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Journal of Cleaner Production 430 (2023) 139677

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Integrating bottom-up building stock model with logistics networks to support the site selection of circular construction hub

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ARTICLE INFO

Handling Editor: Mingzhou Jin

*Keywords:*
Circular construction hub
Circular economy
Demolition waste
Building stock
Site selection
Transportation carbon emissions

ABSTRACT

The circular construction hub is a logistics point for the storage, processing, and distribution of secondary construction materials. However, its site selection is dampened by the lack of detailed spatial information on material flows. In this study, the quantities and the spatial distribution of material flows are projected using a bottom-up building stock model. The material flows are integrated with logistics networks to assess the environmental impact of transporting materials between the building stock and the circular construction hub. The model is demonstrated on the building stock of Leiden, a municipality in the Netherlands. The results show that the location of future construction and demolition activities has a major impact on transportation carbon emissions. As construction decreases and demolition increases, the relative share of transportation carbon emissions from recycling will increase. The comparison between the two candidate sites for the circular construction hub is made to select the site with lower total transportation carbon emissions. By considering the evolution of building stock, the model can help urban planners make a more comprehensive decision on the location of the circular construction hub.

## 1. Introduction

The construction sector plays a crucial role in realizing circular economy targets. In the Netherlands, it consumes 50% of raw materials, generates about 40% of total waste, and contributes to 35% of carbon emissions (Circle Economy, 2020). The reuse of construction and demolition waste (CDW) as secondary materials is an important strategy to close material loops (Pauliuk et al., 2021), while there are many technical, economic, and legal challenges to overcome (Purchase et al., 2022). Therefore, CDW is most commonly downcycled as aggregates for backfilling (e.g., road foundations), making further reuse impossible (Di Maria et al., 2018). The transportation of bulk-volume and low-value building materials accounts for a large part of the total economic costs (Göswein et al., 2018), and causes severe urban congestion and environmental impacts (Guerlain et al., 2019). Organizing efficient logistics for the supply of secondary materials is important for the transition to a circular and climate-neutral construction economy (Metabolic, 2022).

The construction hub is a solution to synthesize the regional building material demand and the upstream supply chains (Ding et al., 2023; Nieuwhoff, 2022a). Despite various definitions and classifications, it is a logistics point outside the city, mainly used for the storage and distribution of building materials (Metabolic, 2022). With the development of closed-loop supply chains, the concept of the circular construction hub was developed by expanding the functions of the traditional construction hub to include the collection, processing, upcycling, and trading of secondary materials (Shan, 2023). It is particularly important for achieving component-level circularity, i.e., directly reusing components from demolished buildings (e.g., windows and doors) instead of breaking them down into material form (Arora et al., 2019). The circular construction hub not only involves the transportation of the materials harvested from CDW to the hub (reverse logistics) but also includes the delivery of materials from the hub to the construction sites (forward logistics) (Van den Berghe and Verhagen, 2021). Thus, the location of the circular construction hub, as well as the spatial distribution of future

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https://doi.org/10.1016/j.jclepro.2023.139677
Received 25 May 2023; Received in revised form 15 October 2023; Accepted 6 November 2023
Available online 10 November 2023
0959-6526/

material flows generated by construction and demolition, will have a significant impact on operating costs and transportation-related environmental impact (Augiseau and Kim, 2021; Wuyts et al., 2022). Previous research has typically focused on either forward logistics or reverse logistics, but without integrating the supply chain of primary and secondary materials (Ding et al., 2023).

Material flow analysis (MFA) maps and quantifies the resources that flow into and out of a given product of human society (Graedel, 2019). MFA models can be categorized into top-down approaches and bottom-up approaches, depending on the level of detail at which the internal structure of the building stock (e.g., building types and time cohorts) is considered (Augiseau and Barles, 2017). Population, floor area per capita, and building lifetime distribution are typically used as drivers to simulate the compositional evolution of the building stock over a long period (also referred to as "dynamic building stock models") (B. Müller, 2006; Mastrucci et al., 2017). Material intensity coefficients of representative buildings are usually multiplied by building floor area to estimate material quantities. However, due to a lack of physical data on individual buildings, the large-scale accounting MFA models cannot be directly used to trace material flows across city boundaries (X. Wang et al., 2023). Therefore, MFA studies conducted at the city or smaller scale are necessary to manage the local building material supply chain and provide actionable recommendations for urban planning (Wuyts et al., 2022). Over the past decades, geographic information systems

