Spatiotemporal building stock modeling for residential decarbonization in the Netherlands

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Chapter 4 Urban mining potential to reduce primary material use and carbon emissions in the Dutch residential building sector[3]

Abstract

Urban mining is regarded as an important strategy to replace primary raw materials in the building sector. This study presents a bottom-up dynamic building stock model to explore the potential of urban mining to reduce primary material consumption and greenhouse gas (GHG) emissions in the residential building sector of the Netherlands. The model builds upon geo-referenced individual buildings, making it possible to analyze the spatiotemporal pattern of material supply from demolition and material demand for construction and renovation. The main results can be summarized as three points. 1) Urban mining cannot meet future material demand due to the new construction caused by population increase and its limited ability to supply the required kinds and amounts of materials. Therefore, large amounts of primary materials still have to be consumed in the future. 2) The generation of demolition wastes and the requirement for materials will be mainly concentrated in the big cities (e.g. Amsterdam, Rotterdam, and The Hague). 3) The GHG emission reduction potential of urban mining is very small and is not as large as the transition to a greener electricity mix. Recycling together with a greener electricity mix would reduce annual GHG emissions by about 40% in 2050 compared to 2020. This study provides a tool to link future material inflows and outflows in space and time. It further helps to assess the performance of strategies aimed at closing the material loops and reducing GHG emissions in the building sector.

Keywords: dynamic building stock model, material flow analysis (MFA), life cycle assessment (LCA), construction and demolition waste (CDW), urban mining, geographical information system (GIS)

4.1 Introduction

The built environment contributes to the generation of large amounts of material consumption, construction and demolition waste (CDW), and greenhouse gas (GHG) emissions [5]. In the European Union (EU), CDW makes up 25-30% of its total waste, and much of that could be recycled [8]. Urbanization and population growth are predicted to continue in the coming decades [237], intensifying material consumption and environmental challenges [238,239]. This trend is intertwined with the transition towards energy-efficient building stock (e.g. reconstruction and renovation) [112,148], which will also cause considerable material consumption and

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CDW generation, and a shift in attention towards embodied GHG emissions [32,240]. In current practices, CDW is typically used for road construction or backfilling [43,241], which are low-value applications that make further reuse impossible [44]. The transition from downcycling to high-quality CDW recycling is essential to close the building material cycles and reduce primary resource consumption and GHG emissions [242].

Urban mining is an important strategy that exploits the anthropogenic material stock in the built environment [243]. In recent years, geographical information system (GIS) datasets have been widely used to extract the information of individual buildings (e.g. geometry, year of construction, and function) [27,98]. GIS data and material intensities (kg/m^2 or kg/m^3) of buildings and infrastructures are usually applied together to determine the material stock at a high spatial resolution (map of material deposit) [244]. [245] and [246] analyzed the spatial distribution of material stock in buildings based on GIS data and material intensities of buildings differentiated by the construction period and utilization at the city scale. In addition to buildings, [247] further included the spatial distribution of materials stocked in roads and pipe networks. [80] integrated the urban mining model with life cycle assessment (LCA) to assess the environmental impact of different end-of-life scenarios.

Material flow analysis (MFA) depicts material flows and stock [108], and its principle has been applied, amongst others, in dynamic building stock models [129]. Some review articles on MFA [24,114–118] show that recent MFA studies particularly focused on bottom-up models that are more data-intensive (e.g. more detailed building archetypes) [84], often in combination with other tools, such as GIS [248], LCA [249], and system dynamic models [121,123]. The MFA model of [112] employed GIS data, building inventory data, and lifetimes of buildings and components to characterize the Swiss residential building stock, which has the potential to geographically aggregate future materials flows to different regional levels.

The linkages between material demand and secondary material supply from urban mining have not been well studied [112]. Hu and colleagues [111] have identified the building lifetime as a key variable influencing CDW generation, whereas the lifetimes of buildings are very long and vary significantly [24,238]. The amount and structure of CDW streams might not align with the material demand for new construction and renovation [247,250]. For example, modern buildings usually use some materials that do not exist in the old buildings to be demolished, such as insulation materials. Given that building materials are mostly large-volume but low-unit-value, transportation distance is an economic barrier, and supply and demand have to be close to each other, especially for the nonmetallic mineral materials (about 50-70 kilometers) [251,252]. Therefore, linking the material outflows and inflows in space and time is critical for making feasible plans in advance to realize a circular economy in the construction industry [253,254].

While the prevailing application of GIS data in recent years can provide spatial dimensions, current models mostly focus on quantifying retrospective material flows and stock in building stock [244,255]. In contrast, prospective MFA models rarely consider the spatial dimension. [251] and [44] analyzed the mismatch between material demand and supply from recycling in time while the mismatch in space was not fully considered. Besides, existing studies mainly focus on the material demand for constructing new buildings while the materials consumed during renovation processes are rarely accounted for [3]. Moreover, previous studies hypothetically conclude the urban mining potential to close material loops simply by comparing material outflows with inflows during building stock development, which omits the limitations of CDW collection practices and secondary material production technologies [44].

In the Netherlands, the construction sector accounts for 50% of raw material consumption, 40% of wastes, and approximately 35% of GHG emissions [155]. The government aims to reduce primary material consumption by 50% in 2030, realize a circular economy, and eliminate GHG emissions in the construction industry by 2050 [44,155,234]. The research questions of this study are:

(1) How will building material demand and the potential supply from CDW develop in space and time until 2050 in the Netherlands?

