction materials, in terms of whether they are imported or domestically produced. For this, two data sources were compared: EXIOBASE v3.8.2 (Stadler et al., 2021) and the 2018 CBS Material Flow Monitor (Delahaye et al., 2023). The absolute values for the material flows were determined in the previous step, so the values from these datasets were only used to estimate the relative amounts of materials that are domestically produced or imported. It is also important to note that the data refers to the country where the semi-finished materials/products were manufactured before they were used in the Dutch construction industry, and not where the raw materials were originally extracted.

First, the 2019 multi-regional use table from EXIOBASE was analyzed. In the use table, the column for the Dutch construction sector was selected in order to acquire all the inputs to the Dutch construction sector from 49 countries/regions across 200 product categories. The building materials analyzed in this study were then mapped to the different EXIOBASE product categories as shown in Table 3.1. It was then possible to calculate, for each building material/product entering the Dutch construction sector, the percentage that was produced in the Netherlands or that was imported from other countries. For the metals, the first EXIOBASE product categories listed in Table 3.1 relate to the basic products made of these materials (e.g. rods, sheets, wires, tubes) and do not include for example fabricated beams, frames, windows, doors, facades, etc. (Eurostat, 2023a). Therefore, the “fabricated metal products” category was also included. In order to divide this category between the steel and iron, copper, and aluminum material flows, the inputs to the “manufacture of fabricated metal products” industry were analyzed. The proportion of steel and iron, copper, and aluminum, that enter this industry were assumed to be an indication of how much of the fabricated metal products are made of these different materials. This proportion was used to allocate the product category between the three metal flows.

For comparison, the 2018 CBS Material Flow Monitor (MFM) was also used to determine to what extent construction materials are imported or domestically produced. The MFM product categories were mapped to the different building materials as shown in Table 3.1. For each product category, the supply table was used to determine the total supply of that product to the Dutch economy and the supply that comes from imports, in million kilos. These values were used to calculate the percentage of each material/product that is imported or domestically produced.

Table 3.1 EXIOBASE and CBS MFM product categories mapped to building material categories.

Building material	EXIOBASE product categories used	CBS MFM product categories used
Steel & iron	• "Basic iron and steel and of ferro-alloys and first products thereof" • "Fabricated metal products, except machinery and equipment"	• "Ijzer en staal" • "Metal.constructiewerk" • "CV-ketels/radiatoren"
Copper	• "Copper products"	• "Koper ed"
	• "Fabricated metal products, except machinery and equipment"	
Aluminum	• "Aluminium and aluminium products"	• "Aluminium ed"
	• "Fabricated metal products, except machinery and equipment"	
Wood	• "Wood and products of wood and cork (except furniture); articles of straw and plaiting materials"	• "Hout primair" • "Triplex e.d.van hout" • "Fineer/plaat v.hout" • "Raam/kozijn v.hout" • "Deuren v.hout" • "Ov.timmerwerk"
Concrete		• "Stenen van beton" • "Overige betonwaren" • "Bouwelem.v.beton" • "Beton/mortel"
Clay brick	• "Bricks, tiles and construction products, in baked clay"	• "Ov. Keramische prod."
Other minerals	• "Sand and clay"	• "Zand" • "Beton/mortel" • "Gips"
Glass	• "Glass and glass products"	• "Vlakglasproducten"
Ceramics	• "Ceramic goods"	• "Keram.Bouwmat/Tegels"
Plastics	• "Rubber and plastic products"	• "Bouwart.v.kunst."
Insulation	(no applicable category)	(no applicable category)

Since the EXIOBASE results were specific to the Dutch construction sector while the MFM results were for the entire Dutch economy, the EXIOBASE values were chosen for the final quantification of material origins for most materials. However, for concrete, the MFM values were used since there was no EXIOBASE product category for concrete, and concrete could be clearly matched to four MFM product categories. In addition, the MFM values were used for the "other minerals" category, which was divided into sand (51%), mortar (33%), and gypsum (16%) according to the proportions of each material within "other minerals" according to van Oorschot et al. (2023). MFM values were used in this case because EXIOBASE showed zero inputs of “sand and clay” to the Dutch construction sector, revealing a data gap in the database. While the EXIOBASE values do have the advantage of being specific to the construction sector, it should be noted that this includes residential and non-residential buildings as well as infrastructure. Therefore, this study assumes that the proportions of imported and domestically produced materials/products are the same for buildings and infrastructure.

The last step of quantifying material origins was determining the proportion of material input that comes from secondary materials. This data was derived from the study by Arnoldussen et al. (2022). For each material, the 2019 material inflow was multiplied by the proportion of secondary input to determine the secondary material inflow in tonnes. The remaining inflow was then divided between an imported and a domestically produced flow, based on the proportions calculated previously. Secondary materials were taken as a separate flow because it was not possible to determine whether they are imported or derived from domestic waste streams. This is because secondary materials have no monetary value and EXIOBASE is based on monetary transactions, meaning that secondary materials only become “visible” when they gain monetary value by being incorporated in a product. Their origin is therefore not traceable.

The last step of mapping the current state of material flows was to determine how the different waste streams from demolition are treated. For this, the percentage of each material that is recycled, incinerated, or landfilled was derived from van der Schuit et al. (2023). These values are specific to construction/demolition waste but include both buildings and infrastructure. For the “other” material categories, the waste treatment rates from Conde et al. (2022) were used, which are specific to building waste (residential and non-residential). For each material, the 2019 material outflow was multiplied by the proportion that is recycled, incinerated, or landfilled to determine the waste treatment flows in tonnes. In addition, according to Conde et al. (2022), about 6% of building demolition waste that is recycled becomes material input for buildings again, while the remaining 94% is downcycled and used as backfilling for infrastructure. Therefore, 6% of the recycled material outflow is assumed to be recycled back into residential buildings in this study as well.

The Excel file in appendix 8.1 contains all data used and calculations performed.

3.2 Quantifying baseline impacts

Since one of the main goals of a circular economy is to reduce climate change impacts (Ministry of Infrastructure and Water Management, 2023), the greenhouse gas emissions (GHG) caused by the material demand for housing in the Netherlands was calculated in order to gain an understanding of the current level of impact and the main contributors. In addition, due to the trend towards using more biobased materials in construction, land use impacts were investigated. Van Oorschot et al. (2023) has calculated the GHG emissions and land use associated with each building material’s primary and secondary production using Life Cycle Assessment (LCA) and the LCA background data database Ecoinvent (Wernet et al., 2016). The impacts calculated for primary material production include all processes from raw material extraction to material production. The impacts calculated for secondary material production consider “building demolition, material transportation, recycling, and secondary material production” (van Oorschot et al., 2023, p.538). These impact values were multiplied by the material inflows calculated for 2019 and combined in order to derive the total GHG emissions and land use of the current material demand for residential buildings. Material production is the main contributor to the embodied impacts of buildings, contributing to about 70% of embodied climate change impacts (Bijleveld et al., 2015; de Klijn-Chevalerias & Javed, 2017).

Therefore, while this impact assessment does not quantify the impacts across the full value chain, it represents the main contributor.

3.3 Creating an inventory of circular options

Options for increasing circularity were inventoried through desk research, gathering existing knowledge from grey and scientific literature. Sources like ARUP & Ellen MacArthur Foundation (2023), Bosch et al. (2023), Conde et al. (2022), and Eberhardt et al. (2022) provided an overview of circular options for buildings and were used to compile an initial list. These sources were found by searching for “circularity strategies for buildings” or were recommended by experts in circular construction. Circular options were included if they were related to delivering the function of housing, and not if they were only relevant to specific house components. This was decided for simplicity and in order to maintain the scope of viewing houses as products, instead of a collection of subproducts with individual circular options.

Since this study aims to investigate circular options for housing in the Netherlands, further research into each option was mainly restricted to this geographical scope. Therefore, often searching in Dutch yielded more relevant results than searching in English. Literature was found using search queries in Google such as “hoeveel transformatie nederland”, “potentie van modulair bouwen nederland”, or “potentie van woningsplitsing”, or looking in Google Scholar more generally for e.g. “adaptable housing”.

Sources were selected if they contained information about the current implementation of the circular option in the Netherlands, its scalability/potential, its estimated environmental impact, or its opportunities and barriers. This information was extracted from the literature and structured into an Excel spreadsheet, with the rows corresponding to different circular options (categorized within the four overarching circularity strategies), and the columns classifying the information by the topics listed previously. The main focus was on gathering quantitative information. Information about the actors involved in each option and the governance that would be required fall outside the scope of this study but would be a relevant area of future research to fully understand the potential of each option.

Most information on circular options for Dutch housing was found to be available in grey literature rather than scientific literature. Therefore, the main sources used were reports by for example the Economisch Instituut voor de Bouw (EIB), Metabolic, Circle Economy, NIBE, W/E Adviseurs, and reports prepared for the Ministry of the Interior and Kingdom Relations.

The resulting list of options and their classification into the overarching circularity strategies was discussed and verified with the team conducting the Product Group Analysis on residential buildings as part of the Work Program on Monitoring and Directing the Circular Economy.

For the circular option of modular construction, interviews with modular construction companies (supplemented with desk research) were used to gain insight into the potential of modular construction, the material intensities of modular buildings, the reusability of modules/components/materials, house lifespans, and the main benefits, and barriers. Two companies were interviewed: one large modular company whose buildings use conventional materials and one small modular company whose buildings use more biobased materials. These companies were recommended by an industry expert at TNO. However, they were ultimately selected because they represent two different modular building propositions with different material compositions, both companies focus on modularity and reusability (not only industrial production), and they both produce a variety of housing types.

3.4 Modelling the impacts of modular construction

Once an overview of circular options for housing was created, the research focus was narrowed to modular construction. Dynamic MFA was used to model the development of dwelling and material stocks and flows over time and analyze how the large-scale adoption of modular housing in the Netherlands could influence the material flows for residential buildings towards 2100. Dynamic MFA is a commonly used method for analyzing material stocks and flows over time and evaluating potential for circularity (B. Müller, 2006; Deetman et al., 2020; van Oorschot et al., 2023; Yang et al., 2022). Given the long lifespan of residential buildings, this dynamic approach to mapping material flows (as opposed to an accounting or static approach) is crucial.

Two scenarios were modelled: a baseline scenario in which traditional construction methods for housing continue to be used between 2019 and 2100 and a modular scenario in which more modular construction methods are used. Modular housing can either use conventional materials like concrete and steel or be wood based (Bertram et al., 2019). In this study, the modular scenario uses conventional materials. A modular scenario using biobased materials is not modelled due to the lack of insight into the reusability of the materials, but the material composition of a biobased modular house is still presented.

Figure 3.2 gives an overview of how the model was made.

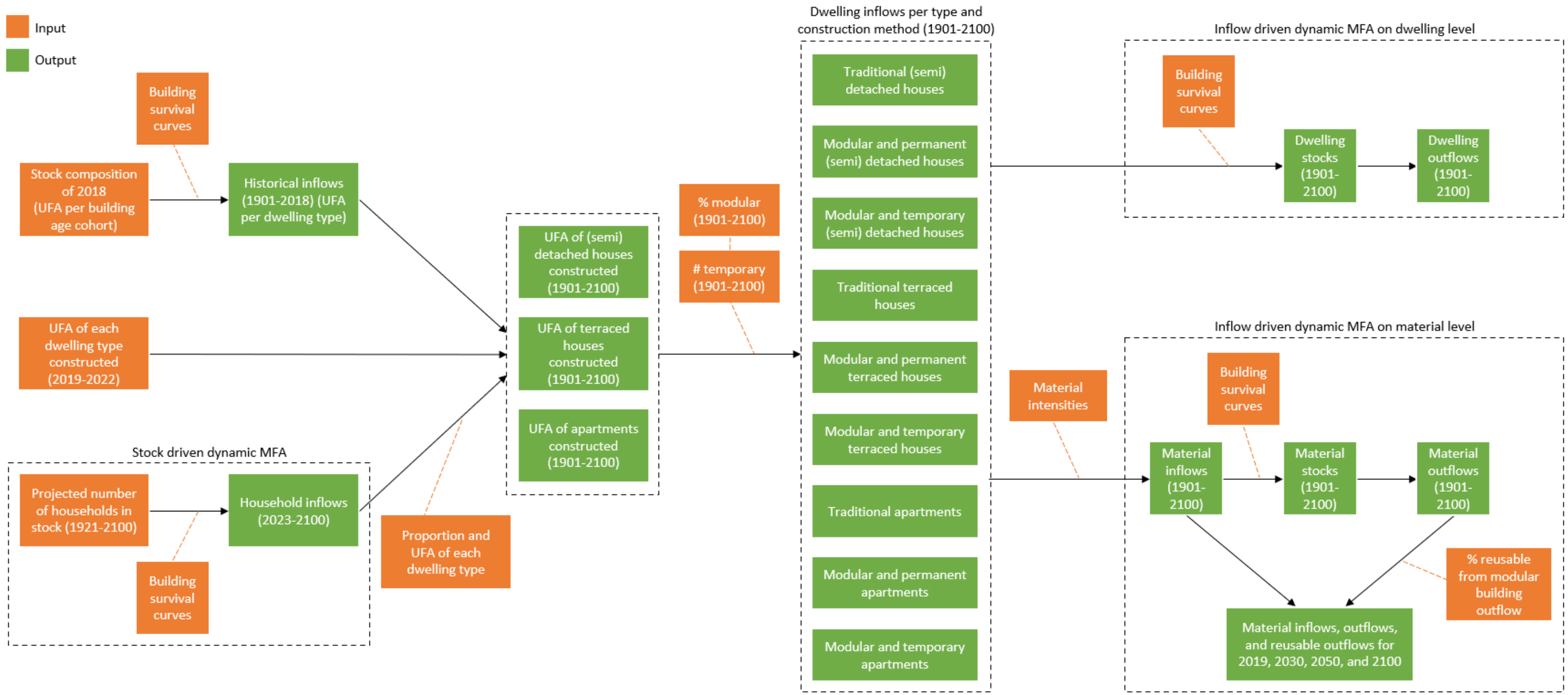

Figure 3.2 Model overview.

