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Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

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Chapter 5

Recycling potential in building energy renovation: a prospective study of the Dutch residential building stock up to 2050

Chunbo Zhang, Mingming Hu, Benjamin Sprecher, Xining Yang, Xiaoyang Zhong, Chen Li, Arnold Tukker

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Abstract

Building energy and construction and demolition waste (CDW) are highly relevant but intertwined issues for the transition towards a carbon-neutral and circular built environment. Ongoing energy renovation uses an increasing number of emerging materials that pose a challenge for recycling. As a response, a novel technological system has been proposed to recycle CDW (including insulation mineral wool and lightweight concrete) for the manufacture of prefabricated concrete elements (PCEs) for use as façades for new (PCE-new) and retrofitting existing (PCE-refurbs) buildings. To explore how this novel system can improve recycling potential as part of building energy renovation efforts, the Dutch residential building stock was selected as a case study. Using a dynamic material flow analysis, we explore the supply-demand balance of secondary raw materials made from CDW (including normal-weight and lightweight concrete, glass, insulation mineral wool, and steel) and the secondary raw materials required for manufacturing PCEs in building energy renovation for the period 2015–2050. Our findings show that with advanced recycling technology, the secondary raw materials recovered from normal-weight concrete waste, glass waste, insulation mineral wool waste, and steel scrap will be more than sufficient to support the manufacturing of PCE-new walls, implying the possibility of closed-loop construction. However, for emerging materials such as lightweight concrete, the related waste will not be sufficient in the near future to meet the raw material demand for large-scale refurbishment with PCE-refurbs. Therefore, the Dutch case shows that the novel technology system offers a promising solution to CDW management problems in building energy renovation, but

primary raw materials will still be needed for the increased use of emerging materials such as lightweight concrete.

Keywords: material flow analysis (MFA), construction and demolition waste (CDW), prefabricated concrete element (PCE), recycling, energy renovation, building stock

Abbreviations

3R	Reduce, reuse, and recycle
ADR	Advanced dry recovery technology
CDW	Construction and demolition waste
CRLWCA	Coarse recycled lightweight concrete aggregate
CRSCA	Coarse recycled siliceous concrete aggregate
DGR	Dry grinding and refining system
EC	European Commission
EED	Energy Efficiency Directive
EoL	End-of-life
EPBD	Energy Performance of Buildings Directive
EU	European Union
FRSCA	Fine recycled siliceous concrete aggregate
FRLWCA	Fine recycled lightweight concrete aggregate
HAS	Heating-air classification system
MFA	Material flow analysis
ODYM	Open Dynamic Material Systems Model
PCE	Prefabricated concrete element
PCE-new	Prefabricated concrete element for new building construction
PCE-refurb	Prefabricated concrete element for existing building refurbishment
RFUA	Recycled fiber wool ultrafine admixture
RGUA	Recycled glass ultrafine admixture
SI	Supporting information
URSCA	Ultrafine recycled siliceous concrete aggregate
VEEP	European Union Horizon 2020 project “Cost-effective recycling of C&DW in high added-value, energy-efficient prefabricated concrete components for the massive retrofitting of our built environment”

5.1 Introduction

5.1.1 Potential of material circularity in building energy renovation

The building sector plays an essential role in resource depletion and waste management. The construction and operation of buildings in the European Union (EU) account for approximately half of all raw material consumption and generate approximately one-third of all waste (EC 2014c). It is generally recognized that a circular economy—with the principle of “Reduce, Reuse, and Recycle (3R)” —should become the basis of circular waste management and material cycles (Kirchherr et al. 2017). Legislative systems for waste management in the EU were established based on the 3R rule (Sakai et al. 2011). Following this, circular construction adopts the 3R rule for construction and demolition waste (CDW) management (Ghaffar et al. 2020). The essence of circular construction is to keep the components and materials of buildings in a closed loop and maximize their value as long as possible (Benachio et al. 2020). Closing the construction loop by recycling CDW is considered an effective means of improving material efficiency and reducing the adverse impacts of CDW.

A significant challenge, however, is that almost 75% of the overall European building stock is energy-inefficient (EC 2010). Considering the large amounts of greenhouse gasses emitted from the operation of buildings, improving energy efficiency is considered a critical strategy for achieving the EU’s 2050 carbon-neutral goal (EZK 2019). The EU deems building energy renovation as a critical solution to shift to an energy-efficient and low-carbon built environment (Esser et al. 2019). Energy renovation is an umbrella concept that is acknowledged as a variety of interventions in buildings to deliver different degrees of energy savings (Economidou 2021). Moreover, employing advanced energy-efficient technologies in new construction also serves to establish a broader range of energy renovations (Esser et al. 2019). Accordingly, obsolete buildings in Europe are to be renovated or replaced to improve their energy performance, which increases the turnover of building materials as a result. Action 5 of Directive COM/2015/6317 (EC 2015b) calls for the “Development of new materials and technologies for the market uptake of energy efficiency solutions for buildings”. In the context of extensive energy renovation in the EU, emerging high-performance materials such as insulating mineral wool, cellular and aerated glass, and lightweight concrete are increasingly used to reduce energy losses through building facades. Relative to 2015, the demand for such insulation materials is expected to increase in the EU by 3.5 % by 2027 (Pavel and Blagoeva 2018).