(2) How much primary material demand can be met by urban mining?

(3) What is the GHG emission reduction potential of urban mining?

This paper applies a bottom-up dynamic building stock model to track future material flows and stock of the Netherlands. The building stock is composed of georeferenced individual buildings, which makes it possible to analyze the spatiotemporal pattern between material demand and secondary materials recycled from demolition waste. The GHG emission reduction potential of urban mining is analyzed.

4.2 Materials and methods

4.2.1 Model overview

The conceptual outline of the model is presented in **Figure 4.1**. $\mathrm{BS}_{\mathrm{t_n}}$ is the building stock at the time $\mathrm{t_n}$ and $\mathrm{BS}_{\mathrm{t_{n+1}}}$ is the building stock at time $\mathrm{t_{n+1}}$. The development of material flows and stock is associated with the building stock dynamics, such as construction, demolition, and renovation. These are driven to a large extent by factors such as population, building age, floor area per capita, and policies, e.g. for the energy transition and circular economy [29,108]. The material outflows considered in this study are from demolition and renovation, and material inflows are due to new construction and renovation. Outflows are partly going to be recycled or used for other purposes and partly landfilled because some materials will be mixed or destroyed during demolition, making their recycling very expensive or impossible [44]. The outflows without collection will become wastes and need to be processed (e.g. landfill). The material inflows contain secondary materials and primary materials. The time frame of this study is from 2020 to 2050 as the government of the Netherlands aims to be completely circular by 2050 [220].

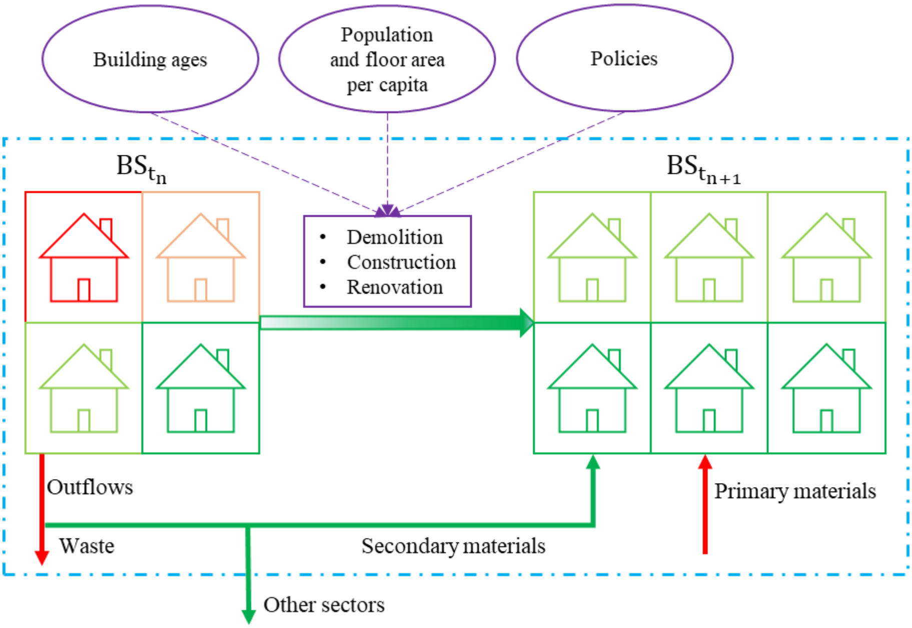

Figure 4.1 Schematic overview of the model. BS_{t_n} is short for the building stock at the time t_n and $BS_{t_{n+1}}$ is for the building stock at time t_{n+1}. The dot-and-dash line in light blue represents the system boundary. The purple color represents the factors that influence the building stock development. The red color represents the energy-inefficient buildings, waste, and the consumption of primary materials. The green color represents the energy-efficient buildings or reused materials. The efficiency of buildings in light green and orange colors is between energy-inefficient and energy-efficient buildings.

4.2.2 Material flow and stock

4.2.2.1 Building stock dynamics

The building stock dynamics are modeled based on [248], which is built upon individual buildings characterized by several attributes, mainly including building ID, construction year, building type, floor area, geometries, locations (city codes), U-values (thermal transmittances) of envelope elements (e.g. wall, roofs, and windows), and material composition. The existing buildings are characterized with basic information (e.g. footprint area and construction year) from GIS data [172] and classified based on the strategy of [27], including single-family houses, mid-terraced houses, end-terraced houses, multi-family houses, and apartment buildings. The geometries (e.g. window-to-façade ratio) and U-values of envelope elements are derived by allocating the archetype information [68] to individual buildings based on construction year and building type. As the GIS data only includes buildings built before 2015, the data gap of buildings in 2016-2020 is filled up with the stock-driven building stock model [248].

A building will be demolished after reaching its demolition year, which is determined by construction year and lifetime:

$$t_{dem} = t_{con} + t_{lifetime} \qquad (1)$$

Where t_{dem} is the demolition year, t_{con} is the construction year, and $t_{lifetime}$ is sampled based on Weibull distribution [206]. Buildings' lifetimes can vary significantly in the real world, depending on their function, ownership, and locations. In this study, lifetime differences between different building types are not considered due to a lack of data. The average lifetime is assumed as 130 years [37] and the shape parameter (k) is 2.95 [248]. Buildings constructed before 1900 are regarded as cultural heritage or protected buildings and will not be demolished in the considered time frame.