The first step was to create a dataset containing the UFA of detached/semi-detached houses, terraced houses, and apartments constructed between 1901 and 2100. The model includes all housing constructed since 1901, so that the eventual outflow of materials from the existing housing stock is taken into account. It is assumed that all houses built before 1901 are protected as historical buildings and are therefore not demolished. The model extends to 2100 due to the long lifespan of houses (around 75 years) and the importance of considering end-of-life module/component/material reusability when evaluating the potential impacts of modular housing. Material flows related to the replacement/renovation of individual components during a building's lifespan, and the reuse flows that are possible here, are not taken into account in this dynamic model, but a are visible in a static MFA model presented in chapter 4.4.

In order to approximate the dwelling inflows between 1901 and 2018, the composition of the housing stock in 2018 from van Oorschot et al. (2023) was used. This dataset defines the UFA of detached/semi-detached houses, terraced houses, and apartments in stock in the Netherlands in 2018, per year of construction dating back to 1901. A survival curve for these buildings was created assuming a Weibull distribution, an average lifespan of 120 years, and a shape parameter of 2.95, since this was found to be a suitable survival curve to be used in dynamic stock models for housing in the Netherlands by Deetman et al. (2020). Given this survival curve, the share of each age cohort that should theoretically still exist in 2018 was derived. Assuming that this share is equal to the amount actually remaining in stock in 2018, the size of the original inflows was calculated. Though these calculated historical dwelling inflows differ slightly from the CBS construction numbers for these years (CBS, 2023d), the method does come close to recreating the CBS values (appendix 8.2). It was chosen to use these calculated inflow values in the model rather than the CBS values in order to yield the correct 2018 dwelling stock composition, which allows for a more accurate approximation of the outflows from the existing housing stock. Calculating the historical dwelling inflows in this way and comparing them to the CBS values also validated the use of a Weibull distribution survival curve and the chosen parameters.

Data for the year 2019 was taken from the quantifications made earlier in this study and, for the years 2020 to 2022, the number of homes constructed in each year was taken from the CBS database (CBS, 2023e). To divide the total number of homes constructed between the different dwelling types, several assumptions were made. Since in 2019, 61% of newly constructed homes were single family homes and 39% were multi-family homes, the same proportion was assumed for 2020-2022 (Arnoldussen et al., 2022). The number of single-family homes was divided between detached/semi-detached homes and terraced homes based on the composition of the stock of single-family homes in 2022, of which 34% were detached/semi-detached houses and 66% were terraced houses (CBS, 2023c). Lastly, the number of each type of dwelling constructed was converted to the UFA constructed, based on the average UFA per dwelling type in 2019 (195 m^2 for detached/semi-detached houses, 123 m^2 for terraced houses, and 69 m^2 for apartment buildings).

To complete the dataset of UFA constructed between 1901 and 2100, it was then needed to project the number of houses that might be constructed between 2023 and 2100. A stock driven dynamic MFA model was used to calculate, based on the projected development of the household stock, the necessary inflows of new housing. As input for this model, the household stock development from 1921-2022 was taken from CBS (2023d). Stock developments from this far back were included in the model so that outflows from the stock existing before 2023 and the need to replace these outflows was taken into account. For 2023-2070, the household stock projections from CBS (2023a) were used. To project the household stock development from 2070-2100, population projections for the Netherlands were taken from Eurostat (2023b). The declining population trend after 2070 was taken from these projections, but the values were scaled, taking the 2070 population estimate from CBS (2023a) as the starting point. Using these population projections (appendix 8.3) and continuing the decreasing trend of people per household that was seen in the 2023-2070 CBS data, the number of households between 2070-2100 was calculated. The complete dataset of household stock development from 1921 to 2100 was input for a stock driven dynamic MFA model, which then calculated the inflows of new houses over this time period. This stock driven model assumes a 120-year average lifespan for housing built before 2019, in accordance with Deetman et al. (2020), and a 75-year average lifespan for housing built in 2019 or later, as this is the typical lifespan used for calculating the environmental performance of newly built residential buildings in the Netherlands (Dutch Environmental Database, 2020). Arnoldussen et al. (2022) projects that in 2050, 48% of new homes constructed will be single family homes and 52% will be multi-family homes, showing the trend towards more multi-family homes in the future. These values together with the assumptions mentioned previously about the proportion of detached/semi-detached homes and terraced homes within "single-family homes" and the average UFA per dwelling type in 2019, were used to convert the calculated dwelling inflows into inflows per dwelling type in UFA.

Once the dwelling inflows per type were calculated for 1901-2100, the share that are built using traditional construction methods and modular construction methods had to be determined. Even though modular construction is not a new concept, the model assumes no modular construction before 2019 since its market share was still small (less than 7%) (Rutten, 2023a). Rutten (2023a) has gathered data on the number of industrially produced homes between 2019 and 2022, in which "industrial housing" is defined as homes which are wind and watertight within 10 days and completed within 50 days. Although not all of these homes are necessarily modular, given the companies included in the quantification, it is assumed that most of them are. According to Rutten (2023a), 14% of new built houses were industrially built in 2022. Therefore, in the baseline scenario, this 14% share is assumed to continue to 2100 (Table 3.2). In the modular scenario, however, the share of modular construction increases from 20% in 2023 (Rutten, 2023b), to 50% in 2030 (as is the goal for industrial housing in the National Circular Economy Program) (Ministry of Infrastructure and Water Management, 2023), and then to 80% in 2100 (interview with company B), growing linearly between the years. Besides being used for permanent housing, modular housing is also often used for temporary housing. The number of modular houses that are permanent and temporary over the years was based on Hagen & de Vos (2023) & Ministry of the Interior and Kingdom Relations (2022).

Table 3.2 Share of modular construction and the number of temporary houses assumed in the two scenarios.

	Baseline scenario		**Modular scenario**	
	% modular	# temporary	% modular	# temporary
2019	6%	1840	6%	1840
2020	8%	2112	8%	2112
2021	10%	2829	10%	2829
2022	14%	4000	14%	4000
2023	14%	4000	20%	8000
2024	14%	4000	24%	12000
2025	14%	4000	29%	12000
2026	14%	4000	33%	9600
2027	14%	4000	37%	8000
2028	14%	4000	41%	6400
2029	14%	4000	46%	4000
2030	14%	4000	50%	4000
…	…	…	…	…
2100	14%	4000	80%	4000

Finally, the inflow driven dynamic MFA models were made: one on the dwelling level and one on the material level. Three different survival curves were used. As described previously, houses built before 2019 were assumed to have a 120-year average lifespan and permanent houses built in 2019 or later were assumed to have a 75-year average lifespan, both following a Weibull distribution with a 2.95 shape parameter (Deetman et al., 2020; Dutch Environmental Database, 2020). However, for temporary houses built in 2019 or later, a fixed lifetime survival curve was used, in which the buildings are in use for exactly 15 years after which they are demounted (Hagen & de Vos, 2023). On the dwelling level, the dwelling inflows and survival curves were used to calculate the dwelling stocks and outflows towards 2100. To convert this to the material level, the dwelling inflows were multiplied by the material intensities of the different dwelling types to derive the material inflows. The material intensities used for traditional buildings were from Arnoldussen et al. (2020, as cited in van Oorschot et al., 2020) and the material intensities for modular buildings were gathered from the modular housing companies interviewed. The same modular material intensities were used for all three housing types, but since the buildings are built modularly, it can be assumed that the material compositions across housing types are similar (interview with company B). The same building survival curves were applied to the materials to calculate the material stocks and outflows over time.

The material inflows and outflows in 2019, 2030, 2050, and 2100 were extracted as the final results. In addition, the material outflow that came from modular housing was multiplied by the reuse percentages provided by one of the modular housing companies in order to quantify how much of the material outflow could be reused in new housing. It is important to note that this reusable outflow refers to the materials that are reusable by means of building component reuse and refurbishment and does not refer to material recycling. In addition, although material outflows from traditional buildings are also reused in some cases, this is assumed to be minimal and therefore excluded. Ultimately, it was possible to visualize the material inflows and outflows for the chosen years under a baseline and modular scenario and analyze how much of the material inflows could be replaced by the outflow given the reusability of modular components. The python code for the model can be found in appendix 8.4.

4 Results

4.1 Baseline stocks and flows

4.1.1 Current situation overview

In 2019, there were 7,891,785 homes in the Netherlands (CBS, 2023b). As can be seen in Figure 4.1, the largest addition to the housing stock came from new construction. Several new homes were also created through the transformation of non-residential buildings into residential buildings and the splitting of houses into two or more separate residences. Homes were mainly withdrawn from the stock due to demolition, although the merging of houses also played a role. The flows for data correction represent administrative adjustments due to, for example, changes in how residential units in nursing homes or student complexes are counted.

Figure 4.1 Number of homes added and removed from the Dutch housing stock in 2019, based on data from CBS (2023a). The orange box representing the stock is not drawn to scale.

As can be seen in Table 4.1, apartments accounted for the largest share of new construction and demolition, followed by terraced houses, and then detached and semi-detached houses (Arnoldussen et al., 2022).

Table 4.1 Number of houses constructed and demolished per housing type in 2019 (Arnoldussen et al., 2022).

	Number constructed	**Number demolished**
Detached or semi-detached houses	17800	1200
Terraced houses	25800	3900
Apartments	27900	5700

4.1.2 Material composition

For the three types of residential buildings analyzed in this study, Figure 4.2 illustrates the different material intensities per year of construction. Detached and semi-detached houses have the highest material intensity, followed by terraced houses, and then apartments. For all three building types, the material intensity has increased over time, but appears to be plateauing. Concrete accounts for the majority of each buildings' composition, followed by other minerals and clay brick, although the amount of clay brick per square meter has decreased. The "other minerals" category includes sand-lime brick, gypsum, bitumen, mortar, stone, and fill sand. Although Figure 4.2 indicates that the amount of wood in residential buildings has also decreased over time, current trends show an increased amount of wood and biobased materials being used (Bosch et al., 2023).

Figure 4.2 Material intensities per type of residential building and year of construction according to Arnoldussen et al. (2020, as cited in van Oorschot et al., 2020, 2023).

4.1.3 Product chain and material stocks and flows

The quantification of the material stocks and flows for the three residential building types in the Netherlands in 2019 can be seen in Figure 4.3. The diagram also illustrates where the construction materials/products come from (in terms of where they are lastly manufactured) and how the materials are treated after demolition.

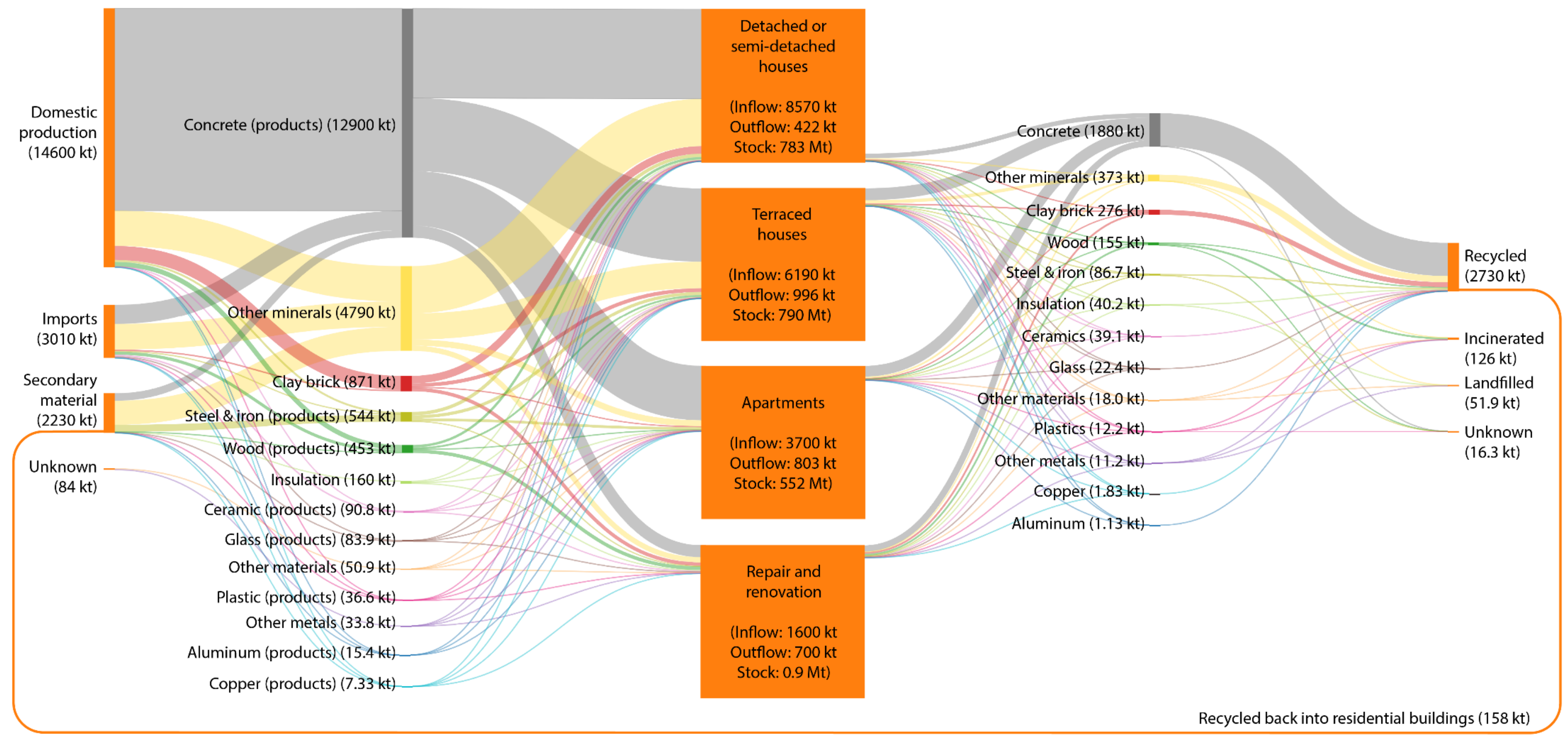

Figure 4.3 Material stocks and flows for residential buildings in the Netherlands in 2019. The orange boxes representing stocks are not drawn to scale.