The demand for emerging materials to meet the demands of large-scale energy renovation not only increases the burden of resources but raises new problems surrounding their disposal. The main mineral-based insulating materials, such as stone wool and glass wool, are recyclable. One of the challenges for recycling is that insulation

materials are lightweight, and the share of insulation also remains a small fraction of the total CDW. Therefore, the current EU weight-oriented CDW recovery targets and low disposal costs in some member states have no incentive to recycle insulating materials. In addition, the transport of insulation is costly because of its low weight-to-volume ratio. At the same time, concrete recycling is costly (Zhang et al. 2019a), hence the recycling of common (normal-weight) concrete waste has not been popularized in the EU, not to mention the recycling of emerging lightweight concrete. Therefore, establishing a cost-effective recycling solution is expected to greatly help close the loop of these emerging materials and support a more circular built environment.

5.1.2 The Netherlands as a case study

The Netherlands has the best practice of CDW treatment among EU member states and worldwide, with a recovery rate of 98% (CLO 2021). However, the Netherlands is also faced with the dilemma that the current destination for downcycled concrete—road base backfilling—is almost exhausted. Furthermore, extracting secondary raw materials from CDW via traditional wet-processing technologies for the building sector is costly (Zhang et al. 2019a, 2020b). For glass and insulation materials, it was reported that glass in CDW can be 100% recycled in the Netherlands; however, more than 60% of these insulation materials are landfilled and incinerated (Mulders 2013). Moreover, in the Netherlands, more than half of the raw materials (gravel, sand, and cement) used for concrete production are dependent on imports (Zhang et al. 2020b). Another crucial point is that a large portion of the dwellings in the Netherlands remain energy-inefficient (Staniaszek 2014). Therefore, the ongoing building energy renovation will likely further aggravate the demand for resources in the Netherlands.

One potential possibility for simultaneously moving towards a circular and low-carbon built environment could be considering CDW as feedstock for building energy renovation. In Europe, a novel technological system has been developed by the ‘VEEP’ EU project for recycling CDW in the manufacturing of green prefabricated concrete elements (PCEs), offering high insulation performance for the renovation of the residential building stock. An advanced dry recovery system (ADR) and heating air classification system (HAS) were developed to recycle normal-weight and lightweight concrete waste *in situ*; and a dry grinding and refining (DGR) system was designed to recover glass waste and insulating mineral wool on-site. Consequently, recycled materials are used to fabricate green PCEs. The green PCE solution is conceived both for new building envelope construction (PCE-new) and for existing building envelope refurbishment (PCE-refurbs). Details of the PCE system are presented in the Supporting Information (SI).

To investigate whether the integrated PCE system offers a promising solution for CDW recycling in building energy renovation in the Netherlands, and whilst considering the

increased use of emerging materials, we sought to determine the extent to which CDW can be recycled as a feedstock in building energy renovation using the Dutch residential building stock as a case study. We apply material flow analysis (MFA) as a widely-used method for evaluating material metabolism by mass in the anthroposphere (Baccini and Btunner 2012). Among the three quantification approaches of MFA modeling defined by van der Voet (1996), dynamic MFA is usually applied to evaluate *ex-ante* and extrapolate trends. As we aim to unveil the recycling potential of emerging waste via an innovative recycling system, a dynamic MFA model was constructed for this study.

5.2 Literature review

To explore the recyclability of CDW, many studies have been conducted using the MFA approach. To position our study, a systematic literature review of MFA application in the field of CDW management was conducted. Relevant literature was searched for in the Web of Science Core Collection from 1945 to 2020 (search terms: TS = (“material flow analysis” OR “MFA”) AND (“construction and demolition waste” OR “CDW”)), yielding 32 results. After screening out five irrelevant studies, the remaining 27 studies are summarized in Table 5.1. It should be noted that this list is not exclusive.

Table 5.1 Literature related to material flow analysis of construction and demolition waste (CDW)