Construction activity is driven by total floor area demand as well as the demolished area at that year:

$$A_{con,t} = FAPC_t \times P_t - S_{t-1} + A_{dem,t} \qquad (2)$$

Where $A_{con,t}$ is the new construction area. $FAPC_t$ is the floor area per capita in year t and P_t is the population [221] in year t. S_{t-1} is the floor area stock of the previous year, and $A_{dem,t}$ is the demolished floor area in year t. According to the policy of the Netherlands [222], all the buildings constructed since 2021 must be nearly Zero Energy Buildings (nZEBs). The proportions of new building types are assumed the same as in 2015 [248]. The Netherlands is still under urbanization [256], so the locations (city codes) of newly constructed buildings are determined by the weight of the population per city [30]. The population map can be found in **Figure S7.3.1** in Appendix.

Renovation activity is determined by annual renovation rates derived from the national control scenario of the Netherlands [156], which is aimed at realizing a climate-neutral energy supply in the built environment. Instead of sampling individual buildings from the building stock, a neighborhood-oriented approach [157] is used to sample building groups at the neighborhood scale. The neighborhoods with high weighted average U-values will be renovated first. Insulation materials are differentiated between conventional and nZEB standards. More details can be found in [248].

4.2.2.2 Building material composition

This study involves 25 kinds of common building materials in the Netherlands (**Table 4.1**). The material composition of an individual building is determined by matching its building type with the material intensities of the corresponding archetype. The material intensities of archetypes for existing buildings are empirically sourced from demolition companies [147], and the material intensities of new buildings are from [211]. The material intensities of archetype buildings can be found in **Table S7.3.1** and **Table S7.3.2** in Appendix. The material composition of individual buildings are estimated by multiplying floor area with material intensities:

$$M_{i,j} = MI_{type,i} \times A_j \qquad (3)$$

Where $M_{i,j}$ is the mass of material i in building j. $MI_{type,i}$ is the material intensity of the corresponding building type. A_j is the floor area of building j.

Table 4.1 Material labels and names.

Label	Material name	Label	Material name
Al	Aluminum	MW	Mineral wool
Ar	Argon	Pl	Plastic
Bi	Bitumen	PUR	Polyurethane foam
CB	Clay brick	Pw	Plywood
Ce	Ceramic	RC	reinforced concrete
Co	Copper	Sa	Sand
CI	Cast iron	SC	Sand cement
Cr	Concrete	St	Steel
EPS	Expanded polystyrene	SW	Softwood
Gl	Glass	WF	Wood fiber
Gr	Gravel	XPS	Extruded polystyrene
Gy	Gypsum	Zn	Zinc
HW	Hardwood	-	-

In this study, existing glasses will be replaced by HR++ or HR+++ glass. For the roof, external wall, floor, and door, renovation is considered by adding a new insulation layer on top of the surface of each envelope element. The details on insulation materials for envelope elements can be found in **Table S7.3.3** in Appendix. The amounts of insulation materials consumed during renovation (excluding windows) are determined as follows [211]:

$$M_{i,j,e} = \left(\frac{1}{U_{insulation,j,e}} - \frac{1}{U_{exi,j,e}}\right) \times k_i \times A_{j,e} \times D_i \qquad (4)$$

Where $M_{i,j,e}$ is the mass of insulation material i required for insulating a surface element e. $A_{j,e}$ is the area of the element of building j. $U_{exi,j,e}$ is the existing U-value of the element and $U_{insulation,j,e}$ is the U-value post insulation. k_i is the thermal conductivity and D_i is the density.

4.2.2.3 Collection and recycling

The steps of processing material outflows from demolition and renovation are based on [44]. The first step is to quantify the annual material outflows and inflows, which can be calculated by grouping individual buildings by city codes and then aggregating the annual outflows and inflows of each material of individual buildings for each city. The second step is to estimate the amounts of material outflows suitable for recycling. The third step is to determine the amounts of recycled materials that can replace primary raw materials required for new construction or renovation.

The supply of collected outflows suitable for recycling is determined as follows:

$$M_{supply,i,t} = M_{outflow,i,t} \times R_{EOL_{collection},i} \qquad (5)$$

Where $M_{supply,i,t}$ is the collected material i from outflows ($M_{outflow,i,t}$) in year t. $R_{EOL_{collection},i}$ is the end-of-life (EOL) collection rate of material i (see **Table S7.3.4** in Appendix), meaning the share of material outflows collected for recycling.

The amount of waste material i in year t is calculated as follows:

$$M_{waste,i,t} = M_{outflow,i,t} \times (1 - R_{EOL_{collection},i}) \qquad (6)$$

The limited amount of recycled material used in annual construction activities is determined as follows:

$$M_{\mathrm{limit},i,t} = M_{inflow,i,t} \times R_{\mathrm{limit,i}} \qquad (7)$$

Where $M_{inflow,i,t}$ is the inflow of material i in year t. $M_{\mathrm{limit},i,t}$ is the maximum limited amount of primary material i that can be substituted by the recycled material in year t, and $R_{\mathrm{limit,i}}$ is the corresponding recycled content potential. The recycled content potential, defined as "the potential maximum fraction of secondary materials in the total input of material production", is used to estimate the maximum amounts of recycled material application in new construction and renovation [44,257]. The recycled content potential of different materials is from the literature [44] and details can be found in **Table S7.3.4** in Appendix.