The results show that 73% of construction materials/products are lastly manufactured in the Netherlands before entering the building stock. Only glass, ceramic, and plastic products rely more on imports than domestic production. In addition, about 11% of the material input for residential buildings comes from secondary material.

Even though more terraced houses and apartments were constructed in 2019 than detached or semi-detached houses, the latter were responsible for the largest inflow of materials due to their higher material intensity and larger UFA. Apartments accounted for the largest number of newly constructed homes, but, due to their lower material intensity and smaller UFA, demanded less material input than the other two housing types.

Of the materials in stock in residential buildings in 2019, 37% were in detached and semi-detached houses, another 37% were in terraced houses, and 26% were in apartment buildings. It is important to note that the orange boxes representing material stocks in Figure 4.3 are not drawn to scale in order to make the material flows visible. The magnitude of the material stock relative to the flows can be seen in Figure 4.4.

Detached and semi-detached buildings accounted for the smallest material outflow, despite having the largest material inflow. This makes them the largest contributor to the growing material stock. The largest material outflow came from terraced houses because, even though more apartments were demolished, terraced houses have a higher material intensity and larger UFA. In addition, it can be seen that a significant portion of the material outflow (24 %) comes from repair and renovation activities.

The results indicate that 93% of demolition waste is recycled. However, only a small fraction of this flow (6%) is recycled back into residential buildings, while most is downcycled for use in infrastructure. As can be seen in Figure 4.3, the material that is recycled back into buildings only meets about 7% of the demand for secondary material input, suggesting that the majority of secondary material in houses comes from the waste streams of other sectors. It is also possible to see that, even if all demolition waste was perfectly reused or recycled back into housing, only 15% of the total material demand for new construction could be met. Conde et al. (2022) estimates that this value is closer to 20%, but this still falls short of meeting the material demand. This indicates that, in order to achieve circularity for residential buildings, the main focus should be on reducing the material inflow required.

Figure 4.4 Material inflow, stock, and outflow for residential buildings in 2019, showing the magnitude of the stock.

4.2 Baseline impacts

For each construction material used, Figure 4.5 shows the GHG emissions and land use impacts for primary and secondary production, as calculated in van Oorschot et al. (2023). Aluminum and copper have the highest GHG emissions per kilogram produced, followed by insulation materials, steel and iron, and plastics. The mineral products have lower GHG emissions per kilogram produced, and wood has the lowest. For almost all materials, secondary production results in less GHG emissions than primary production. The only exception is wood, which has higher GHG emissions for secondary production. In addition, wood has significantly higher land use impacts.

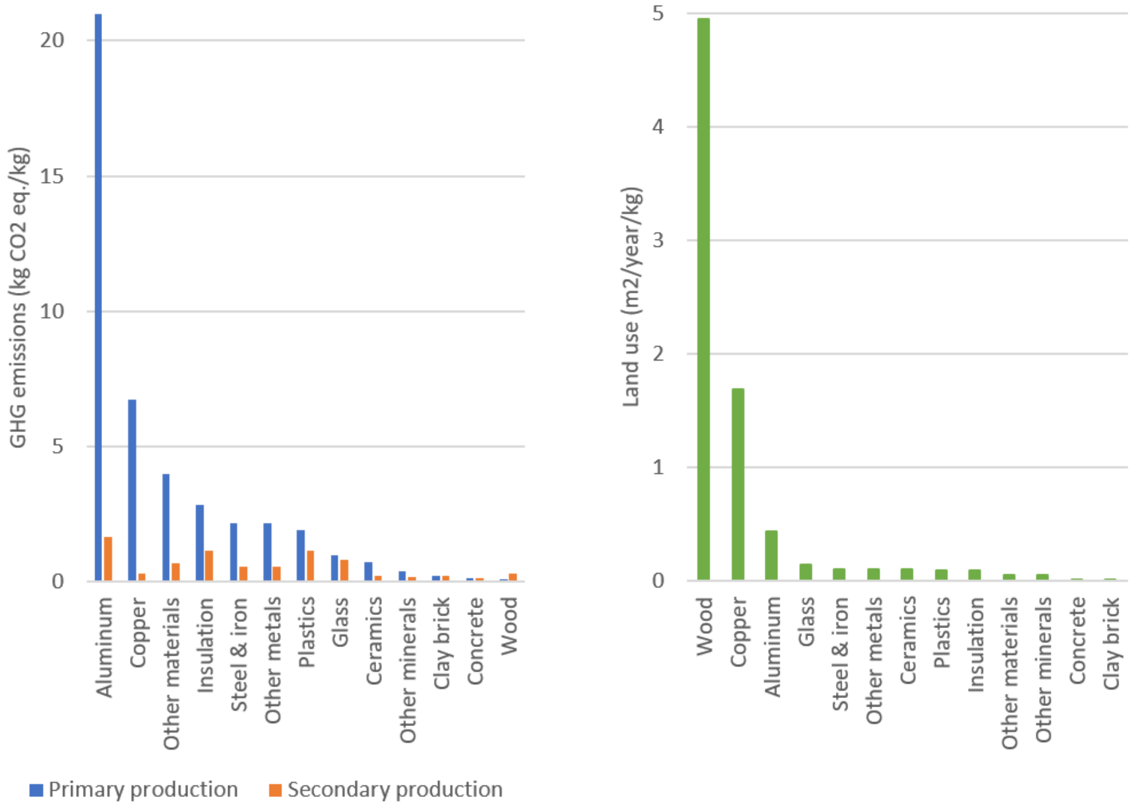

Figure 4.5 GHG emissions and land use for the production of each construction material (van Oorschot et al., 2023).

Even though concrete and other minerals have some of the lowest GHG emissions per kilogram, the sheer amount that is used in construction means that these two material categories contributed to most of the GHG emissions of the material input for residential buildings in the Netherlands in 2019 (61%) (Figure 4.6). Wood contributed to most material-related land use impacts (85%).

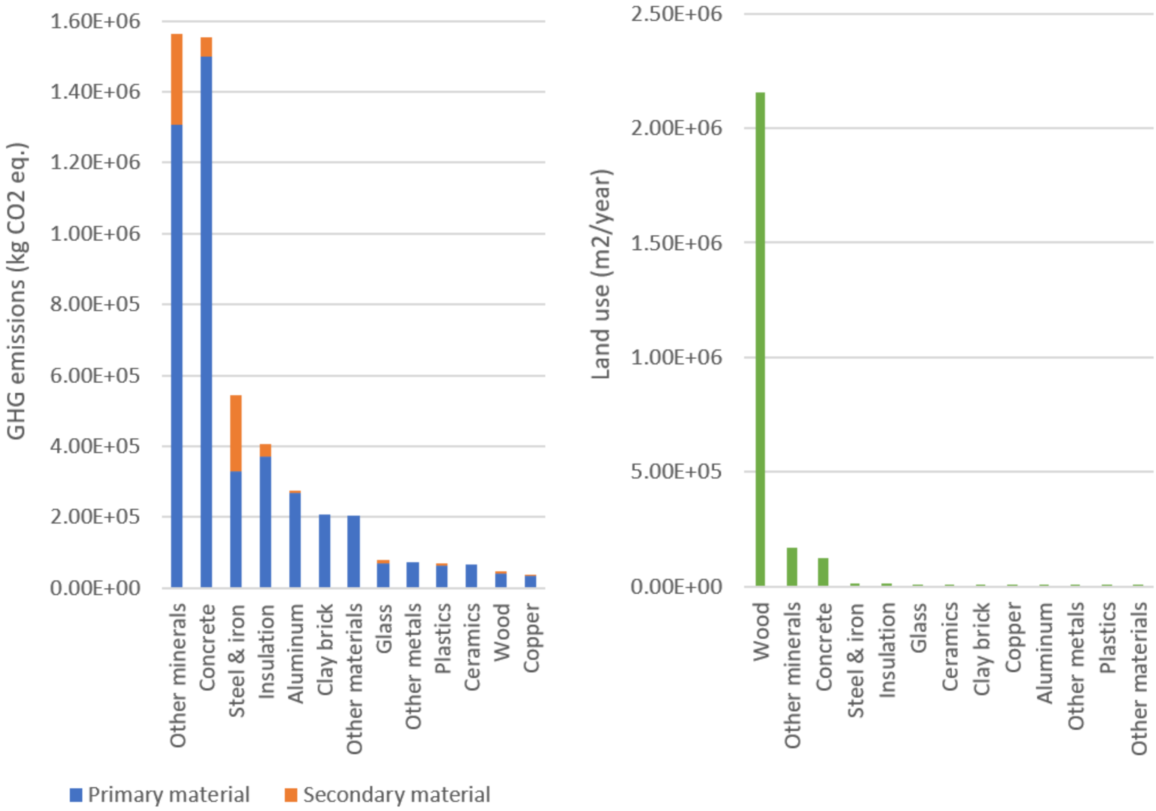

Figure 4.6 Total GHG emissions and land use impacts from the material input for residential buildings in the Netherlands in 2019.

4.3 Circular options

The principles of a circular economy can be used to reduce the environmental impact of the materials required for housing. The following section describes various circular options for residential buildings, grouped within the four overarching circularity strategies: substitution, narrowing the loop, slowing the loop, and closing the loop.

4.3.1 Substitution

4.3.1.1 Biobased materials

About 3% of material inputs for housing are currently biobased (Bosch et al., 2023). However, Conde et al. (2022) and van der Velde & van Leeuwen (2019) estimate that this could increase to 50% if biobased materials are implemented to their full technical potential. Since biobased materials are less carbon intensive than traditional materials, are regenerative, can store carbon, and are lighter, their use can contribute to minimizing the mass and greenhouse gas emissions of materials used in construction (van der Velde & van Leeuwen, 2019).

Table 4.2 compares the embodied greenhouse gas emissions of a traditional corner house and apartment with a biobased corner house and apartment, showing that the biobased alternatives have 30-40% less impact (van der Velde & van Leeuwen, 2019).

Table 4.2 Embodied greenhouse gas emissions of a traditional vs. biobased corner house and apartment (adapted from van der Velde & van Leeuwen (2019)).

	Traditional building		**Biobased building**	
	% biobased by weight	kg CO_2 eq./ m2 GFA/ year	% biobased by weight	kg CO_2 eq./ m2 GFA/ year
Corner house	1.2	6.43	67	3.86
Apartment	0.5	5.39	50	3.80

However, while biobased materials like wood cause less GHG emissions during production, the impact on land use is significantly higher compared to other construction materials (Figure 4.5, Figure 4.6) (van Oorschot et al., 2023). It is important to note that the impacts of this land use on, for example, biodiversity, are not adequately taken into account in current LCA methodologies, though this is crucial to consider when evaluating the true environmental impact of a more biobased economy (Pawelzik et al., 2013). Lastly, it is important to note that the ability of biobased materials to store CO_2 is often seen as a sustainability advantage, but in the bigger picture, this carbon storage is temporary, making it crucial to prioritize sustainable forest management (Barendregt et al., 2023).

Bosch et al. (2023) modelled a scenario in which 50% of the materials used for newly constructed ground-level homes and 30% of the materials used for newly constructed apartment buildings are biobased by 2030. The study concludes that this could result in a 6.7% reduction in CO_2 emissions, an 11.7% reduction in material use, a 3.4% reduction in cost, and a 4.2% reduction in environmental impact. Buildings would use an average of 50% less material by weight since biobased materials are lighter. In this study, biobased construction is found to reduce the CO_2 emissions per square meter of GFA by 36%, and this increases to 77% if the CO_2 uptake of the biobased materials is taken into account.

If 48% of material inputs for residential buildings would be biobased by 2050, Conde et al. (2022) estimates that this would reduce the greenhouse gas emissions of the material input by 58% (or

123% if the carbon storage is taken into account). The mass of the material input would also decrease by 65%.

If 80% of newly constructed buildings between 2018 and 2050 would be biobased, overall material demand would decrease by 50%, with wood demand tripling compared to a business-as-usual scenario. 29% of the material demand could be met by secondary materials, despite the outflow of material representing 83% of the inflow. This is because of the limited high-value recycling rates and maximum recycled contents in current practices, as well as the differences in the material compositions of the inflows and outflows. Climate change impacts would be reduced by 45%, but 16,300 square kilometers of land would be needed for wood production (which is 39% of the Netherland's total surface area). This is in comparison to a business-as-usual scenario where 4,900 square kilometers (12%) is required (van Oorschot et al., 2023).

Wood from Dutch forests will not be sufficient to meet the demand from increased timber construction. Already for the current wood demand, 94% is imported. The amount of wood harvested from Dutch forests that is suitable for construction (currently 0.1 million cubic meters per year) would only be enough to construct about 3,900 timber frame houses and 1,900 cross-laminated timber houses per year. Therefore, increasing the amount of biobased construction will require an increased dependence on timber imports, which goes against one of the goals of a circular economy which is to increase supply security (Luijkx et al., 2021). However, Luijkx et al. (2021) predict that, on the European scale, it will be possible to meet the increased demand for wood. The yearly European demand for wood is projected to increase by 24.7 million cubic meters due to an increase in timber frame construction. Through the adoption of more sustainable forest management practices, 50 million additional cubic meters of wood could be produced per year in Europe, and this would be enough to cover the increased demand (Luijkx et al., 2021). However, biobased materials are increasingly being seen as a more sustainable alternative for many products, and this must be considered when evaluating the availability of biomass. Demand for wood for energy generation could also reduce the biobased materials available for construction (van der Velde & van Leeuwen, 2019). In addition, it is important to make sure that the demand for biomass does not jeopardize food supply (Barendregt et al., 2023).