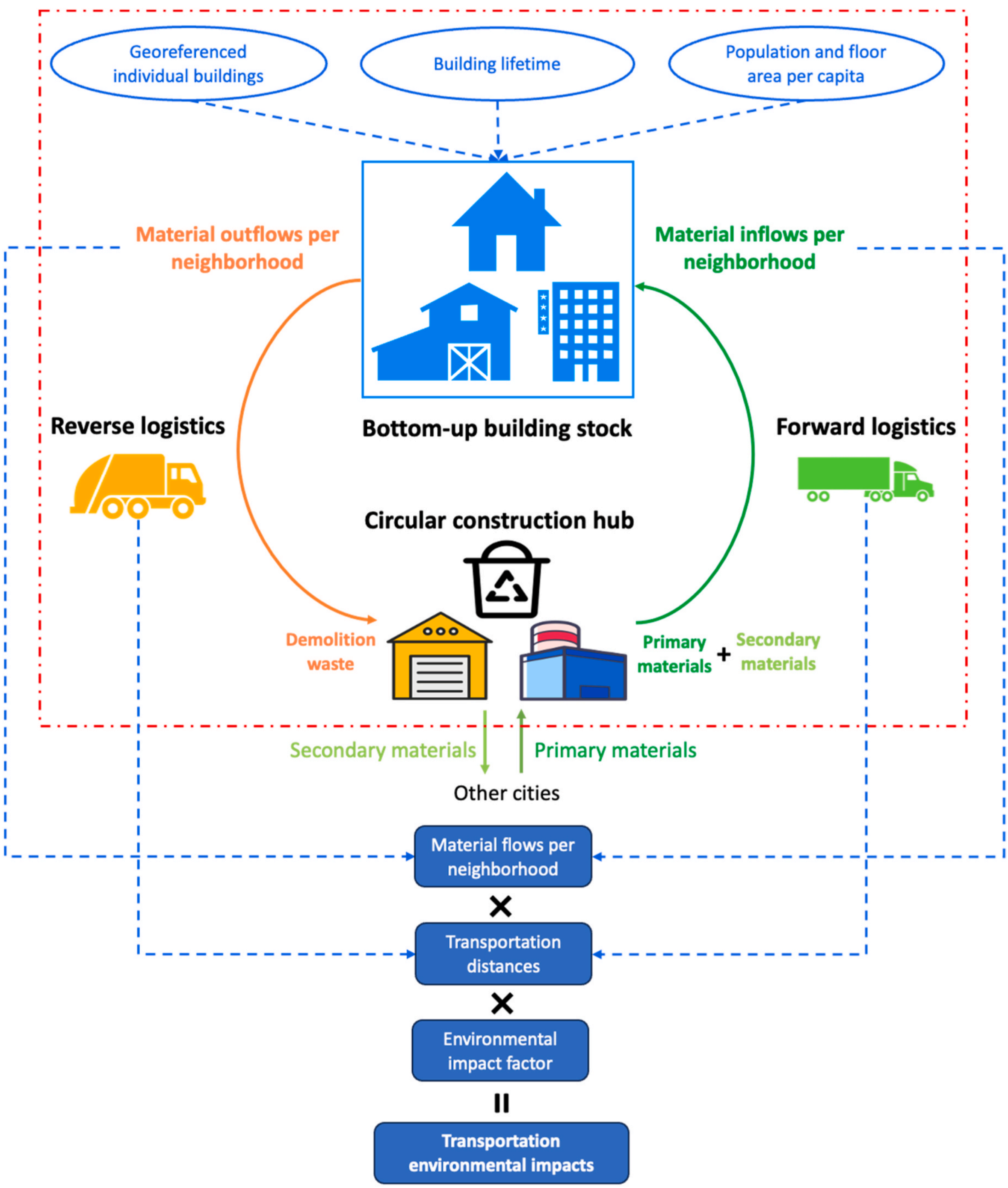


**Fig. 1.** The model overview. The dot-and-dash line in red represents the system boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(GIS) have been gradually used to reveal the spatial distribution and historical accumulation of building material stocks (Lanau and Liu, 2020; Tanikawa and Hashimoto, 2009), but they are rarely applied in prospective MFA models (Göswein et al., 2019). The lack of detailed spatial information on future material flows hinders the application of MFA in tracking the material movements between the building stock and circular construction hubs (Wuyts et al., 2022).

This paper integrates building material flows with logistics networks to support the site selection of the circular construction hub. A bottom-up building stock model is developed to project the volumes and potential spatial distribution of future construction and demolition material flows. The locations of the material flows are linked to the potential locations of the circular construction hub to calculate the distances of the material logistics networks. Both forward and reverse logistics are considered. The Dutch city of Leiden is selected as a case study for model demonstration. The transportation carbon emissions of two candidate locations are compared to determine the preferred location for the circular construction hub. The main research questions of this study are:

(1) What is the potential development pattern of the building material flows in space and time?
(2) What is the preferred location for the circular construction hub in terms of minimizing the environmental impact of material transportation?

## 2. Materials and methods

### 2.1. Model overview

The modeling framework is shown in Fig. 1. It includes the bottom-up building stock, the circular construction hub, and the logistics networks for building materials. The bottom-up building stock consists of georeferenced individual buildings. The evolution of the building stock size and composition as well as the associated material flows, are modeled according to the MFA principles of (B. Müller, 2006). The circular construction hub is connected to the building stock through forward logistics networks, i.e., the transportation of primary and secondary materials for new construction, and reverse logistics networks, i.e., the transportation of demolition waste to the hub. It can temporarily store building materials before delivery, and process secondary materials (Nieuwhoff, 2022b). Surplus secondary materials are used to meet the material needs of other cities, while the material deficits are filled with materials supplied by other cities. The amounts of material flow per neighborhood are multiplied by transportation distances and environmental impact factors of transportation modes to assess the transportation-related environmental impact of candidate sites.

### 2.2. Bottom-up building stock model

#### 2.2.1. Building stock characterization

The initial building stock is characterized based on the BAG (Basisregistratie Adressen en Gebouwen) GIS database (BAG, 2018), which is maintained by all municipalities in the Netherlands. It contains the addresses, construction year, footprint area, height, and function of each building. Following the strategy of (Yang et al., 2020), the building floor area is calculated by multiplying the footprint area by the stories of each building. The building stories are equal to the building height divided by an average floor height of 3 m (García-Pérez et al., 2018). According to the building classification system of (Verhagen et al., 2021), buildings are classified into residential and utility buildings. Residential buildings include single-family houses, row houses, apartment buildings, and high-rise buildings (more than 5 stories). Utility buildings include office buildings, commercial buildings, and other buildings. Each building is georeferenced with a neighborhood code. The attribute table for each building is shown in Table S1.

The floor area stock in year $t$ ($S_t$) is calculated as follows:

$$S_t = \sum_{i=0}^{n_t} A_i \tag{1}$$

Where $A_i$ is the floor area of the building $i$. $n_t$ is the total number of buildings in year $t$.