To determine how many primary materials are replaced by recycled materials, the annual surplus of recycled materials ($M_{\mathrm{surplus},i,t}$) is used. It is calculated as follows:

$$M_{\mathrm{surplus},i,t} = M_{supply,i,t} - M_{\mathrm{limit},i,t} \qquad (8)$$

If $M_{\mathrm{surplus},i,t}$ is less than zero, it means that the supply of the collected material from outflows is not enough to reach the maximum recycled content potential. If $M_{\mathrm{surplus},i,t}$ is greater than zero, it means that there is residual collected material supply, which can be used for other sectors. The formula below shows the calculation of recycled materials used ($M_{\mathrm{recycled},i,t}$) in the annual residential building construction and renovation:

$$M_{\mathrm{recycled},i,t} = \begin{cases} M_{supply,i,t}, & M_{\mathrm{surplus},i,t} < 0 \\ M_{\mathrm{limit},i,t}, & M_{\mathrm{surplus},i,t} \geq 0 \end{cases} \qquad (9)$$

The annual primary material demand ($M_{\mathrm{primary},i,t}$) is calculated as follows:

$$M_{\mathrm{primary},i,t} = M_{inflow,i,t} - M_{\mathrm{recycled},i,t} \qquad (10)$$

The EOL recycling rate ($R_{recycling,i,t}$) is used to measure the proportion of the collected material that is used in construction and renovation in year t [44]. It is calculated as follows:

$$R_{\mathrm{EOL}\_recycling,i,t} = \frac{M_{\mathrm{recycled},i,t}}{M_{supply,i,t}} \qquad (11)$$

The substitution rate ($R_{\mathrm{substitution},i,t}$) is used to measure the proportion of the primary material that is substituted with recycled materials in year t [44]. It is calculated as follows:

$$R_{\mathrm{substitution},i,t} = \frac{M_{\mathrm{recycled},i,t}}{M_{inflow,i,t}} \qquad (12)$$

4.2.2.4 Life cycle assessment

In this study, environmental impact is represented by GHG emissions measured as kg CO_2-eq [215]. All the GHG emissions of primary and recycled materials, treatment of wastes, and transportation are modeled with ecoinvent database 3.6 (cut-off system model) [138]. Electricity mix change will significantly influence the GHG emissions of material production [258], so the method by [216] is applied to create future background databases that represent future scenarios for electricity generation by combining ecoinvent and IMAGE database 3.0 [217]. We select two scenarios: the scenario (SSP2) based on the middle of the road following a representative concentration pathway (RCP) of 6 W/m^2 and the scenario (SSP2 450) based on a more ambitious middle of the road following RCP 4.5 (SSP2 450, greener electricity supply) [218]. The LCA software Activity Browser [131] is used to combine these datasets using the superstructure approach [142] to retrieve the GHG emission factors (see section **7.3.4**) of relevant processes.

The material-related GHG emissions are calculated as follows:

$$GHG_{i,t} = M_{i,t} \times (F_{i,t} + S_{\mathrm{truck}} \times L_{material,\mathrm{truck}} \times F_{\mathrm{truck,t}} + S_{\mathrm{ship}} \times L_{material,\mathrm{ship}} \times F_{\mathrm{ship,t}}) \qquad (13)$$

Where $GHG_{i,t}$ is the GHG emissions of material i in year t. $M_{i,t}$ is the mass of material i. $F_{i,t}$ is the GHG emission factor of material i production or recycling. In the Netherlands, building materials are mainly transported by truck and ship. S_{truck} is the share of materials transported with trucks (72%) and S_{ship} is the share of materials transported with ships (28%) [211]. The average transportation distances are 96 km ($L_{material,\mathrm{truck}}$) and 123 km ($L_{material,\mathrm{ship}}$), respectively [211]. $F_{\mathrm{truck,t}}$ is the GHG emission factor of truck and $F_{\mathrm{ship,t}}$ is the factor for ship.

In this study, wastes are landfilled and the GHG emissions are calculated by summing up for all the waste materials as follows:

$$GHG_{landfill,t} = \sum M_{waste,i,t} \times (F_{landfill,t} + F_{\mathrm{truck,t}} \times L_{\mathrm{landfill,truck}}) \qquad (14)$$

Where $GHG_{landfill,t}$ is the GHG emissions of waste treatment at year t. $F_{landfill,t}$ is the GHG emission factor of landfills. The average transportation distance for landfilled waste ($L_{\mathrm{landfill,truck}}$) is 50 km [259].