Main barriers for biobased construction are that is more expensive, and that it is less familiar than traditional construction with traditional materials (van der Velde & van Leeuwen, 2019). Industrialization, however, is currently facilitating the increase in timber construction, allowing for greater production capacity, resource efficiency, and reduced failure costs (Luijkx et al., 2021).

4.3.2 Narrowing the loop

4.3.2.1 House splitting

Most of the current housing stock consists of family homes, while three-fourths of house-seekers are one or two person households (Wassenberg & ten Kate, 2023). Through house splitting, the current housing stock can be used to its maximum potential, reducing the need for new construction and preventing the associated environmental impact (Bosch et al., 2023). New homes can also be created faster and without the need for additional land (Wassenberg & ten Kate, 2023). In particular, many elderly people live in homes that have become too large for them. House splitting gives them the opportunity to stay in their home, but in a smaller part of it (de Jonge, 2023).

There are seven types of house splitting: simply moving in with others without a contract, when rooms are rented out by the current residents of the house, getting a joint contract with friends, room-by-room rental in a house, "soft splitting" where some facilities are shared, architectural splitting, and legal house division (Wassenberg & ten Kate, 2023). House division created 1,855 new homes in 2019 and 2,200 new homes in 2021 (CBS, 2023b). Bosch et al. (2023) estimates that house sharing could create 6,000 additional living spaces per year, for a total of around 50,000 between 2023 and 2030. Geuting et al. (2023) estimates that the potential could be even higher, with the possibility to create 80,000-160,000 additional homes through house division by 2030. Figure 4.7 and Figure 4.8 show the percent of the 2023 housing stock that could realistically be used for house division, per housing type and building age (Geuting et al., 2023). Since the elderly population realistically has the most interest in house division, the estimates by Geuting et al. (2023) only consider elderly-owned homes. This suggests that the overall potential of house splitting could be even greater.

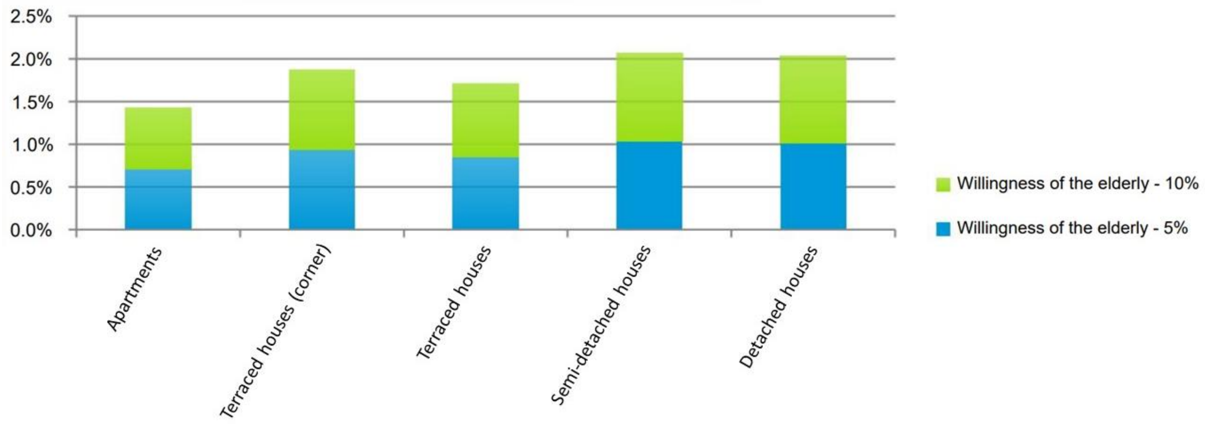

Figure 4.7 Share of housing stock with potential for house division, per housing type (Geuting et al., 2023).

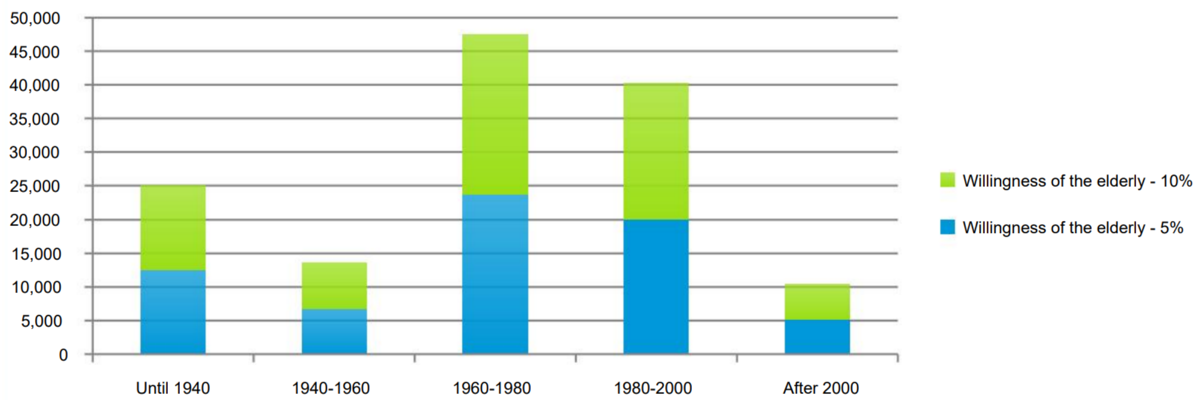

Figure 4.8 Share of housing stock with potential for house division, per period of construction (Geuting et al., 2023).

However, several barriers to house splitting exist. People are often unaware of the possibilities and regulations surrounding house splitting, and, in some municipalities, house splitting is not allowed or restricted (de Jonge, 2023). There can also be disadvantages from a tax perspective (Bosch et al., 2023). Furthermore, the Dutch housing policy is based on individual households. For example, rent allowance is not possible if friends rent a house together, if there is room-by-room rental, or with "soft splitting". Some are opposed to house splitting because, with more people living in a house, there is more risk of disturbance to neighbors. Some forms of house splitting can also require expensive renovations, like with architectural splitting, but this is still cheaper than building a new house. Lastly, house splitting requires different and possibly more management by housing corporations (Wassenberg & ten Kate, 2023).

4.3.2.2 Building smaller houses

Constructing smaller houses would also reduce the material demand and environmental impact of new construction. Bosch et al. (2023) created a scenario for 2023-2030 in which 25% of the planned construction of ground-level houses was replaced with apartment buildings and all housing types were constructed 10% smaller. The study finds that reducing home sizes in this way would result in a 7.5% reduction in CO_2 emissions, an 8.1% reduction in material demand, a 7.3% reduction in cost, and an 8.2% reduction in environmental impact.

4.3.2.3 Adding floors on top of existing buildings

Building more floors on top of existing buildings reduces the material needed for the construction of new homes since foundations do not need to be built. According to Bosch et al. (2023) the vertical extension of existing buildings reduces the material demand per square meter by 80% and the CO_2 emissions per square meter by 26%, compared to a newly constructed apartment building.

Geuting et al. (2023) estimates that 97,900 homes could be created on top of existing apartment buildings, with most potential lying in urban areas. Of these 97,900 homes, 43% could be built on top of apartment buildings that were constructed between 1965 and 1992, 40% could be built on top of apartment buildings from 1992 to 2008, and 17% could be built on top of apartment buildings built after 2009. Buildings above 12 floors high are difficult to extend, and therefore 92% of the potential lies in extending buildings that are between 3 and 8 floors high. It is typically possible to add one or two additional floors. Besides the homes that could be realized on top of existing apartment buildings, there is also large potential to build homes on top of existing non-residential buildings, but this potential has not yet been quantified (Geuting et al., 2023).

Current initiatives for vertical extension are scattered and small scale, which means knowledge about costs, revenues, processes, and possibilities is limited. In addition, since each project is individually approached to find a custom solution, the process is expensive and time consuming and requires specific expertise (de Jonge, 2023). However, the vertical extension of buildings could be facilitated through standardization and modular construction and can be combined with existing renovation plans to improve the energy performance of buildings (de Jonge, 2023; Geuting et al., 2023).

4.3.2.4 Transforming existing non-residential buildings into housing

Since 2012, about 15% of new homes have been created through the transformation of non-residential buildings. This has mostly been through the transformation of offices, but increasingly also shops and other commercial buildings (Gelinck & Kersten, 2022). Transformation created 12,490 new homes in 2019, 10,215 new homes in 2020, and 10,480 new homes in 2021 (CBS, 2023b). Though most "low hanging fruit" has already been transformed, there is still potential to continue to create homes through transformation (Gelinck & Kersten, 2022).

The Dutch government has set the goal of creating 15,000 new residences per year through transformation up until 2030 (Ministry of Infrastructure and Water Management, 2023). In 2021, there was more than 20 million square meters of unused space in existing buildings. 11.5% of the office building stock was empty, which is equivalent to 5.5 million square meters. 1.8 million square meters of this empty office space is estimated to have transformation potential, which could create 26,000 new homes. Therefore, between 2022 and 2030, it is estimated that between 4,500 and 7,000 new homes could be created through the transformation of office buildings per year. In addition, from the currently vacant retail buildings, about 10,000 homes could be created. This means that between 2,250 and 3,600 homes could be created per year through retail transformation between 2022 and 2030. The number of homes can be further increased by reducing the floor area per household. Gelinck & Kersten (2022) conclude that, under a business-as-usual scenario, between 6,500 and 10,600 homes will be created per year through transformation between 2022 and 2030. With support from policy, however, this could increase to between 17,000 and 22,000 per year (Gelinck & Kersten, 2022).

Since elements like foundations, floors, stairs, and roofs do not need to be built, transformation reduces the material needed per square meter by 88% and the CO_2 emissions per square meter by 56%, compared to a newly constructed building (Bosch et al., 2023; Conde et al., 2022). Bosch et al. (2023) developed a scenario in which the number of homes created through transformation grows from 9,000 per year in 2023 to 28,000 per year by 2030, and 95,000 new homes are created by 2030 through vertical extension as described in the previous section. If implemented, this scenario would lead to a 9.8% reduction in CO_2 emissions, a 19.4% reduction in material demand, a 1.5% reduction in cost, and an 8.3% reduction in environmental impact. Combined, the strategies of transformation and vertical extension provide the greatest impact reductions compared to high value reuse, smaller construction, biobased building, and industrialization, according to Bosch et al. (2023). This is logical since decisions made early in the design process, such as re-evaluating whether a new building is even necessary, typically have the largest impact reduction potential (ARUP & Ellen MacArthur Foundation, 2023). In the longer term, 7% of new housing construction could be avoided each year up until 2050 through transformation, which is equal to 135,000 square meters of new construction avoided per year (Conde et al., 2022).

Barriers for transformation include the availability of information about the existing structure and its residual lifespan, outdated aesthetics, regulations for transforming heritage buildings, and legal requirements for residential buildings that might not be met by office buildings (ARUP & Ellen MacArthur Foundation, 2023; Remøy & van der Voordt, 2014). In addition, uncertainty in terms of what problems may arise presents a financial risk (Bosch et al., 2023). Furthermore, in 2021, 55% of vacant offices were located in office districts and 25% were in business parks. These areas are not considered suitable or attractive for housing, requiring the surrounding area to be transformed to some extent as well (Gelinck & Kersten, 2022; Remøy & van der Voordt, 2014).

Despite these barriers, several aspects also incentivize the transformation of buildings. Investment costs for transformation are about 10% lower than for new construction and heritage buildings can be preserved by giving them a new function (ARUP & Ellen MacArthur Foundation, 2023; Bosch et al., 2023). Particularly for vacant office buildings, transformation can be an attractive opportunity. Selling a vacant office building is a financial loss for the owner since office buildings are valued according to their potential rental yield. Renovating an office building for a different office market segment is a risky investment given the high office vacancy levels. Demolition and new construction takes time and resources and creates a period of no rental income. As an alternative, transformation makes use of the existing building and has a short development time compared to new construction (Remøy & van der Voordt, 2014).

4.3.2.5 Industrialization and prefabrication

Over the past few years, the amount of industrially produced homes has increased from 4,461 in 2018 (7% of newly constructed homes), to 10,100 in 2022 (14%) (Bosch et al., 2023; Rutten, 2023a). The goal of the National Circular Economy Program is to meet half of the new construction demand with industrially and digitally produced housing by 2030 (Ministry of Infrastructure and Water Management, 2023).

Industrialized construction can reduce material consumption since digital design tools can be used to create material efficient designs, and manufacturing processes can be optimized to reduce waste

(Kedir & Hall, 2021). According to Bosch et al. (2023), an industrially made building is about 18% lighter than a traditionally made building, however data gathered through interviews shows that industrially made buildings can be up to 80% lighter (company A; company B). Since with industrialized construction, the building elements or even entire buildings are produced in a factory, fewer and simpler construction activities need to take place on the construction site. As a result, there is less energy consumption at the construction site, and it is estimated that nitrogen emissions on site can be reduced by about 50% (Bosch et al., 2023; Kedir & Hall, 2021). Less trips are also needed to and from the construction site (Bosch et al., 2023). However, specific transportation impacts are highly dependent on the distance between manufacturing sites and construction sites, the materials used, whether the products are panelized or volumetric, the level of prefabrication, etc. (Kedir & Hall, 2021).

Additional benefits of industrialized construction include the ability to create higher quality and lower cost housing, a more predictable production price, less risk of error, and less susceptibility to weather conditions (Bosch et al., 2023; de Ruiter & Koning, 2023; Ministry of Infrastructure and Water Management, 2023). The buildings can be quickly assembled, meaning the need for housing can be more quickly addressed, and the disruption of construction to the surrounding neighborhood is minimized (de Ruiter & Koning, 2023). Less labor is also needed, depending on the level of industrialization (de Ruiter & Koning, 2023). Furthermore, industrialization can facilitate a material tracking system between actors in the supply chain due to the increased digitalization of activities (Kedir & Hall, 2021). The use of more biobased materials is also facilitated due to a more controlled production environment (Bosch et al., 2023; Ministry of Infrastructure and Water Management, 2023).