#### 2.2.2. Demolition

In this study, buildings built before 1920 are assumed to be historic buildings that will not be demolished (Municipality of Leiden, 2017). The demolition year ($t_{demolition}$) of other buildings is calculated as follows:

$$t_{demolition} = t_{construction} + t_{lifetime} \tag{2}$$

Where $t_{construction}$ is the construction year of the building, which is obtained from the GIS data (BAG, 2018). $t_{lifetime}$ is the lifetime, which is sampled based on the numpy package of Python, according to the Weibull distribution (Miatto et al., 2017; Zhang et al., 2023). The density function of the Weibull distribution is:

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{k}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}, x \geq 0 \\ 0, x < 0 \end{cases} \tag{3}$$

Where $k$ is the shape parameter and its value is 2.95 (Deetman et al., 2020). λ is the scale parameter, which is determined is as follows (Yang et al., 2022a):

$$\lambda = lifetime_{mean} \div \Gamma\left(1 + \frac{1}{k}\right) \tag{4}$$

Where $lifetime_{mean}$ is the average lifetime of Dutch residential buildings and its value is 130 years (Deetman et al., 2020).

The total floor area of buildings demolished in year $t$ ($A_{demolition,t}$) is calculated as follows:

$$A_{demolition,t} = \sum_{j=0}^{n_{demolition,t}} A_{demolition,j,t} \tag{5}$$

Where $A_{demolition,j}$ is the floor area of building $j$ to be demolished in year $t$. $n_{demolition,t}$ is the total number of buildings to be demolished in year $t$.

#### 2.2.3. Construction

New construction is driven by demolished floor area, population, and floor area per capita (B. Müller, 2006). The floor area of new construction in year $t$ ($A_{construction,t}$) is calculated as follows:

$$A_{construction,t} = P_t \times FAPC_t - S_{t-1} + A_{demolition,t} \tag{6}$$

Where $P_t$ is the population in year $t$. $FAPC_t$ is the floor area per capita in year $t$. $S_{t-1}$ is the floor area stock of the previous year.

The floor area of new construction in a neighborhood in year $t$ ($A_{neighborhood,construction,t}$) is calculated as follows:

$$A_{neighborhood,construction,t} = A_{construction,t} \times F_{neighborhood} \tag{7}$$

Where $F_{neighborhood}$ is the weighting factor of newly constructed floor area per neighborhood.

### 2.3. Analysis of building material flows

This study includes 7 types of the most common building materials in the Netherlands: ceramics, brick, concrete, steel, wood, cast iron, and aluminum. The material composition of each building is estimated as follows:

$$W = MI \times A \tag{8}$$

Where $W$ is the material weight of the building. $MI$ is the material intensity, which is differentiated by building type and can be found in Table S4. $A$ is the building floor area.

The total material outflow weight of a neighborhood in year $t$ ($W_{neighborhood,outflow,t}$) is calculated as follows:

$$W_{neighborhood,outflow,t} = \sum_{k=0}^{n_{neighborhood,demolition,t}} W_j \tag{9}$$

Where $W_j$ is the material weight of the demolished building $j$. $n_{neighborhood,demolition,t}$ is the number of buildings demolished in a neighborhood in year $t$.

The total material inflow weight of a neighborhood in year $t$ ($W_{neighborhood,inflow,t}$) is calculated as follows:

$$W_{neighborhood,inflow,t} = MI \times A_{neighborhood,construction,t} \tag{10}$$

$W_{neighborhood,inflow,t}$ is supplied by both recycled materials ($W_{neighborhood,recycled,t}$) and primary materials ($W_{neighborhood,primary,t}$).

To ensure the quality and mechanical properties, current legislation limits the proportion of harvested materials that can be used to produce new materials (Verhagen et al., 2021). The amount of secondary materials used in local construction is not only determined by the end-of-life collection rate ($R_{EOL\_collection}$), but also by the recycled content potential ($R_{recycling\_limit}$) (Yang et al., 2022b). The end-of-life collection rate is defined as the proportion of materials collected from the demolition waste (Verhagen et al., 2021). In this study, a high-level circular demolition process is assumed to increase the direct reuse of materials from demolition (Arora et al., 2019). Building materials are collected individually to avoid the contamination and mixing of materials as much as possible (Verhagen et al., 2021). The recycled content potential is defined as the potential maximum share of secondary materials used in the total material input for new construction (International Resource Panel, 2011). The values for end-of-life collection rates and recycled content potential are given in Table S5.

The amount of the secondary material actually used in local construction in year $t$ ($W_{recycled,t}$) is calculated as follows:

$$W_{recycled,t} = \begin{cases} W_{limit,t}, W_{secondary,t} \geq W_{limit,t} \\ W_{secondary,t}, W_{secondary,t} < W_{limit,t} \end{cases} \tag{11}$$

Where $W_{limit,t}$ is the limit on the amount of secondary materials used in annual new construction. $W_{secondary,t}$ is the amount of secondary materials collected from the local material outflows.

$$W_{limit,t} = W_{inflow,t} \times R_{recycling\_limit} \tag{12}$$

Where $W_{inflow,t}$ is the total weights of material inflows in year $t$.

$$W_{secondary,t} = W_{outflow,t} \times R_{EOL\_collection} \tag{13}$$

Where $W_{outflow,t}$ is the total weight of material outflows in year $t$.