4.3 Results

4.3.1 Building and material stock

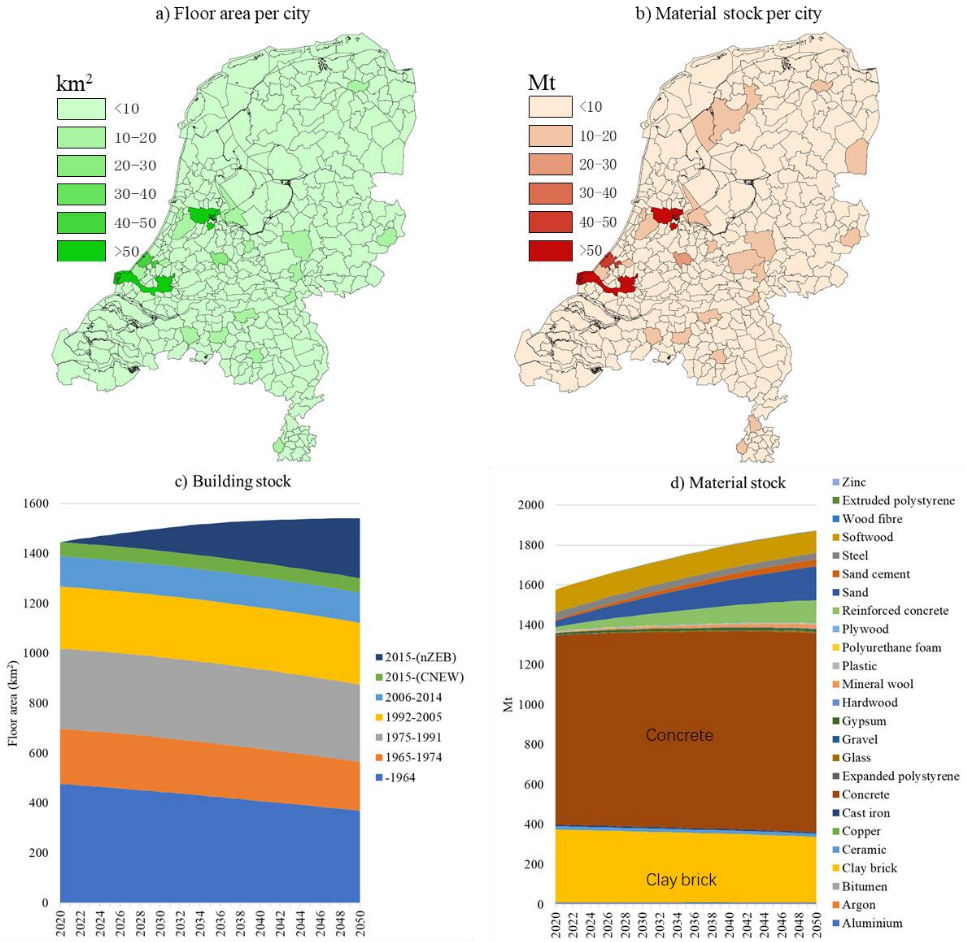

Figure 4.2 The existing building and material stock and its projected future development.

Figure 4.2a and **Figure 4.2b** show that both buildings and materials are concentrated in big cities, such as Amsterdam, Rotterdam, and The Hague. In **Figure 4.2c** and **Figure 4.2d**, both building and material stock will increase, while the increase of material stock is more obvious than that of building stock. Most existing buildings will still exist by 2050, and the buildings constructed after 2015 only occupy about 19% of the total building stock in 2050. The buildings constructed before 1964 are demolished most, but still have the largest share in 2050 (24%). Concrete (above 50%) and clay bricks (approximately 20%) dominate the material stock during the studied period.

4.3.2 Spatiotemporal material flows

Figure 4.3a shows that most of the material outflows are from Amsterdam, Rotterdam, and The Hague. From **Figure 4.3b** we can see that material outflows increase with time. Concrete (about 60%) and clay bricks (approximately 24%) occupy the largest share of material outflows. It can be found in **Figure 4.3d** that the material inflows are mainly distributed in big cities, especially in Amsterdam. **Figure 4.3e** shows that annual material inflows will decrease. The material inflows are dominated by concrete, sand, and reinforced concrete. Comparing **Figure 4.3b** with **Figure 4.3e**, we can find that the material inflows are much more than the outflows. The structure of material inflows is not in line with the structure of material outflows. For example, the share of clay bricks is very large in outflows but can almost be omitted in material inflows. **Figure 4.3c** and **Figure 4.3f** show that the spatial distribution of increased floor area is in line with the material deficit, meaning that big cities will construct more buildings and required more materials in the future. However, The Hague will not require as many new buildings and materials as Amsterdam and Rotterdam.