However, since more activities are carried out by machines, less craftsmen and more machine operators are needed. The way of working is simpler and more repetitive and traditional construction workers may see this as a threat to their profession (de Ruiter & Koning, 2023). Another disadvantage of industrialized construction is that design options are predetermined to a certain extent, which can limit the ability to meet the design characteristics desired (de Ruiter & Koning, 2023; interview with company A).

A barrier for industrial construction is that it has high upfront investment costs needed for factories and machinery. In addition, although an industrial business model is generally cheaper, it can only survive with continuity and volume, and the housing sector is highly discontinuous. The discontinuous market might limit the economic viability and growth of industrial construction (R. Zuidema, personal communication, September 19, 2023). Furthermore, decisions to renovate existing buildings rather than building new homes could limit the growth of industrial housing (de Ruiter & Koning, 2023).

Bosch et al. (2023) estimates that increasing industrialized construction to 50% by 2030, would only result in a 1% reduction in CO_2 emissions, a 5.2% reduction in material use, a 5.6% reduction in cost, and a 1% reduction in environmental impact. However, this impact estimate only considers the material related impacts (assuming an 18% lighter material composition) and does not take into account for example the reduced construction waste, reduced emissions on the construction site, and reduced transportation.

4.3.2.6 Material efficient design

A final option for narrowing resource loops is minimizing the material intensity of buildings through lightweighting and smart design. For example, initial research suggests that concrete use could be cut in half through biomimetic design. Reducing the concrete used in foundations and structures by

50%, could reduce the primary material consumption of new construction by 18% and reduce greenhouse gas emissions by 7%. However, in reducing the material intensity of buildings, the structural integrity and energy performance of the buildings should not be compromised (Conde et al., 2022).

4.3.3 Slowing the loop

4.3.3.1 Renovation and retrofitting

Renovating and retrofitting the current housing stock can extend the lifespan of existing buildings and reduce the need for new construction.

Half of the current renovation activities for residential buildings in the Netherlands (in monetary terms) are related to improving a building's energy performance and sustainability. These renovations include improving the roof insulation (30%), installing solar panels (21%), replacing heating installations (16%), improving exterior wall insulation (12%), etc. (Arnoldussen et al., 2022). Renovating an existing house to be natural gas free increases the building's material related CO_2 emissions. For a 1960s apartment building, the material related impacts increase from 3.58 kg CO_2 eq/m2/year to 3.94-4.01. For a 1960s terraced house, the material related impacts increase from 3.23 kg CO_2 eq/m2/year to 3.69-3.70. However, the energy related CO_2 emissions for an apartment building can decrease from 67 kg CO_2 eq/m2/year to 31, and the energy related CO_2 emissions for a terraced house can decrease from 55 kg CO_2 eq/m2/year to 34. Therefore, the increase in material related emissions caused by energy renovations is more than compensated by the decreased energy related emissions. Improving the environmental performance of a building can ensure that it continues to meet sustainability requirements and can extend the useful life of the building. For example, after the energy renovation of a 1960s home, it can typically be used for an additional 30-40 years, and possibly even 60 years (W/E Adviseurs, 2018).

The other half of renovation activities are not related to improving sustainability. In the rental sector, these activities are mainly focused on renovating facades and installations. In the owner-occupied sector, bathroom and kitchen renovations account for nearly half of all non-sustainability related renovations, followed by painting and building extensions (Arnoldussen et al., 2022).

Of the total environmental impact of the materials used for residential buildings in the Netherlands in 2019 (in MKI), only 43% was caused by new construction and transformation. The remaining 57% was caused by renovation activities, with 50% being caused by improving the energy performance and sustainability of dwellings and 7% being caused by other renovations. Electrical installations were responsible for most of the renovation impacts (60%), of which 94% was attributed to solar panels (Arnoldussen et al., 2022).

Renovating and retrofitting housing on a large scale is difficult due to the diversity of the housing stock. Therefore, van Stijn & Gruis (2019) propose retrofitting existing houses with "modular, mass customizable, and cyclable retrofit products". Modularity would allow for component-by-component retrofit, which could occur over time rather than all at once, making it more financially feasible and facilitating future adaptations. The mass customization (made possible through industrialization) would make it possible to meet the diverse retrofit needs of the housing stock. Lastly, cyclability would ensure that the retrofit products can be reused/recycled at the end of their life. Van Stijn & Gruis (2019) state that such renovation practices could increase the lifespan of existing buildings and slowly help develop a circular housing stock.

4.3.3.2 Repair and maintenance

Structural repairs could increase building lifespans and prevent 33% of buildings from being demolished. This could reduce the materials demanded for new construction by 2%. BIM models and the "internet of things" could facilitate this by providing information on when parts need repair (Conde et al., 2022). In 2019, 2% of the material related environmental impacts of residential buildings came from repair and maintenance activities (Arnoldussen et al., 2022).

4.3.3.3 Design for disassembly and component reuse

Currently, less than 10% of materials used in construction can be disassembled (Conde et al., 2022). However, Conde et al. (2022) estimates that there is technical potential to increase this to 45%.

One of the main barriers is that products designed for disassembly now will enter the housing stock for decades and, therefore, the benefits of reuse and the return on investment will only be experienced in the longer term when the materials/components can be recovered and reused. However, by 2080, it is estimated that design for disassembly could reduce primary material consumption by about 9% per year (Conde et al., 2022). To ensure that the buildings/components are durable and can be reused for multiple life cycles, more material might also initially be used. In the short term, this may go against material and emission reduction goals (Barendregt et al., 2023).

Eberhardt et al. (2019) found that designing the concrete structures of an office building for disassembly could reduce its climate change impacts by 15% or 21%, depending on whether the components are reused two or three times after an 80-year building lifespan. When combined with material substitution (replacing concrete structures with steel, wood, or glass), the impacts could be further reduced.

In a scenario where buildings between 2018 and 2050 are built with more circular/reusable components, van Oorschot et al. (2023) finds that the cumulative material demand over this period could decrease by 45%, compared to a business-as-usual scenario. 34% of the cumulative material demand could be met by secondary materials, despite the outflow representing 75% of the inflow. Climate change impacts would be reduced by 43% and land use would increase to 7,100 square kilometers (compared to 4,900 in a business-as-usual scenario) since more biobased materials are also assumed to be used.

4.3.3.4 Standardization

The standardization of, for example, the dimensions of building elements and connection mechanisms, facilitates the repairability and reusability of components. Standardized products also produce less waste during manufacturing since their production processes have been optimized. A challenge for increasing standardization is that the uniqueness of a building is typically associated with a higher value, however unique buildings can still be constructed with standardized elements (ARUP & Ellen MacArthur Foundation, 2023).

4.3.3.5 Modular construction

Modular construction essentially combines industrialized construction with design for disassembly and a level of standardization, allowing for module/component/material reuse and facilitating building repair, adaptability, and recycling. According to the Ministry of the Interior and Kingdom Relations (2021), this combination has the potential to address many of the construction sector's current challenges. The industrialized production can help to more quickly address the housing shortage, reduce material consumption, make housing more affordable, reduce (nitrogen) emissions, help address the labor shortage, create higher quality buildings, and make material flows and energy consumption easier to monitor. In particular, modular construction methods can yield a

40% increase in productivity which could yield 23,280 additional homes per year by 2030 (if the market share by 2030 is 50%) (Buijs et al., 2019). The ability to disassemble modular buildings and their degree of standardization allows the buildings to adapt to new needs and for components to be reused in future buildings, helping work towards a circular economy (Buijs et al., 2019; Ministry of the Interior and Kingdom Relations, 2021; interviews with company A and B). This also gives the modular buildings residual value at their end of life, unlike traditional buildings (Buijs et al., 2019).

Modular construction is not a new concept and has tried to gain traction in the past, however the expected productivity and economic gains could never be achieved, the houses were seen as ugly and cheap, and many companies went bankrupt. However, the current housing and labor shortages are leading to a renewed growth of modular housing, combined with advancements in digital production technologies which allow for more efficient manufacturing processes, greater design variability, and better supply chain management. A market is most likely to adopt modular construction if there is a high demand for housing and a shortage of labor. For it to succeed, there needs to be continuous high demand and repeatability (Bertram et al., 2019). Though modular construction is most suited for buildings that have a high level of repetition, this does not mean that all projects have to look the same. With digital design and manufacturing tools, machines can be programmed to make a wide variety of houses within a standard system (de Ruiter & Koning, 2023; company B). While traditional construction methods will likely not be entirely replaced, one of the companies interviewed anticipate that 80% of new construction in the Netherlands could be built with their industrialized, modular construction method (interview with company B). Though all housing types can be built in a modular way, apartment buildings provide the easiest start due to the high level of repeatability (Buijs et al., 2019). According to Rutten (2023a), 10,100 homes were industrially built in 2022 and, given the list of companies included in this quantification (appendix 8.5), most of these are likely modular as well.

In a study by Daiwa House (2023), a modular apartment building was found to be about four times lighter than a traditional apartment building. Over its entire lifecycle, the modular building had between 38% and 79% less CO_2 emissions, depending on the timeframe considered. If used for 15 years, the modular building had 79% less CO_2 emissions than a traditional building, since the modular building could be disassembled and reused while the traditional building was demolished far before necessary. If used for 75 years (the standard lifetime of residential buildings), the modular building had 55% less CO_2 emissions since the modules could be reused. Taking a 150-year timeframe, it was assumed that a traditional building would have to be built twice while the modules of the modular building could be refurbished and reused, leading to 47% lower CO_2 emissions. Within a 200-year timeframe, both the modular and traditional buildings would have to be constructed three times, and are ultimately demolished, without possibility for further reuse, only recycling. The modular building would then have 38% less CO_2 emissions (Daiwa House, 2023).

However, several challenges exist for modular construction. Modules are limited to a size that that is possible to transport, and high-rise buildings are more difficult to construct (Bertram et al., 2019; interviews with company A and B). As an industrialized construction method, modular housing factories need to be built, requiring large upfront investments and time, which delays the upscaling potential (Buijs et al., 2019). In finding investors, it can be difficult to convince them about the retained end of life value of modular buildings (interview with company A). Furthermore, modular construction requires an entirely different approach. It is important to start thinking modularly at the beginning of the design process instead of designing a building and then redesigning it to be built with modules. In this sense, buildings have to be designed to fit the manufacturing process (interviews with company A and B). This means that designers and builders must collaborate from the beginning of a project, requiring organizational changes (Buijs et al., 2019). Lastly, since technology and the designs of modular housing concepts will continue to develop over time, the future reuse potential of building components might be less than anticipated. For example, an old beam might not be usable as a beam again because the design has changed. However, the material could still be converted into a different component. Product development will not stop, so this mismatch is an inevitable challenge (interview with company B).

4.3.3.6 Adaptable housing

Designing housing in such a way that it can adapt to new needs, like changes in family size or the need to relocate, helps extend the useful life of buildings, components, and materials and prevents buildings from becoming obsolete (ARUP & Ellen MacArthur Foundation, 2023; Femenias & Geromel, 2020). Hereby, new construction and the related material flows can be avoided. Designing for adaptability also reduces the material flows needed for renovation activities (Femenias & Geromel, 2020).

W/E Adviseurs and the Dutch Green Building Council have developed a tool to calculate the adaptive capacity of a building based on, for example, the detachability of the building's components, the floor to ceiling heights, the movability of walls, the amount of daylight that enters the building, the positioning of stairs/elevators, and the extent to which the floor plan is interrupted by load-bearing structures (W/E Adviseurs & DGBC, 2022). Besides giving an understanding of how adaptability can be increased, this tool enables a building's adaptive capacity to be taken into account in sustainability assessments.

According to Femenias & Geromel (2020), adaptable housing also contributes to social sustainability by being able to address diverse user needs, creating intergenerational value, increasing the control users feel over their living environment, and giving stability to residents, since moving house to accommodate new needs becomes less necessary.

A barrier for adaptable housing is that the initial material input and environmental impact might be higher to ensure durability and adaptability (ARUP & Ellen MacArthur Foundation, 2023). In Finland and Denmark, the main barrier is the disinterest of the housing developers. Housing developers worry that designing for internal adaptability would involve extra costs, while residents would likely pay the same amount. The financial benefits are therefore not clear, with the main benefit being for the user and not the developer. Even if the building structure is designed for adaptability, the building services are often not, presenting one of the main obstacles. This is because the architect is typically not involved in planning the building services and because adapting building services is costly. Another barrier is that the focus of current construction is to meet current housing needs, and not the needs that might arise in the future (Tarpio et al., 2022).

4.3.3.7 Design for climate resilience

Digital tools for climate projections can be used to assess the future conditions that a building might be exposed to, such as flooding, heavier rainfall, more extreme heat waves, or stronger wind forces. Designing with these future conditions in mind, helps ensure the longevity of a building. However, such future proof designs often require more initial material input (ARUP & Ellen MacArthur Foundation, 2023).

4.3.3.8 Using durable materials and components

The use of durable materials and components increases a building's lifespan and improves the potential to disassemble and reuse elements. It also reduces the need for maintenance. However, the initial material input and environmental impact may be higher (ARUP & Ellen MacArthur Foundation, 2023).