$W_{recycled,t}$ is allocated to each neighborhood based on the weight of each material demand per neighborhood:

$$W_{neighborhood,recycled,t} = W_{recycled,t} \times \frac{W_{neighborhood,inflow,t}}{W_{inflow,t}} \tag{14}$$

Material deficits are filled by primary materials, the amount of which is calculated as follows:

$$W_{neighborhood,primary,t} = W_{neighborhood,inflow,t} - W_{neighborhood,recycled,t} \tag{15}$$

### 2.4. Environmental impact of material transportation

In this study, only the transportation between neighborhoods and the circular construction hub is considered, while the material transportation between the circular construction hub and other cities is not considered because it does not affect the comparison results. The total environmental impact ($EI$) of transportation is calculated as follows:

$$EI_{total} = \sum_{1}^{n_{neighborhood}} \sum_{t_0}^{t_n} EI_{neighborhood,recycling,t} + EI_{neighborhood,primary,t} \tag{16}$$

Where $n_{neighborhood}$ is the number of neighborhoods. $t_0$ is the start year of the period considered. $t_n$ is the end year. $EI_{neighborhood,recycling,t}$ is the transportation environmental impact associated with recycling, including the transportation of material flows from the neighborhood to the circular construction hub and the transportation of secondary materials from the circular construction hub to the neighborhood. $EI_{neighborhood,primary,t}$ is the environmental impact of transporting primary materials from the circular construction hub to the neighborhood.

The environmental impact of transportation related to recycling is calculated as follows:

$$EI_{neighborhood,recycling,t} = \left(W_{neighborhood,outflow,t} + W_{neighborhood,recycled,t}\right) \times L_{neighborhood} \times F_{transportation} \tag{17}$$

Where $L_{neighborhood}$ is the distance between the circular construction hub and the neighborhood. $F_{transportation}$ is the environmental impact factor of transportation.

The environmental impact of transportation related to primary materials is calculated as follows:

$$EI_{neighborhood,primary,t} = W_{neighborhood,primary,t} \times L_{neighborhood} \times F_{transportation} \tag{18}$$

### 2.5. Case study

Here we use a case study in Leiden, a municipality in the Netherlands, to demonstrate the developed model. The initial building stock of Leiden consists of 53,173 individual buildings (BAG, 2018), as shown in Fig. 2. Leiden has 54 neighborhoods and its map is shown in Fig. S1. The timeframe for building stock evolution in this study is from 2020 to 2050. The future population of Leiden is shown in Table S2. The floor area per capita is calculated based on the population of Leiden in 2020, i.e., 67 m$^2$ for residential buildings and 73 m$^2$ for utility buildings.

**Fig. 2.** The map of buildings in Leiden.

These values are assumed to be constant over the period considered in this study. The weighting factor of the newly constructed floor area per neighborhood is derived from the construction plan of the municipality of Leiden (see Table S3).

Taking into account the accessibility of transport, land availability, and the locations of the major construction projects in the coming years, (van Luik, 2021) proposed two candidate sites for a circular construction hub in Leiden. One is on the east side of Leiden, next to the A4 motorway (Site A4). The other is on the west side of Leiden (on the territory of the municipality of Oegstgeest), convenient to the A44 motorway (Site A44). The location of these two sites is shown in Fig. S2. The transportation distances between the candidate sites and each neighborhood are estimated based on the driving mode of Google Maps (Google LLC, n. d.) and can be found in Table S6.

The transportation sector plays an important role for the Netherlands in achieving the climate-neutral targets in 2050 (Dutch government, 2019), so climate change is selected as the impact category, and carbon emissions are measured in kg $CO_2$-eq (IPCC, 2013). It is assumed that all the building materials and demolition waste are transported by truck. The carbon emission factor of the truck is 0.0002 kg $CO_2$ eq/(kg·km), which is taken from the ecoinvent database of version 3.6 (Wernet et al., 2016). The candidate sites are compared to determine which site results in lower transportation carbon emissions.

## 3. Results

### 3.1. Building stock evolution

In Fig. 3a, the current floor area stock is mainly distributed around the city center, where the buildings are mostly old and of small sizes, such as row houses. The neighborhood of Pesthuiswijk has the largest floor area because the buildings are very tall and dense. For example, there are many high-rise buildings in the Leiden University Medical Center (LUMC). Fig. 3b shows the structural change of the building stock from 2020 to 2050. The size of the building stock reaches 21, 244, 330 $m^2$ in 2050, an increase of 20% compared with 2020. In 2050, the new buildings constructed after 2020 account for 22% of the total stock. This means that most of the existing buildings will still be in use in 2050. The shares of residential and utility buildings are comparable. The "Utility-Other" buildings account for more than 1/3 of the total floor area stock. From Fig. 3c, we can see that the annual floor area demolished will generally increase, except for a few special years. For example, the demolished floor area will be very large in 2039, mainly due to the demolition of a large commercial building. In most years, residential buildings dominate the demolished floor area, especially row houses. However, the annual constructed floor area shows a different pattern. Fig. 3d shows that it will gradually decrease due to slower population growth and a relatively smaller amount of demolition. In addition, more