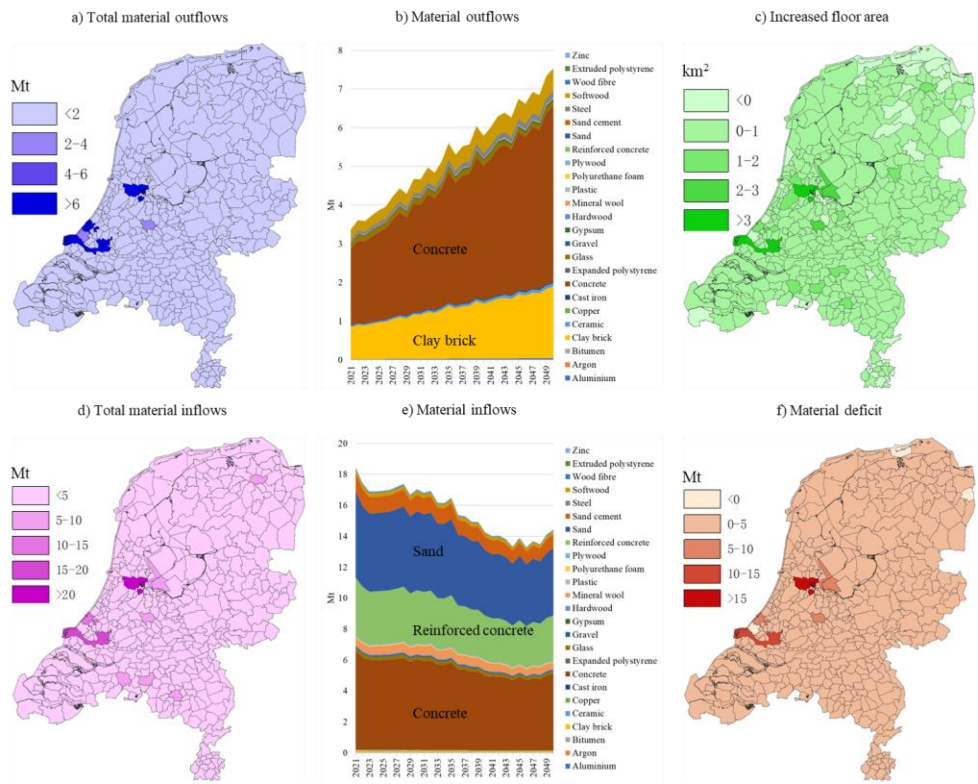

Figure 4.3 The material flows and increased floor area in space and time.

4.3.3 Substitution potential

Figure 4.4a shows that the supply of collected materials from outflows is mainly concrete and clay brick, and their amounts increase with time. In **Figure 4.4b**, the recycled material streams used in new construction and renovation mainly include concrete, wood, and glass. In 2035, the consumption of recycled materials begins to fall while the material supply from collections continues to increase, meaning that some of the recycled materials (e.g. concrete) have reached their maximum recycling potential and the residual collected materials (supply surplus) can be used in other sectors. This is also shown in **Figure 4.4c** that large amounts of the concrete surplus are generated in the 2035-2050 period. The clay brick is noteworthy as its surplus is much more than other materials. The reason is that clay brick is not intensively used in new buildings anymore. Comparing **Figure 4.3e** and **Figure 4.4d**, we can find that large amounts of primary materials (e.g. concrete and sand) will still be consumed although some material inflows are met by recycled materials.

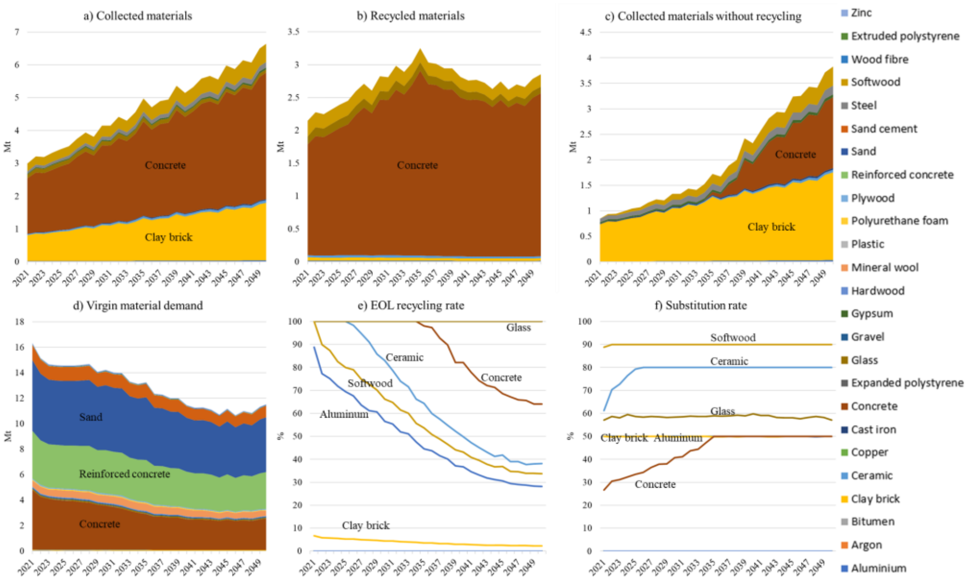

Figure 4.4 Figure 4.4a-d show the fate of demolition waste and the demand for virgin materials after considering the substitution effect of recycling. Figure 4.4e-f show the EOL recycling rates of collected material outflows and the substitution rates of secondary materials.

Figure 4.4e shows that the EOL recycling rates gradually decline for most materials. The EOL recycling rate of glass is always 100%, as the amount of recycled glass is much less than its maximum recycling content potential, and all the collected glass is consumed in new construction and renovation. This is followed by concrete, which is not enough to reach its maximum recycling content potential before 2035, while after about 2035, it begins to reach the maximum recycling content potential and the concrete surplus begins to exist. The maximum recycling content potential points of aluminum (2021), ceramic (2025), and softwood (2021) are much earlier than concrete (2035). The EOL recycle rates of other materials (e.g. clay bricks) are very low. From **Figure 4.4f** we can see that the substitution rates of many materials reach their maximum recycling potentials before 2035. The substitution rate of glass is about 59%, much lower than its maximum recycling content potential (91%), as the collected amount cannot meet the demand.