4.3.4 Closing the loop

4.3.4.1 Recycling materials

Currently, 93% of materials from residential buildings are recycled. 69% of the recycled material is concrete, 13% is other minerals (mainly limestone and sand), 10% is clay brick, and 3% is steel and iron. However, only a small fraction (6%) is recycled back into residential buildings, while most is downcycled for use in roads. Increasing the amount of high value recycling and reuse is necessary to help close material loops for residential buildings. A limiting factor is that buildings that are being demolished now have not been designed for disassembly, and current demolition practices make high value material recovery difficult. The infrastructure needed for material recycling and reuse is also lacking since it is labor and cost intensive to scale up (Conde et al., 2022). However, as mentioned previously, even if all demolition waste was perfectly reused or recycled back into housing, only 15% of the total material demand for new construction could be met, while Conde et al. (2022) estimates that this value is closer to 20%.

Besides increasing the high-value recycling rates of demolition waste, the recycled content of building materials can also be increased to reduce the impacts of primary material use. According to Conde et al. (2022), 8% of the material demand for buildings currently comes from secondary materials. When considering only residential buildings, this study estimates that about 11% of the material input comes from secondary materials. The secondary material input mostly consists of recycled steel and iron (35%), concrete (28%), and sand (22%) (Arnoldussen et al., 2022). Each construction material also has a maximum recycled content potential: concrete (50%), clay brick (50%), wood (90%), glass (91%), ceramic (80%), gypsum (40%), bitumen (50%), steel (85%), cast iron (96%), and aluminum (50%) (Verhagen et al., 2021). Conde et al., (2022) estimates that secondary materials could account for 49% of material input for buildings. This would reduce emissions by 18%. Metabolic and Copper8 (2022) estimate that, by 2030, 58% of the material input could come from secondary materials.

The lack of information about the quality of secondary materials, the lack of certification systems, and the uncertainty around how secondary materials can or should be used disincentivizes their use. In addition, secondary materials are often more expensive than primary materials due to the extra processing required, the lack of economies of scale, and the exclusion of environmental externalities in pricing schemes (Conde et al., 2022).

4.3.4.2 Circular demolition

Currently, buildings are demolished through brute force, mixing material streams and limiting the potential for reuse and high value recycling. The amount of components and materials that could be reused or recycled at high value would increase substantially if advanced demolition practices were used, in which buildings are disassembled or selectively demolished (Conde et al., 2022).

The demand for secondary materials is currently still low, which disincentivizes circular demolition practices. In addition, in preparation for circular demolition, it takes time to inventory the components and materials present in a building and assess their condition, reusability, detachability, and value. This could be facilitated, however, through the increase in digitalization and the use of material passports. The actual circular demolition process also takes more time than traditional demolition, though costs remain similar. A benefit of circular demolition is that the value of the recovered materials can, on average, make up for about 15-25% of the demolition cost (Metabolic & Copper8, 2022).

4.4 Deep dive on modular construction

Since little research has been done about modular construction, this chapter aims to quantify its potential impact as a circular option for residential buildings, based on primary data gathered from two Dutch modular building companies.

As mentioned previously, modular housing can use conventional materials or be biobased. Though many designs and variations are possible, Figure 5.7 shows the materialization of a modular apartment building using conventional materials compared to a traditional apartment building and a modular terraced house using biobased materials compared to a traditional terraced house. Both modular variants are about 80% lighter than their traditional counterparts. Since the buildings themselves are lighter, the foundations can also be made lighter (interview with company A).

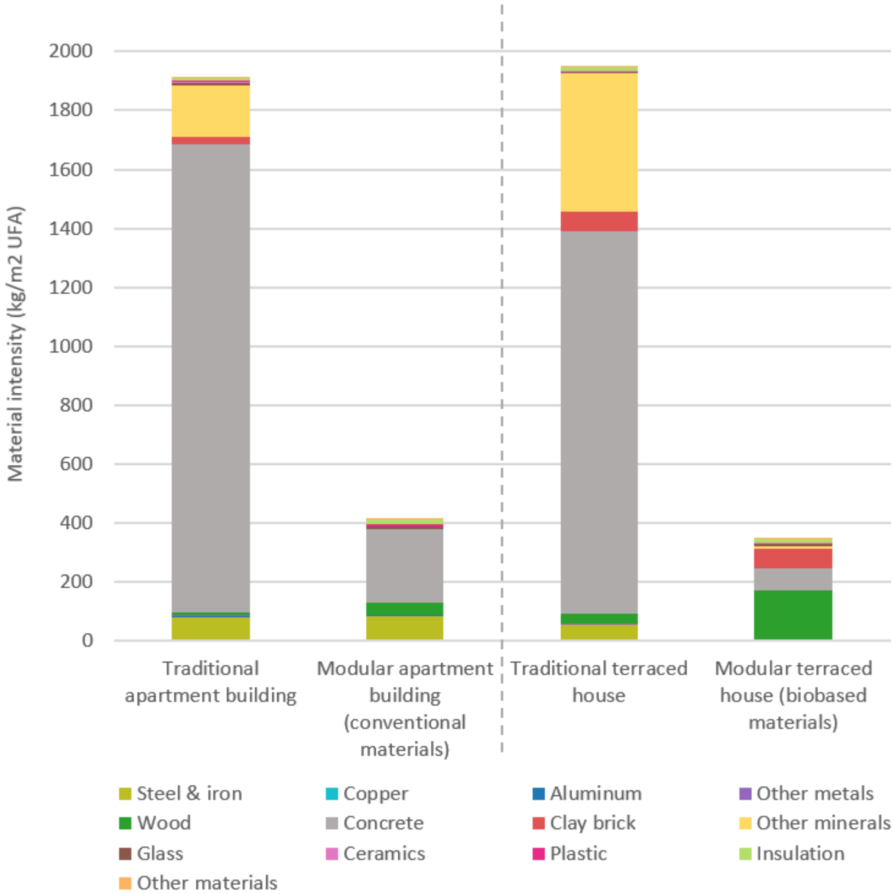

Figure 4.9 Material intensities of traditional and modular housing variants. The traditional material intensities are from Arnoldussen et al. (2020, as cited in van Oorschot et al., 2020, 2023) and the modular material intensities are from two Dutch modular building companies (company A and B).

Figure 4.10 and Figure 4.11 show the results of the dynamic MFA that was performed to analyze the potential impact of implementing more modular housing in the Netherlands. The amount of material outflow that is reusable remains small under both scenarios, with 1.4% of the outflow being reusable in 2100 in the baseline scenario and 4.9% being reusable in 2100 in the modular scenario. While this is more than a threefold increase, it illustrates that scaling up modular construction at the rate assumed in this study, will not yield significant reusable material outflows before 2100. This is due to the 75-year average lifespan assumed for permanent modular buildings, which means that, in 2100, only about half of the modular buildings built between 2019 and 2025 are starting to be demounted (and in these years modular construction is assumed to account for only about 20% of new built housing). Of the reusable outflow in 2100 under the modular scenario, 65% is concrete and 25% is steel.

Though the increase in reusable outflow is small between the two scenarios, due to the smaller material inflow required under the modular scenario, the reusable outflow is able to meet 12.7% of the material demand for new construction by 2100, while in the baseline scenario this is only 1.8% because of the still large inflow.

The results illustrate that the main benefit of modular construction lies in the lighter material intensity of the buildings rather than in the reusability, at least in the timeframe considered in this study and when renovation activities are not taken into account. Already by 2030, the inflow is 33% smaller in the modular scenario compared to the baseline scenario. In 2050, it is 40% smaller and in 2100, 60%. This suggests that modular construction is an effective “narrowing the loop” strategy, reducing the demand for initial material input and thereby also the material-related environmental impact.

The results also show, that under the baseline scenario, the outflow of materials becomes larger than the inflow in 2100, suggesting that a circular economy for housing could theoretically be achieved if recycling practices are drastically improved. The outflows surpass the inflows at this point due to the accumulation of outflows from the building stock and the decreasing population assumed past 2070 and therefore decreasing demand for housing. In the modular scenario, the material outflow becomes larger than the inflow already in 2050, due to the smaller material inflow required for modular construction.

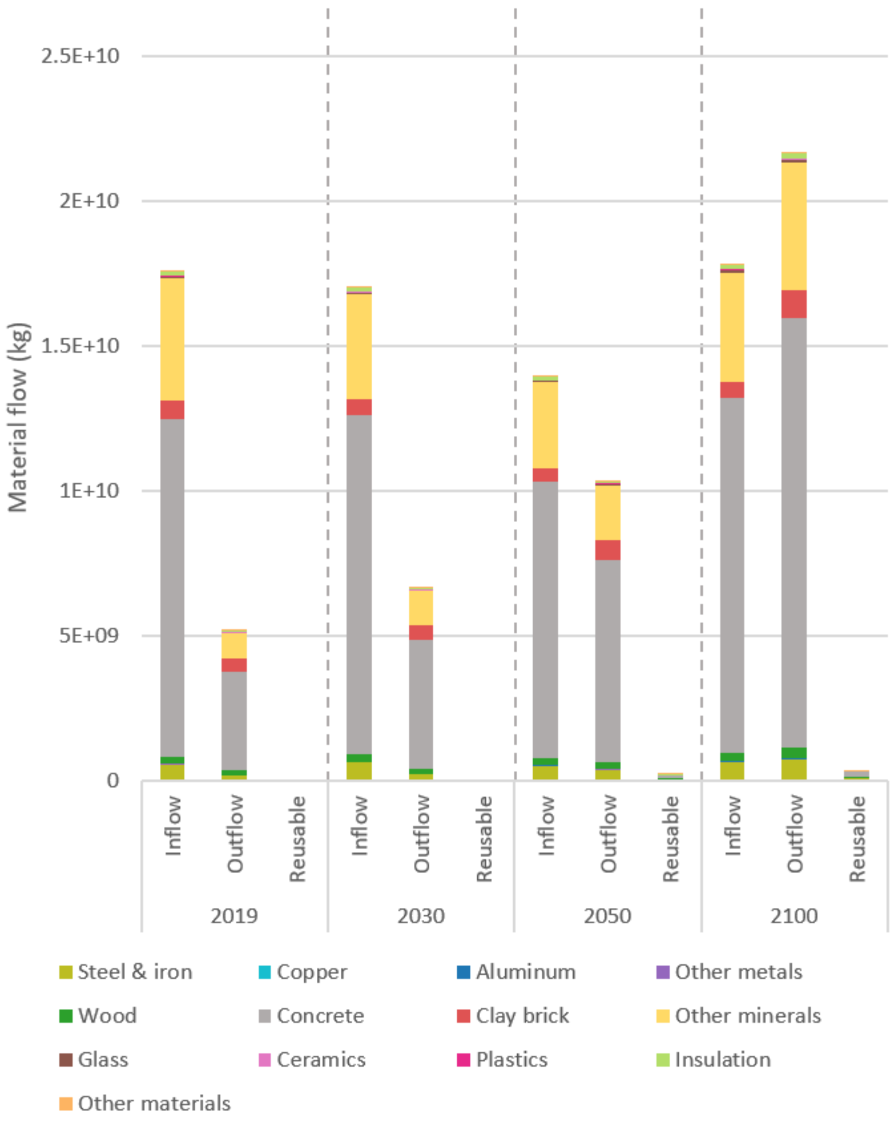

Figure 4.10 Baseline scenario.

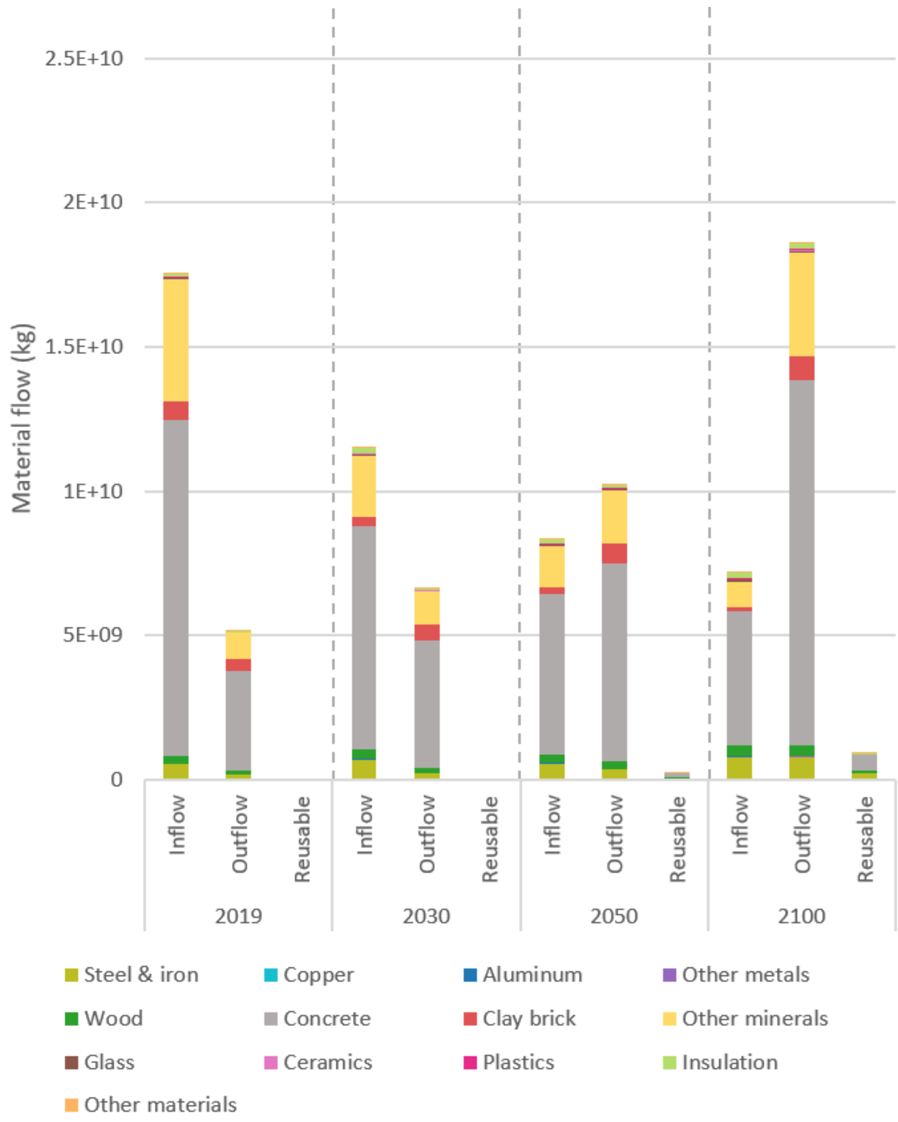

Figure 4.11 Modular scenario.