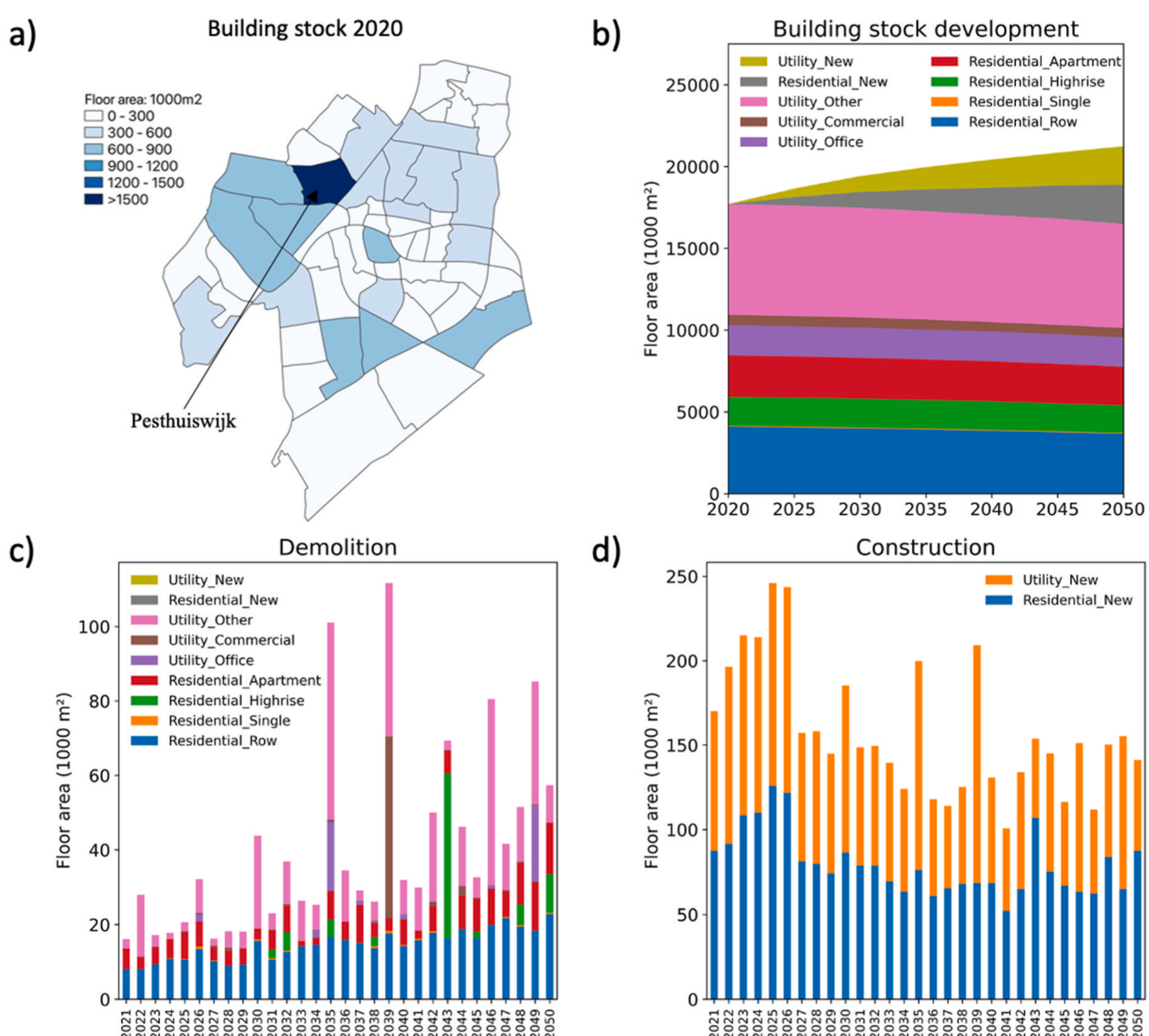


**Fig. 3.** The building stock development in Leiden, the Netherlands. In Fig. 3a, the floor area of individual buildings is aggregated and displayed at the neighborhood scale.

residential buildings will be constructed than utility buildings.

### *3.2. Material flows*

In Fig. 4a, the material outflow is mainly distributed in the neighborhoods around the city center, especially for Cronestein and Noordvest. Fig. 4b shows that the following neighborhoods have the most material inflow: Boshuizen, Tuinstadwijk, and Academiewijk. The amounts of both material outflow and material inflow in the city center areas are not large because many of these buildings are assumed not to be demolished in the period considered (i.e., historic buildings). Material inflow and material outflow are not spatially consistent. The comparison between Fig. 4c and d shows that the material inflow far exceeds the material outflow, meaning that the secondary materials from demolition cannot cover the material demand for new construction. However, the material outflow will gradually increase while the material inflow shows an opposite trend. Concrete and brick dominate both material outflow and material inflow. In Fig. 4e, the ratios of recycled materials to demolition waste are roughly equivalent to the end-of-life collection rates (see Table S3). This indicates that most of the collected materials are returned to the building stock, as the local supply of secondary building materials is much lower than the material demand. Fig. 4f also shows that the material demand is mostly met by primary materials, especially brick (80%), concrete (81%), and wood (82%).