4.3.4 GHG emissions

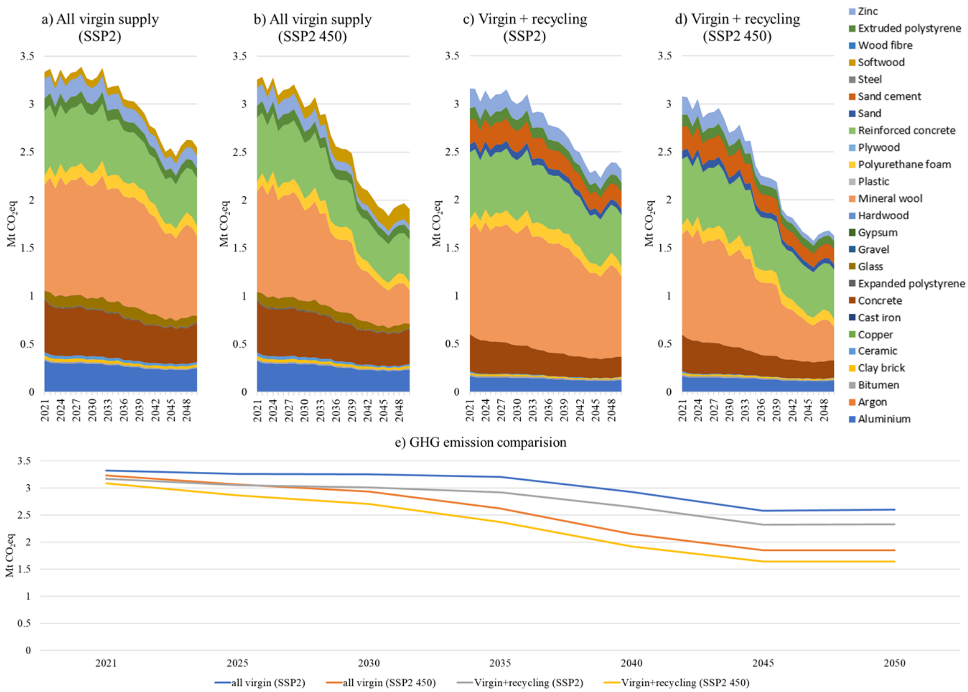

Figure 4.5 Material-related GHG emissions. In figure a-b, the substitution of recycled materials is not considered and all the materials required for construction and renovation are met by virgin materials. In figure c-d, virgin materials are partly replaced by recycled materials.

From **Figure 4.5a-d** we can find that the GHG emissions declines with time in all scenarios. Mineral wool, concrete, and reinforced concrete account for the most GHG emissions. Comparing **Figure 4.5a** with **Figure 4.5c** and **Figure 4.5b** with **Figure 4.5d**, we can find that the GHG emissions of concrete decrease due to the substitution effect of recycling. The GHG emissions of mineral wool decline significantly due to the greener electricity mix. In **Figure 4.5e**, the GHG reduction effect of a greener electricity mix is greater than substituting primary materials with recycled materials.

4.4 Discussion

This study presents a bottom-up dynamic building stock model to link future material demand and secondary material supply from urban mining. The potential of urban mining to reduce primary material use and GHG emissions in the Dutch residential building sector is investigated with the consideration of spatiotemporal dimensions. The mismatch between supply and demand is analyzed to find out what kind of materials have the biggest surplus or deficit. Compared with previous studies, the presented model focuses on future material composition evolvement of the building stock and builds upon individual buildings with georeferenced information, which enables the spatialization of material stock and flows. In addition, the material inflows and outflows during energy-efficiency renovation processes are accounted for at the building component level. Moreover, instead of directly comparing material outflows with inflows [112,248], our model not only considers the amounts of collected materials during demolition but also accounts for the amounts of recycled material used in annual construction activities. It can help local governments better manage CDW and understand the potential contribution of urban mining to realize circular economy and climate change targets.

4.4.1 Potential for substituting primary materials

The results above demonstrate that the material demand for new construction and renovation outweighs the supply of secondary materials because the increased population leads to more material demand for constructing new buildings. It might be challenging to achieve the Dutch target of reducing primary material consumption by 50% (2030) and 100% (2050) in the residential building sector through urban mining [234]. In previous studies [112,248], the material outflows are projected to nearly reach the amounts of annual material inflow by about 2050, indicating the big potential of recycling CDW to meet material demand for construction and renovation activities. Differently, the present study shows that the potential of urban mining to meet material demand is very limited as our model considers the recycling practices (i.e. CDW collection rates and recycled content potential).

This study uses fixed EOL collection rates and recycled content potential that is limited by current practice and legislation [44], while the technically recycling rates of some mineral materials can be very high and even reach 100%, such as concrete [5]. The recycled content potential might increase due to future technology and legislation change [260], so the substitution potential of urban mining might be underestimated in this study. Besides, intersectoral strategies could be made to reuse the residential material outflow surplus in another sector where it is in shortage, or vice versa [251], which also influences the substitution potential of urban mining in the residential building sector.

The economic perspective of building material recycling should also be paid enough attention to. In our research, materials are individually collected from CDW, which is a time-consuming and labor-intensive process [44], and might be economically challenging for developed countries where the labor cost for deconstruction is very high [240,261]. It is essential to change the legislation that currently limits the proportion of secondary materials in material inflows and promote the innovation of the circular business model for better managing the building material supply chain [1,44,262–264].