The model created to derive the above results does not take into account the material flows required for renovation during a building's lifespan. The static MFA in Figure 4.12 illustrates the component inflows and outflows for the construction and renovation of a modular house built with conventional materials during a 75-year lifespan. 75% of the total outflow can be reused as components in new modules. 84% of this reusable outflow comes from the original construction materials and 16% comes from the renovation outflows. Therefore, the reusable outflows shown in Figure 4.10 and Figure 4.11 can be assumed to represent most of the reusable outflows that would become available during a modular building's lifespan.

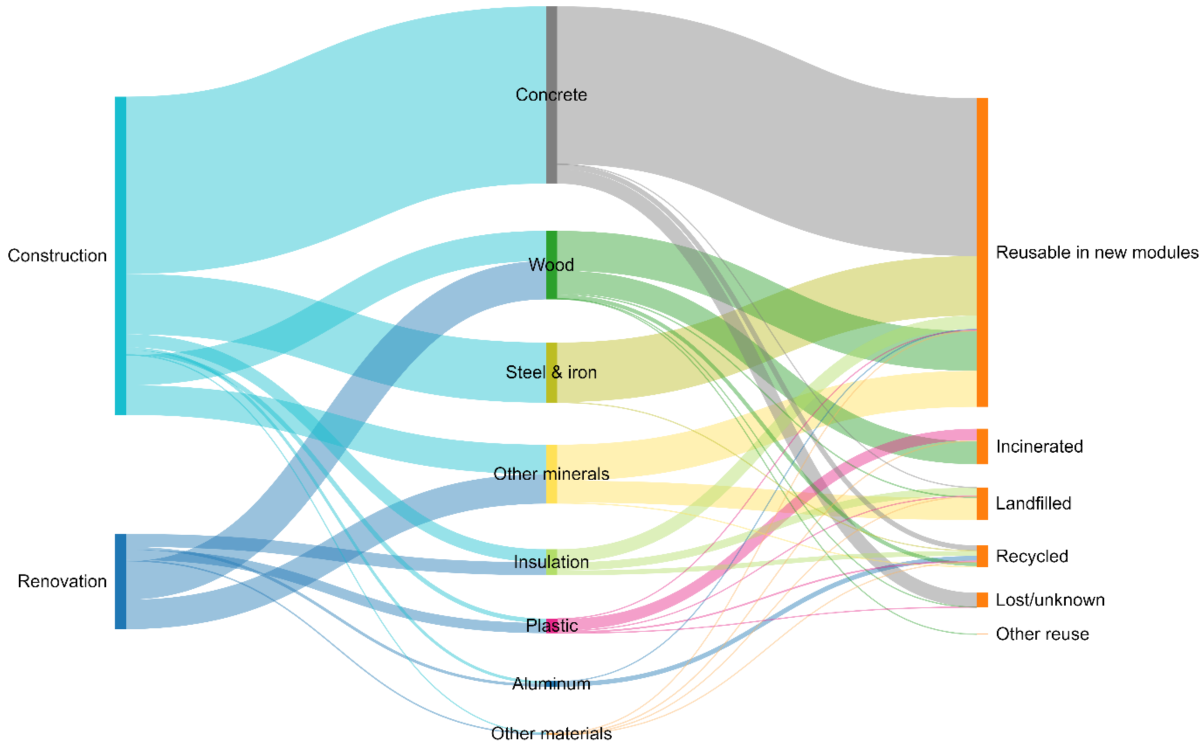

Figure 4.12 Material flows during the 75-year lifespan of a modular house built with conventional materials (derived from data from company A).

4.5 Option impacts overview

Table 4.3 Overview of circular options for housing in the Netherlands, with estimates of potential and impacts on material inflow.

	Circular option	Potential	Reduction in material inflow
Substitution	Biobased materials	50% of material input	-11.7% between 2023-2030 -50-65% by 2050
Narrowing the loop	House sharing	50,000 - 160,000 homes by 2030	
	Building smaller houses		-8.1% between 2023-2030
	Adding floors on top of existing building	97,900 homes	-80% per square meter -19.4% between 2023-2030 (when combined with transformation)
	Transforming existing non-residential buildings into housing	6,500 – 22,000 homes per year	-88% per square meter -19.4% between 2023-2030 (when combined with topping up)
	Industrialization and prefabrication	50% of new construction by 2030	-5.2% between 2023-2030 if 18% lighter material composition is assumed
	Material efficient design	50% less concrete can be used in foundations and structures	-18%
Slowing the loop	Renovation and retrofitting		
	Repair and maintenance	Prevent 33% of building demolition	-2%
	Design for disassembly and component reuse	45% of building components Assuming most designed for disassembly	-9% per year by 2080 -45% between 2018-2050
	Standardization		
	Modular construction	50% of new construction by 2030	-80% per square meter -33% in 2030 -40% in 2050 -60% in 2100
	Adaptable housing		
	Design for climate resilience		
	Using durable materials and components		
Closing the loop	Recycling materials	Secondary materials could meet 49-58% of material demand by 2030	Not necessarily reduction in total inflow, but reduction of primary inflow
	Circular demolition		

5 Discussion

5.1 Quantifying current material stocks and flows

In this study, the material stocks and flows for residential buildings in the Netherlands were quantified for the year 2019, based on past studies. The goal was to gain an understanding of the current state from which circularity can be improved and to compile a dataset of baseline values such that they are usable by the COIN project. As part of this mapping of the current state, the origins of the different building materials were also investigated.

In this quantification, there is uncertainty in the fact that average material compositions and UFAs were assumed per housing type, since there is a lot of variability in the materials used in the construction sector. However, when average material intensities are applied to a sample size as large as all housing the Netherlands, the resulting values might not be far off. However, the average material intensities assumed for residential buildings in the Netherlands differ throughout the literature, so the results of this study are dependent on the average material intensities used. While for the existing housing stock it is necessary to use average material intensities, moving forward, creating a database of the exact materials used in new construction projects could help monitor material stocks and flows more accurately. This would likely be possible given that every newly constructed building is now required to have an MPG assessment.

The material origins calculated show where construction materials or products were last processed, before being used in the Dutch construction sector. Although EXIOBASE was used to determine the origins of most of the materials in this study, the CBS MFM was used for determining the origins of concrete and “other minerals”. Since these two material categories represent the majority of the material inflow for housing, the calculated flow of materials that is domestically produced and imported in 2019 is mainly reliant on the data from the CBS MFM. The CBS MFM only shows the imports to the entire Dutch economy, and not specifically to the construction sector. Therefore, the results are dependent on the assumption that the share of imported vs. domestically produced concrete and “other minerals” is the same across all product categories in the Dutch economy. The origins that were based on the EXIOBASE database are specific to the Dutch construction sector (buildings and infrastructure) but are only as accurate as EXIOBASE is. Some activities are not recorded in EXIOBASE, such as clay extraction in the Netherlands, even though clay is extracted every year (van der Schuit et al., 2023). In addition, since EXIOBASE is based on monetary flows, the price of production being different in different countries influences the magnitude of the flows. This could be making it appear as though more of a material is coming from a country where production is more expensive, skewing reality. Using hybrid tables could help address this issue, since the monetary values are converted into physical values, but hybrid tables are only available for 2011 and are more manipulated than monetary tables. This issue reiterates the need for a database of physical material/product flows in monitoring the transition towards a circular economy, as is being compiled in the CBS Material Flow Monitor, which combines both monetary and physical information (Delahaye et al., 2023), and is the goal of the Raw Material Information System (GRIS) that is under development.

The share of each material stream that is recycled, incinerated, or landfilled, was based on data about the entire Dutch construction sector, including infrastructure. Therefore, this study assumes that the materials for infrastructure and buildings follow similar waste treatment processes, while this might not be the case. In addition, the flow of secondary materials should technically be included within either the domestic or imported flows, but since it is unknown where the materials are recycled, it is kept as a separate flow in this analysis.

5.2 Quantifying baseline impacts

The GHG emissions and land use associated with the material input for residential buildings in 2019 was also quantified. However, the impacts of other stages in the value chain such as component manufacturing, transportation, construction, demolition, and waste treatment were not. Therefore, the GHG emissions and land use impacts of the housing sector are not fully illustrated in this study. Data on the component composition (rather than material composition) of the different housing types and access to the “Nationale Milieu Database”, which contains LCAs for a wide variety of construction products used in the Netherlands, would make it possible to calculate the environmental impacts throughout the entire value chain (Dutch Environmental Database, 2023). Nevertheless, the impacts of material production do account for about 70% of a building’s embodied climate change impacts, so the GHG emissions quantified in this study do represent the main share (Bijleveld et al., 2015; de Klijn-Chevalerias & Javed, 2017). Future research should also investigate impacts besides GHG emissions and land use to obtain a more complete picture of the environmental impact.

Environmental impacts were only calculated for the current state, since the impacts of the different processes involved in the lifecycle of buildings will be different in the future due to, for example, changes in the energy mix. Some studies do project how these impacts could develop towards the future under different scenarios, enabling prospective LCAs (Sacchi et al., 2022; Yang et al., 2022). In this way, the environmental impacts of future circular housing scenarios could be calculated as well. This was outside the scope of this study but would be necessary for truly analyzing the environmental impact of different circular options.

5.3 Creating an inventory of circular options

In creating the inventory of circular options, most information was derived from grey literature, and while these sources may not have undergone the formal scientific peer review process, most have been either written or reviewed by industry experts and are relevant specifically to the Netherlands.

Validation of the inventory of options with the team conducting the Product Group Analysis on residential buildings supports the assumption that the main circular options have been included, however it is not an exhaustive list. For example, limiting the geographical scope of the literature search to the Netherlands means that circular options for buildings that are applied in other countries and may be usable in the Netherlands are not included.

Since the primary goal of the literature search was to gather quantitative information about the potential and environmental/circularity impacts of each circular option in the Netherlands, the main sources regarding these topics have been included and the main research question and third sub-question are answered. However, this focus on potential and impacts means that the results provide a mostly technical perspective and more qualitative literature on circularity in Dutch housing is not included. Although social and economic opportunities and barriers are mentioned for several of the options, a more in depth analysis of these aspects is needed to fully understand the potential of each option. In addition, the regulations and actors involved in each circular option fall outside the scope of this study but are an important direction for future research in order to fully understand the transition that each option requires. Lastly, the method of searching for information on the topics of current implementation, scalability/potential, estimated environmental impact, and opportunities and barriers, means that the disadvantages of each option were given less of a focus. This could be creating an overly positive view.

In addition, not all strategies have been quantified in the existing literature in a way that is comparable. As a result, Table 4.3 is partially incomplete and a direct comparison cannot be made between all options. Especially the option of renovating and retrofitting the existing housing stock is promising but has not been quantified in a comparable way, e.g. in terms of the reduction in material inflow that could result over time. This shows the importance of quantifying the impacts of all options in one study or using a consistent method.

The options inventory also raises the question of whether the mass of material inflow is an effective indicator for assessing and comparing circular options for housing. For example, the use of biobased materials significantly reduces the mass of material inflow for residential buildings because they are lighter than the traditional alternatives. This makes it an effective strategy for reducing material mass, but this does not consider e.g. the increased land use required. In addition, some strategies like designing for adaptability and durability might require a larger initial material input but can have benefits in the long term. Therefore, though strategies to narrow the loop provide the most immediate circularity benefits for residential buildings, it is important that, besides the reduction in material input, indicators such as environmental impacts, product lifespans, and the ability of outflows to satisfy inflows are also considered. This study aimed to include estimates of GHG emissions, total environmental impacts, and the ability to close material loops when this information was available in the literature, but this was not available for all options.

The two interviews with modular building companies were crucial in being able to acquire primary data about the material compositions and reuse potential of modular houses and to gain insight into its potential, benefits, and barriers. However, both companies interviewed are solely modular building companies, and therefore might be biased or overly optimistic about the prospects of modular housing. In order to obtain different perspectives and gain a full understanding of the advantages and disadvantages of modular housing, it would be important for future research to interview traditional building companies or companies that have both traditional and modular housing variants as well.

While the options inventory gathers information about the potential and impacts of different circular options, it is clear that a combination will be necessary to truly work towards a circular economy and minimize the material demand and environmental impact of residential buildings. Therefore, though understanding the potential impact of each strategy individually is an important first step, the next step should involve modelling all options together and testing different combinations, so that the synergistic or counteractive relationships can be explored. This is particularly relevant for modular construction since it inherently relates to several of the other circular options and can further be combined with for example, the use of biobased materials or the topping up of buildings. Such an analysis where different options are combined was done to some extent in Bosch et al. (2023) and is also one of the goals of the ongoing Product Group Analysis on residential buildings being conducted as part of the Work Program on Monitoring and Directing the Circular Economy.

5.4 Modelling the impacts of modular construction

The last phase of the research involved modelling the potential impact of modular construction on material flows for housing in the Netherlands, to gain insight into its potential as a circular option.

Primary data was obtained from two Dutch modular building companies for the analysis, giving insight into the material composition of a modular apartment building (built with conventional materials) and a modular terraced house (built with more biobased materials). While these material compositions are of two different housing types, because the buildings are constructed using a modular approach, it can be assumed that the material intensities across different housing types are very similar (interview with company A). However, in comparing the two material intensities, it is important to note that the modular apartment building has an aluminum façade while the modular terraced house has a brick façade. Since aluminum is significantly lighter than brick, this is making the modular apartment building relatively lighter, and the modular terraced house relatively heavier. Nevertheless, both modular material compositions are significantly lighter than their traditionally built counterparts. In addition, it should be noted that there are a wide variety of modular housing systems and designs, so the material compositions used in this study are not necessarily representative of all modular housing variants. Material compositions that are not as light would yield less material inflow reductions towards 2100.