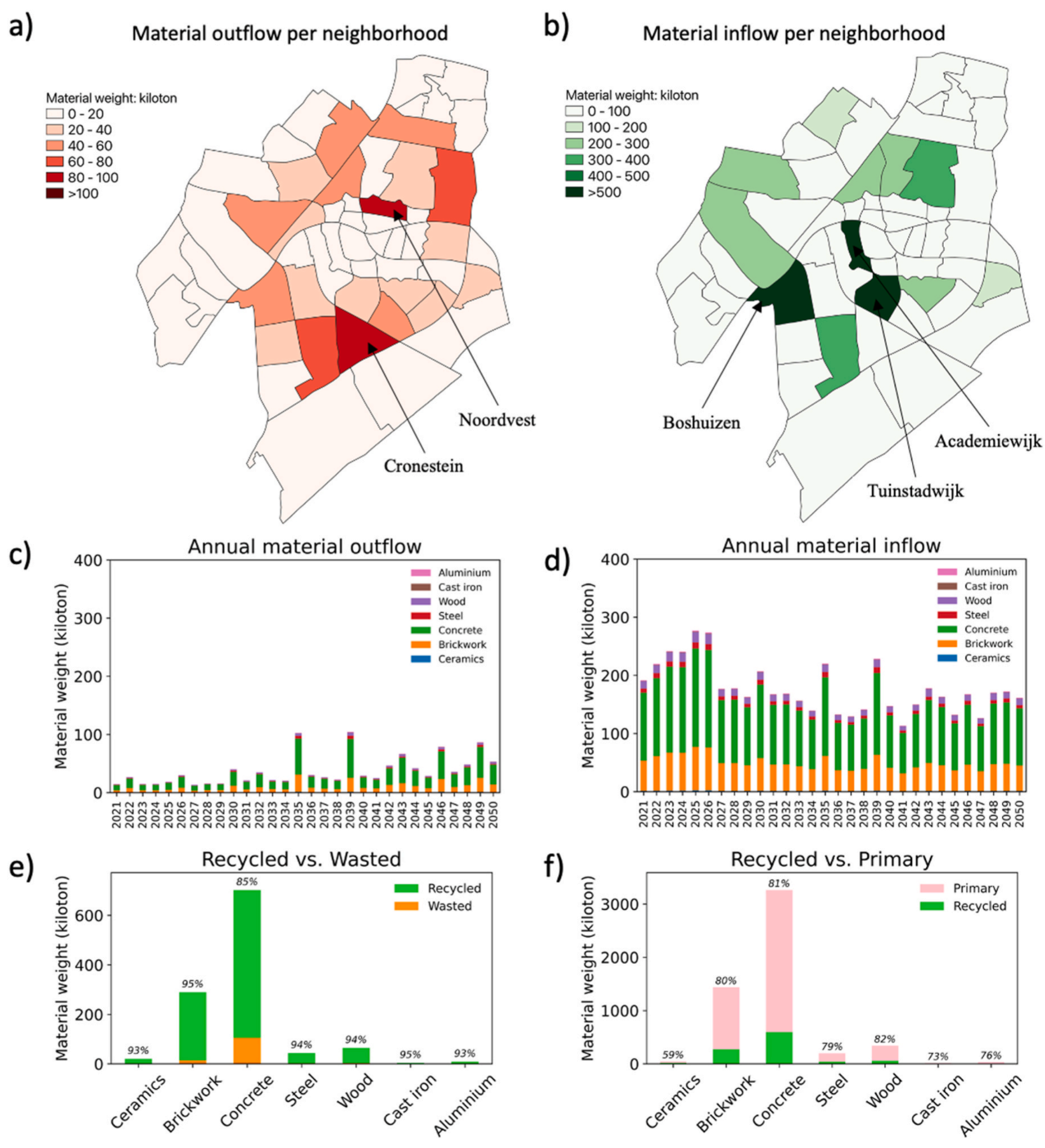


**Fig. 4.** Material flows in space and time. In Fig. 4a and b, the material flows are displayed at the neighborhood level. The material weights in Fig. 4a, b, Fig. 4e, and Fig. 4f are the sum of the material weights from 2021 to 2050. The percentages in Fig. 4e are the ratios of recycled materials to material outflow. The percentages in Fig. 4f are the ratios of primary materials to material inputs. "Recycled materials" are those materials that are not only collected for the production of secondary materials, but are also used in the construction of new buildings within the city.

### 3.3. Transportation carbon emissions

Comparing Fig. 5a and b, we can see the large differences in the spatial distribution of transportation carbon emissions of the two candidate sites. The neighborhoods with high transportation carbon emissions are located on the side that is far away from the circular construction hub. The spatial distribution of transportation carbon emissions is mostly consistent with the spatial distribution of material inflow in Fig. 4b. This indicates the large contribution of forward logistics to the total transportation carbon emissions. In Fig. 5c, concrete and brick contribute the most to transportation carbon emissions (nearly 90% in total), followed by wood (6%) and steel (4%). The transportation carbon emissions of Site A44 are lower than those of Site A4 for each material. Fig. 5d shows that the transportation carbon emissions of Site A44 are 4534 t $CO_2$ eq, while the transportation carbon emissions of Site A4 are 5155 t $CO_2$ eq. Site A4 results in 14% more transportation carbon emissions than Site A44. Primary materials dominate the cumulative transportation carbon emissions, while the share of recycling-related transportation carbon emissions will increase, reaching about 34% in 2050.

## 4. Discussion

This study integrates building material flows per neighborhood with logistics networks to support the site selection of the circular construction hub. Material flow development is simulated using a bottom-up building stock model built upon individual buildings from GIS data. Each neighborhood is linked to the circular construction hub to estimate the transportation distances of the logistics networks. The model is used to compare the transportation carbon emissions of two candidate sites for the circular construction hub in Leiden, the Netherlands. Our model can help policymakers comprehensively understand the local demand and supply chain of both primary and secondary building materials.

### 4.1. Large impact of future construction and demolition on transportation emissions

Our study shows that there are large differences in the transportation carbon emissions between neighborhoods. We find that the amount of material flows per neighborhood has a large impact on transportation demand. The location of demolition and construction activities influences transportation distances. Therefore, future demolition and construction agendas are critical for selecting the location of the circular construction hub. Given the long lifespan of the circular construction hub, the timeframe considered should not be too short. However, it is somewhat challenging for urban planners to provide accurate information on when, where, and what kind of buildings will be built in the long future (e.g., several decades). Thus, there is a balance between the length of the time period and the accuracy of the locations of construction and demolition.