4.4.2 Potential for GHG emission reduction

The GHG emission reduction effect of urban mining is not as important as that of greening the electricity for material production. When a greener electricity mix is combined with a decrease of material inflows, and an increase of material outflows, the annual GHG emissions will decrease fastest, albeit only by about 40% in 2050 compared with 2020 (**Figure 4.5e**). Large amounts of concrete are still required in the future, and they contribute to a great share of GHG emissions. Thus, increasing the recycled content potential of concrete is critical for GHG emission reduction (see **Figure S7.3.2** in Appendix). Mineral wool is a widely used insulation material while reducing its application and finding alternative materials with low GHG emissions (e.g. bio-based materials) are essential [5]. In this study, the fixed recycled content potential is used but might increase in the future, so the GHG emission reduction potential of urban mining might be underestimated.

4.4.3 The mismatch between demand and supply

There is a structural contradiction between material supply and demand. On the one hand, the collected materials from waste streams do not contain some of the materials required for new construction and renovation, such as insulation materials. On the other hand, some of the collected materials from CDW will not be required too much anymore for new construction, such as clay bricks. Therefore, the choice of building materials in new construction can affect the EOL recycling rate of some materials.

The spatial mismatch between demand and supply is not obvious in this study because material deficit exists for most cities. The population will probably concentrate in metropolitan areas due to urbanization and the shrinkage of some small cities. Thus, different cities might be confronted with different situations in terms of secondary material surplus and deficit. Several neighboring municipalities can jointly plan demolition and new construction to reduce or avoid the mismatch in space and time.

The temporal mismatch between demand and supply could be resolved by better planning demolition and construction in advance to increase the overall EOL recycling rates. At the early stage, most of the recycled materials can enter the material inflows for new construction and renovation (material deficit). Nevertheless, as with the increase of demolition and the decrease of new construction, some materials gradually reach their maximum recycle content potential (material surplus).

4.4.4 Limitations and research opportunities

Some important limitations are associated with our study and can be further improved by future studies:

(1) Future demolition and construction activities could be better investigated. This study determines the future building demolition based on sampled lifetimes, and estimates new building construction based on population and floor area per capita, while it can be very far from reality, especially for mid-term prediction (from 2020 to 2050 in this study). The household size and living space per person [232] also vary significantly between different cities (see **Figure S7.3.1** in Appendix) and may change over time due to many factors (e.g. gross domestic product and immigration) [30]. Our model weights the new construction area based on the population of each city, but the population increase and migration between cities may significantly influence the spatial distribution of new construction [20,265]. Future researchers can collaborate with the governments to gain knowledge on future urban planning and socioeconomic development forecast.

(2) The future building types and technologies should be explored. The material structure of outflows and inflows are highly related to the types of buildings to demolish or construct [5,266]. As with the population increase in big cities and the scarcity of land, more high-rise apartment buildings with intensive reinforced concrete use would be built than single-family houses and terraced houses. Despite the limited GHG emission reduction potential of recycling, bio-based materials (e.g. wood) can be an alternative construction product to concrete and steel, because some bio-materials can sequester carbon emissions and act as carbon storage [5,35].

(3) The onsite material collection of demolition waste and the production of secondary materials need to be studied. The recycling of mineral materials is particularly complex [41]. Concrete, for example, is a mix of many primary materials, such as cement, sand, aggregates, and water. However, our model just assumed that the concrete from CDW is directly to substitute the primary concrete (actually similar to reuse) has not fully considered the details of production processes (e.g. crushing collected concrete into reusable aggregates). In this study, steel is collected from the outflows but its use in reinforced concrete production is not reflected. Therefore, an intermediate material classification system is required to link the material outflows and new material production [267]. Besides, future researchers can focus on the LCA of secondary material production to investigate the more accurate GHG emission reduction potential of urban mining [262].

4.5 Conclusion

This study presents a bottom-up dynamic building stock model that tracks the building stock development as well as the material stock and flows. The primary material substitution and GHG emission reduction potential of urban mining are explored by linking material demand and the material supply recycled from demolition waste.

The results demonstrate that urban mining can only replace a small share of primary material consumption mainly because the increasing population will require more new buildings. A great structural mismatch exists between recycled materials and the materials required for new buildings since some collected materials from CDW will not be used too much in new construction and renovation. In contrast, there will be large amounts of concrete outflow and inflow, showing the great recycling potential of concrete. The GHG emission reduction potential of urban mining is very limited and not as large as the transition to a greener electricity mix. Mineral wool only accounts for a very small share in terms of weight but will contribute to a great proportion of GHG emissions. Therefore, low-carbon insulation materials are required to replace it, such as bio-based insulation materials.

The model can depict the mismatch between material inflows and outflows in space and time, which provides the opportunity to better plan demolition and construction for high-quality CDW management. Future studies could focus on cross-region materials flows. For example, the recycled material outflows of shrinking cities might be used in emerging cities next to them. Neighboring cities can make recycling strategies together to improve CDW management. In addition, future research can combine residential buildings, utility buildings, and infrastructures that consume similar materials. This would better depict the overall material flows between different sectors, and thus make more systematical policy strategies for CDW management, especially for saving the cost of voluminous mineral material storage and logistics. Moreover, given that new construction requires large amounts of materials, extending the lifetime of existing buildings by extensive renovation rather than demolition and reconstruction can greatly reduce both CDW generation and primary material consumption.