The dynamic MFA made in this study is based on the modular building that uses conventional materials. This was because data on the reuse potential for the biobased alternative was unavailable and because, by using the modular variant that uses conventional materials, the circular option of using biobased materials is not being evaluated at the same time. However, future research could analyze the reusability of the biobased modular variant. In addition, the model assumes that after 2019, the UFA per housing type remains constant. Even though this might not resemble reality, it also ensures that the circular option of building smaller houses is not being evaluated at the same time.

The model illustrates that the use of a Weibull distribution survival curve, assuming a building lifespan of 120 years, and a shape parameter of 2.95 works well when modelling the stock dynamics of housing in the Netherlands built before 2019, validating the findings of Deetman et al. (2020). Whether the choice of a 75-year lifespan for housing built in 2019 or later was a representative choice is not possible to know and the results are dependent on this choice. Assuming a shorter lifespan would make more reusable material available sooner but would also require a larger inflow of new construction to replace the houses that have reached their end of life, increasing material demand. Assuming a longer lifespan would reduce the need for as much new construction, which would reduce material demand, but this would also reduce the share that can be built modularly. The reusable outflow by 2100 would also be smaller since the deconstruction of buildings would take place later. For a full analysis of the system dynamics, different lifespans would have to be tested in the model. However, despite the lifespan assumed, the modular scenario would likely still require lower material inflows than the baseline scenario. The main difference would be in the magnitude and timing of the reusable outflow.

Even though modular construction can facilitate an increase in the number of homes that can be constructed each year (Bertram et al., 2019; Buijs et al., 2019), the dynamic MFA model assumes the same level of productivity in both the baseline and modular scenario. The modelled number of homes that will need to be built in the upcoming years already indicate a necessary increase in productivity. Therefore, this study views modular construction as a way to reach this higher production demand, rather than a way to increase production even further. Whether permits will actually be granted for all of this new construction is to be seen.

The results of the dynamic MFA show the possible impact on material flows if the share of modular housing in the Netherlands would increase from 14% in 2022 to 80% in 2100. Although this growth in market share is based on current trends and goals, it may be optimistic given the barriers for modular construction. Nevertheless, the model does illustrate the system dynamics and explores the range of what is possible.

However, in the baseline scenario, the model yields material outflows for 2019 that are about twice as high as the outflows quantified in the 2019 accounting model, suggesting that the outflows in other years are likely overestimated by the model as well. However, even if the calculated outflows are higher than in reality, it remains true that the outflows for the foreseeable future will mainly be from demolished traditionally built houses that are currently in the housing stock. This means that improving the recycling of demolition materials will remain important. In addition, it remains true that modular construction significantly decreases the material input necessary for new construction and is therefore an effective narrowing the loop strategy.

Under the modular scenario, the reusable outflow remains low. As mentioned previously, this is due to the 75-year average lifespan assumed for permanent modular buildings since, in 2100, only about half of the modular buildings built between 2019 and 2025 are starting to be demounted (and in these years modular construction is assumed to account for only about 20% of new built housing). However, even if 80% of new construction immediately starts to be built in a modular way, the reusable outflow in 2100 only increases by 65%, and is only able to meet 21% of the material inflow in 2100 (as opposed to 12.7% in the original modular scenario). This means, that even when an immediate transition to modular construction is assumed, the reusability of materials will not be sufficient to meet the demand for material inputs by 2100. Future research could look past the year 2100 to further analyze the reusability of material outflows.

The dynamic MFA model does not take renovation flows into account; it only considers the first construction materials, and the material outflows at a building's end-of-life. However, in the 2019 accounting model we can see that renovation materials account for 8% of the total material inflow and 24% of the total material outflow. While a static MFA model was made to visualize the renovation flows during a modular house's lifecycle and the reusability of the material outflows, neither this static model nor the dynamic model take into account the timing of renovation flows nor that reuse can only happen a certain number of times before the building components ultimately become waste as well. Therefore, an improved dynamic MFA model should firstly, take into account renovation flows using component lifespans and the need for components to be replaced during the lifespan of a building and secondly, take into account the number of times a component can be reused by using a combination of economic and technical component lifespans. This improved model would yield higher material inflows and reveal more reusable outflows. However, the dynamic MFA model made in this study does account for the majority of reusable outflows since 84% of reusable outflows come from the original construction materials, as can be seen in Figure 4.12.

6 Conclusion

The aim of this research was to map the current state of material stocks and flows for residential buildings in the Netherlands, inventory relevant options for improving circularity, and conduct a more in-depth analysis of how the option of modular construction could influence material flows for housing. While activities such as building transformation, repair, renovation, and recycling do take place to some extent, the mapping of the current state illustrates that the housing sector is still largely linear, with only 11% of material inputs being derived from secondary sources and only 6% of demolition materials being recycled back into housing. Based on the literature, house splitting, transforming existing non-residential buildings into housing, and adding floors on top of existing buildings appear to be the most impactful options for reducing the material input required for residential buildings and the associated environmental impact. While house splitting avoids new construction almost completely and could create between 50,000-160,000 new homes by 2030, transforming and topping-up existing buildings could reduce the material inflow needed for new construction by 19.4% between 2023 and 2030.

Besides these circular options, the dynamic material flow analysis performed in this study reveals that increasing the amount of modular housing could reduce yearly material inflows by 33% in 2030, 40% in 2050, and 60% in 2100, making it an impactful narrowing the loop strategy. While modular construction facilitates the disassembly and reuse of building components and materials, the results show that if modular construction is scaled up, by 2100, only 4.9% of the total material outflow will be reusable, since most reusable components will still be in the housing stock due to the long lifespan of buildings. Therefore, the main circularity benefit lies in the significantly lighter material composition of modular buildings, which can be up to 80% lighter. This is a characteristic of the fact that they are industrially constructed. The reusability is not as beneficial, at least in the timeframe considered in this study (up to 2100) and when renovation activities are not taken into account. However, future research should look past 2100 and include the renovation cycles throughout a building's lifespan to fully understand the potential reuse benefits of modular construction.

Besides significantly reducing material consumption, industrialized and modular construction can help to more quickly address the housing shortage, make housing more affordable, reduce on site (nitrogen) emissions, help address the labor shortage, create higher quality buildings, and make material flows and energy consumption easier to monitor. In this way, it can help address many of the Dutch housing sector's current challenges, besides working towards circularity goals. Modular construction can also be combined with other circular options such as using biobased materials and topping up existing buildings. One of the main barriers, however, is that industrialized construction requires large upfront investments and requires continuous demand to be economically viable, in a market that is characterized as highly discontinuous. In addition, technology and modular housing designs will continue to develop over time, which could limit the reusability of modules or components in the future. However, even if component reuse is not possible, the fact that modular buildings are demountable facilitates repair, renovation, and recycling.

In conclusion, the findings of this research suggest that modular construction, house splitting, transformation, and topping-up existing buildings should be prioritized to reduce the material input for residential buildings in the Netherlands and work towards increased circularity while meeting the demand for housing. Besides these strategies, however, the recycling of demolition materials should continue to be improved, since the material outflows for the foreseeable future will still mainly be from demolished traditionally built houses that are currently in the housing stock.

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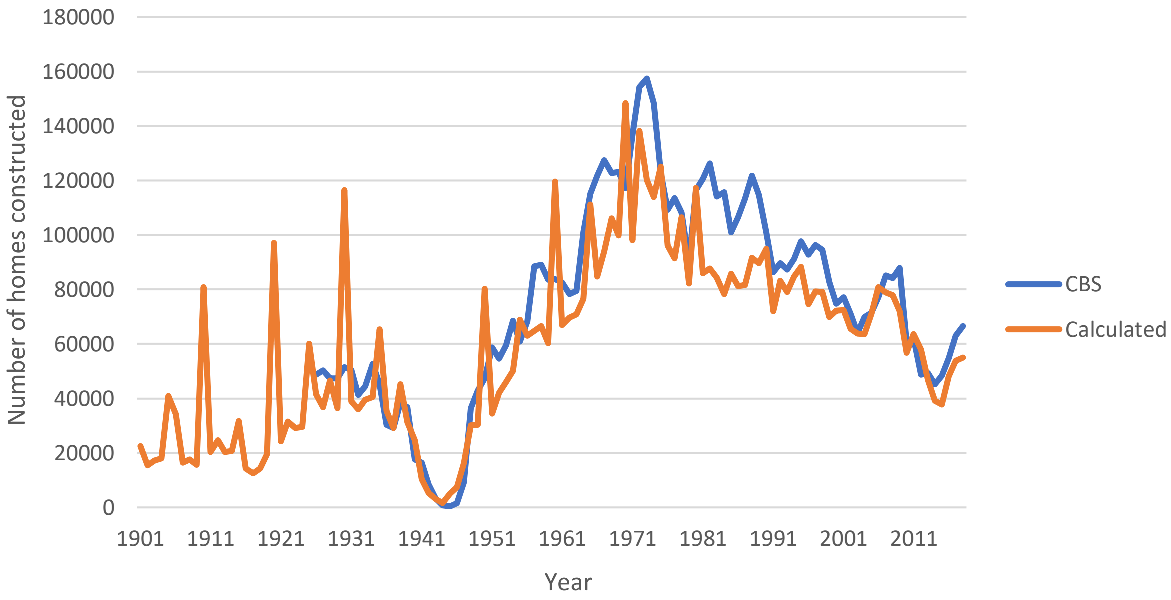
8 Appendices

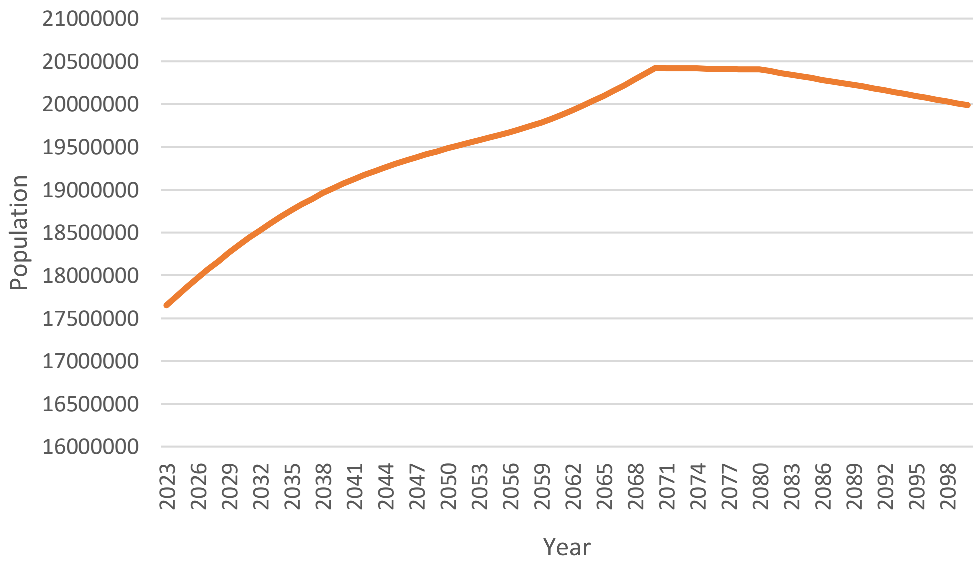
8.1 Accounting MFA data for 2019

Appendix 8.1 is a supplementary Excel file, which can be found in the following GitHub repository: https://github.com/raquelkuperus/thesis-appendices.git.

8.2 Comparison of CBS and calculated values for the number of homes constructed between 1901 and 2018



8.3 Assumed projected population for the Netherlands



8.4 Dynamic MFA model code.

Appendix 8.4 is a supplementary python script, which can be found in the following GitHub repository: https://github.com/raquelkuperus/thesis-appendices.git.

8.5 Number of industrially produced homes in 2022 (Rutten, 2023a)

Bouwproductie industriële woningen 2022 (Bron: Marjet Rutten)

Naam concept	laag of hoog-bouw	verwacht 2022	werkelijk 2022	waarvan flexibel
Daiwa House	beide	2.200	2.500	2.000
Plegt-Vos	beide	1.400	1.250	2
Trebbe	beide	1.000	990	230
Barli Base	beide	1.000	810	250*
Dijkstra Draisma	beide	750	783	0*
MorgenWonen VolkerWessels	beide	800	600	120
De Meeuw Nezzt	beide	750	460	460
Fijn Wonen - Van Wijnen	beide	800	300	0*
Hodes	beide	400	200	120
Ursem Modulaire Bouwsystemen	Beide	360*	200	200
Finch Buildings	hoog	450	159	0
Goedhuis – Welstand	laag	176	156	0
Casco totaal	beide	200	150*	0*
Domoticube – De Gebouwheer	beide	225*	150*	100*
Dura Vermeer Blokje Om(hoog)	beide	130	130	0*
Skilpod	beide	100	120	0
RAP Wonen	beide	136	100*	50*
Uuthuuske - The New Makers	laag	150	100*	50*
Homes Factory	beide	100	100	100
Startblock	laag	150	90	90
QYUUBS BV	beide	200	82	75
Kraaikamp Wagenbouw		80*	80	80
One – Heijmans	laag	100*	75*	75*
Slimm – Heembouw	laag	100	70	2
Mhome	beide	86	52	52
Mill Home			40	5
Premodu – Emergo	laag	12	20	20
Iwood	beide	6	8	2
FLETTS	hoog	208	0	0
Lumey		200	0	0
MOOS	Beide	350	0	0
Diverse kleinere aanbieders	Beide	705	325*	80*
Totaal		**13.324**	**10.100**	**4.163**

** inschatting, (nog) geen opgave ontvangen*