In conventional dynamic MFA models, the building stock development is simulated based on several main drivers, such as population, floor area per capita, and building lifetime distribution functions (B. Müller, 2006; Pauliuk and Heeren, 2020). It is consistent with the well-known IPAT equation, where the impact is determined by human population, affluence, and technology (Göswein et al., 2019). Floor area

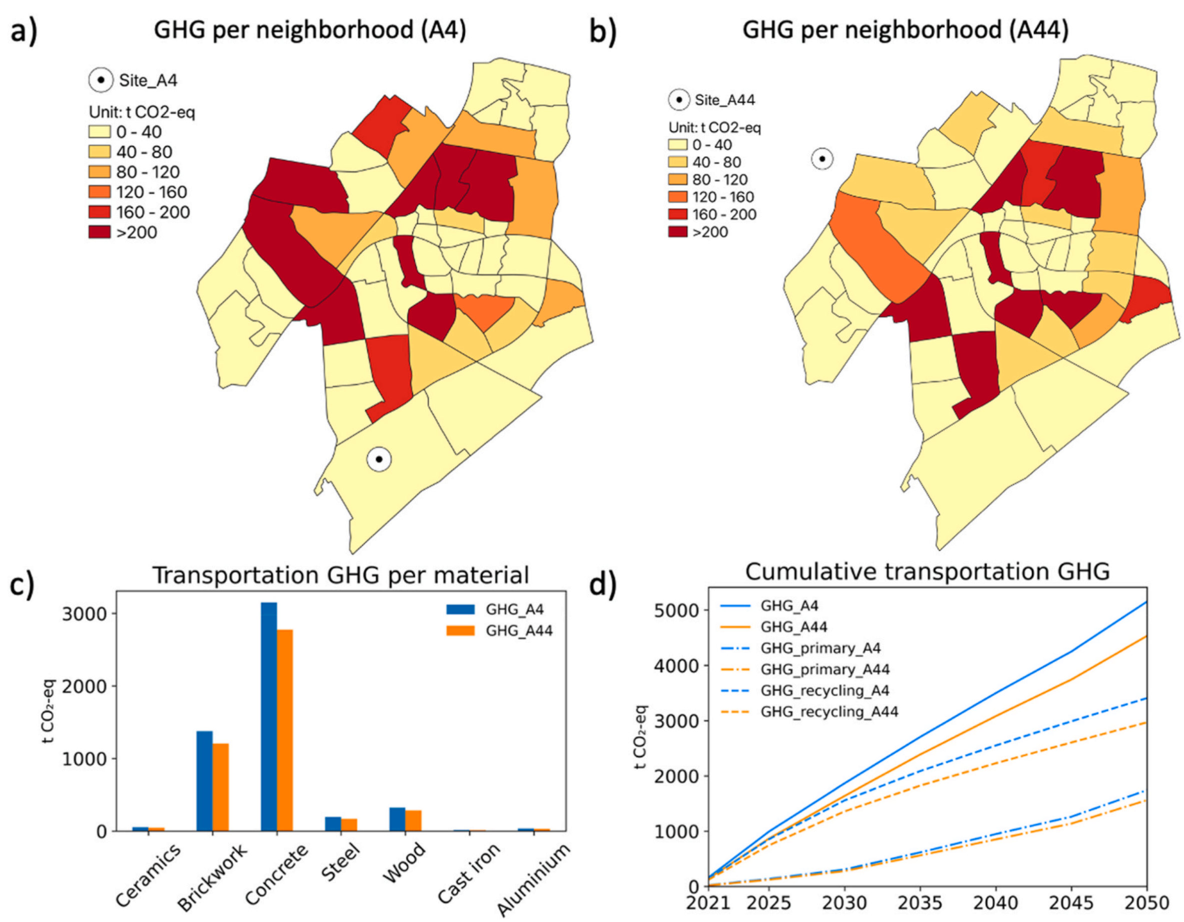


**Fig. 5.** Comparison of transportation carbon emissions between the two potential sites. The carbon emissions in Fig. 5a, b, and Fig. 5c are the sum of the transportation carbon emissions for each year from 2021 to 2050. In Fig. 5d, the total emissions include the transportation carbon emissions of both primary and recycled materials.

per capita corresponds to the affluence of IPAT equation. The structure of the building stock, i.e., building types and age cohorts and their material inventory, represents the technology dimension. However, previous models have typically focused the large-scale and long-term development trend of the building stock (Hu et al., 2010; Mastrucci et al., 2017). For a given city, the main drivers of MFA cannot be directly used by urban planners, who tend to design the urban morphology of buildings and infrastructure through many specific demolition and construction projects (Z. Wang et al., 2023). Compared with conventional MFA models, our model is based on georeferenced individual buildings, and takes the urban construction agenda into account, which allows tracking the spatial distribution and movement of material flows. This provides a direction for the application of MFA models in solving practical urban planning problems. Therefore, more micro-socio-economic factors can be integrated into MFA models to transform MFA from theoretical "analytical models" into pragmatic "decision-making tools" for formulating sustainable development policies (Lanau et al., 2019).

### 4.2. Increasing transportation carbon emissions from recycling

Unlike the supply of primary materials, which involves only forward logistics, the supply of secondary building materials involves both reverse logistics and forward logistics. This means that the increase in the number of demolished buildings leads to a "double" demand for material transportation. Therefore, the relative share of transportation carbon emissions of demolition waste recycling will gradually increase (see Fig. 5d). This trend is consistent with the study of (Yang et al., 2022b). In this study, the material inflows will gradually decrease over time, while the material outflows will gradually increase. One reason is that buildings have a long lifespan, so they remain in use for a long time. Another reason is that the annual population growth rate will gradually decline, which cannot sustain large-scale construction activities. The upgrading of the existing building stock (e.g., the reconstruction for energy-efficient buildings) will increase the demand for building materials as well as material transportation (European Commission. Joint Research Centre, 2018). This will pose challenges for high-level recycling of demolition waste to meet the material demand for new construction and to close the material loops within the construction sector because new buildings will consume some materials that are not present in the demolished buildings (e.g., insulation materials).

Concrete and brick should be given sufficient attention. They represent the majority of the existing building material stock, making them the dominant demolition waste (Gálvez-Martos et al., 2018). In addition, large amounts of concrete and bricks are also consumed in the construction of new buildings (see Fig. 4d). Therefore, better management of concrete and brick waste recycling is crucial to close the material loops and reduce transportation-related environmental impact in the built environment. Component-level circularity for concrete and bricks should be particularly advocated (Arora et al., 2019) because crushing the concrete and bricks for secondary material production will consume huge amounts of energy and might not be cost-effective. Design for disassembly (e.g., the prefabricated components of industrialized buildings) is a highly encouraged idea for component-level reuse, especially for structural parts (Stephan and Athanassiadis, 2018). However, given the long lifetime of buildings, direct reuse of these buildings components is in the far future, which cannot meet the demand for building components in the coming decades.

### 4.3. Policy implications and model application

This study shows that site A44 is preferable for the circular construction hub in terms of minimizing transportation carbon emissions. Both the scale and location of future construction and demolition activities should be considered when selecting the site for the circular construction hub. As the relative proportion of transportation carbon emissions from demolition waste recycling increases, due attention should also be paid to the supply chain of secondary materials, particularly concrete and bricks. Urban planners should provide more information on the long-term construction and demolition agenda to achieve more plausible results.

The building stock model presented in this study is based on individual buildings from GIS data and is therefore able to characterize the material flow of the building stock with high spatial resolution. The integration of future material flows and logistics networks can provide insight into the material movement between neighborhoods and the circular construction hub. Therefore, it can support the siting of the circular construction hub and determine the annual capacity of the circular construction hub to store and process secondary materials. Although the model is used to estimate the transportation carbon emissions for only one circular construction hub, it can be adapted to multiple hubs by adding a module that selects the nearest hub for each neighborhood. The model can be applied in all the cities in the Netherlands. Theoretically, the model can also be applied in other countries as long as the required data is available.

To our knowledge, this is the first study to use a bottom-up dynamic building stock model to address the issues related to site selection. Although some existing studies are able to map the current material stock (Guo et al., 2021; Lanau and Liu, 2020; Miatto et al., 2019), they did not consider the locations of potential consumers of secondary materials from demolition waste (Wuyts et al., 2022). In contrast, our study matches future material demand with secondary material supply in terms of quantity and spatial location, and integrates material flows with logistics networks based on Google Maps (Google LLC, n.d.), which allows for a systematic analysis of the closed building material supply chain at the city level.

### 4.4. Limitations and research opportunities

This study has the following limitations, which may provide opportunities for future research:

(1) This study mainly considers the evolution of the building stock from a technical perspective, while in reality, it is influenced by many socioeconomic factors that are difficult to capture. For example, the floor area per capita may change due to income and household size (CBS, 2018; IRP, 2020). Due to the lack of data, the demolition year of the existing buildings is randomly generated according to the Weibull distribution, which does not account for differences in the average life of different building types. This will greatly influence the amount of new construction and demolition, and the associated material transportation demand. Future research can work with urban planners to understand more about urban development strategies and land use.

(2) The material flows of renovation are not considered (Liu et al., 2022). Extensive energy efficiency renovations of existing buildings will consume large amounts of materials (CE Delft, 2020), especially thermal insulation materials (e.g., glass wool and expanded polystyrene) (Heeren and Hellweg, 2019). The low-density insulation materials take up more space and cause more transportation trips and carbon emissions.

(3) This study does not include water transportation. Some cities have many rivers that can be used to transport bulk materials, such as concrete and bricks. In addition, the use of renewable energy and electric vehicles will change the carbon emissions of trucks (Xu et al., 2023). Future research can investigate the impact of transportation mode transition on carbon emissions.

(4) Our research only takes the siting of the circular construction hub in the municipality of Leiden as an example. Future research can extend it to a larger scale, e.g., to investigate secondary material demand and supply of multiple cities, and to analyze the movements of materials between cities (Wuyts et al., 2022). For

example, the siting of multiple regional circular construction hubs should consider the surplus of secondary materials transported to neighboring cities and the material deficit filled by neighboring cities. In addition, the model can be further developed to find the optimized model, rather than just comparing candidate sites.

## 5. Conclusion

This study integrates the bottom-up building stock model with logistics networks to support the site selection of the circular construction hub. The use of GIS data and the future construction plan allows the characterization of material flows in space and time. Both forward logistics and reverse logistics are considered to calculate the environmental impact of transporting building materials. The model is demonstrated with a case study for the Dutch city of Leiden. The results show that there are large differences in transportation carbon emissions between neighborhoods. As the number of demolished buildings increases, the relative share of transportation carbon emissions from demolition waste recycling will gradually increase. The comparison between the two candidate sites shows that the site next to the A44 motorway generates lower transportation carbon emissions. The model can be used to analyze the local building materials supply chain and support the siting of construction hubs. Future research can extend the model to include material flows from renovation and material exchange with surrounding areas to provide a more comprehensive understanding of material supply and demand.

## CRediT authorship contribution statement

**Xining Yang:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing. **Mingming Hu:** Conceptualization, Methodology, Review & Editing. **Wenhui Shan:** Data curation, Visualization. **Chunbo Zhang:** Writing – review & editing. **Tiankun Li:** Writing – review & editing. **Yingji Pan:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgments

The authors would like to thank the support of the Hebei Natural Science Foundation (No. G2023203005), the Multigreen project “Merian Fund Cooperation China-The Netherlands (CAS) Green Cities 2019” (No. 48219704), the EU Horizon 2020 project ICEBERG “Innovative Circular Economy Based solutions demonstrating the Efficient recovery of valuable material Resources from the Generation of representative End-of-Life building materials” (No. 869336), and funding from the Chinese Academy of Sciences.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139677.

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