Literature	Model	Region	Study aims/notes
1 (Lederer et al. 2020)	Static, 2014	Vienna	MFA was used to quantify how waste reduction, reuse, and recycling of mineral CDW from buildings and infrastructure can contribute to reducing the demand for raw material imports for construction minerals.
2 (Zhang et al. 2020b)	Static, 2015, 2025	The Netherlands	Quantifies how technological innovation could contribute to upgrading waste concrete treatment from downcycling to recycling.
3 (Marcellus-Zamora et al. 2020)	Static, 2007–2017	Philadelphia, USA	Characterizes the flow of recoverable CDW, quantify aggregated CDW diversion, and evaluate recycling patterns for a portion of the CDW.
4 (Gassner et al. 2020)	Dynamic, 1990–2015	Vienna	Estimation of material turnover of urban transport systems, including both infrastructure and vehicles.
5 (Wu et al. 2020)	Static, 2007–2017	Australia	Quantifies the compositions and generation of CDW and reveals its cross-regional mobility.
6 (Noll et al. 2019)	Dynamic, 1971–2016	Samothraki, Greece	Strategy design on reducing, reusing, and recycling CDW on islands where waste treatment options are limited.
7 (Tanginthai et al. 2019)	Static, 2012	Great Britain, Thailand	Examines relevant policies on how to achieve more sustainable management of concrete and cement.
8 (Heeren and Hellweg 2019)	Dynamic, 2015–2055	Switzerland	Used a bottom-up probabilistic modeling approach to determine material stocks in Swiss residential buildings and associated carbon emissions.

9	(Jain et al. 2019)	Dynamic, 2012–2050	India	A bottom-up approach to explore how CDW generation rate varies across different classes of cities.
10	(Zhang et al. 2018)	Static, 2015	Chongqing, China	Explores the carbon mitigation and land-use reduction of different strategies for concrete waste management.
11	(Suzuki et al. 2018)	Dynamic, 1981–2015	Japan	Investigates the potential fate of engineered nanomaterials in the construction sector.
12	(Miatto et al. 2017c)	Dynamic, 1905–2015	USA	A bottom-up stock-driven model to evaluate long-term metabolism, and materials accumulated in the road network.
13	(Miatto et al. 2017a)	Dynamic, 1970–2010	Worldwide	Estimates the extraction of nonmetallic minerals and associated uncertainty about consumption by different sectors.
14	(Schiller et al. 2017a)	Dynamic, 1919–2010	Germany	Analyzes and quantifies the entire material cycle of bulk nonmetallic mineral building materials by considering the use of recycled aggregates in concrete building elements.
15	(Condeixa et al. 2017)	Dynamic, 2000–2010	Rio de Janeiro, Brazil	A bottom-up approach to assess the materials in use and further flows of CDW from the residential building stock.
16	(Lockrey et al. 2016)	Static, 2002–2025	Hanoi, Vietnam	Estimates construction and demolition concrete waste in Hanoi and Vietnam.
17	(Li et al. 2016)	Static, did not specify a time	A six-story building in Hebei, China	Proposes a model at a project level to quantify construction waste for building construction projects.
18	(Dahlbo et al. 2015)	Static, did not specify a time	Product-level, Finland	A combined method to holistically evaluate the environmental and economic performance of the CDW management system.
19	(Wiedenhofer et al. 2015)	Dynamic, 2004–2009	EU25	Quantifies stocks and flows for nonmetallic minerals in residential buildings, roads, and railways.
20	(Hu et al. 2013)	In general	In general	Examines concrete recycling as a case study to illustrate a framework of life-cycle sustainability analysis combining MFA with life-cycle analysis.
21	(Knoeri et al. 2013)	Static, did not specify a time	Product level	Provides a product- comparison of conventional concrete and concrete with recycled aggregates.
22	(Hoque et al. 2012)	Static, 2001	Catalonia, Spain	Analyzes resource consumption in the construction sector.
23	(Chong and Hermreck 2011)	Static, 2005, 2006	Las Vegas, Kansas, Portland, Seattle, USA	Quantifies energy demand for transporting and recycling construction steel.
24	(Hu et al. 2010b)	Dynamic, 1949–2050	Beijing, China	Quantifies the CDW in Beijing to support strategic waste management.
25	(Kapur et al. 2009)	Static, 2000–2004	USA	Develops a country-level stock and flow model to investigate the life-cycle of cement.
26	(Weil et al. 2006)	Static, did not specify a time	Product-level, Germany	A micro-level comparison of the environmental benefits of (per m ³) of concrete with or without recycled aggregates.
27	(Bertram et al. 2002)	Static, 1994	16 European countries	Copper mass balance assessment for waste management in multiple European countries.

Based on the literature review, MFA has been applied to investigate CDW at the product level (18, 21, and 26), building project level (17), regional level (1, 2, 3, etc.), and global level (13). The method has also been used in combination with life cycle assessment (10, 25, etc.) and life cycle costing (18) to evaluate the financial and environmental impact of CDW management. Most previous studies have focused on non-metallic mineral wastes such as concrete, whereas the recycling potential of emerging materials and renovation waste has not yet been examined.

Based on this review, regional-level dynamic MFA was selected for this study. Therefore, to fully consider the impact of the emerging waste (insulation mineral wool and lightweight concrete), we developed a dynamic MFA model to evaluate the supply-demand balance between the secondary raw materials made from CDW and the raw materials required for the manufacturing of PCEs for the period 2015–2050. Moreover, we explored how waste from energy renovation affects the mass accounting of CDW using dynamic MFA.

5.3 Methods and data sources

5.3.1 Conceptual framework

The estimation of the dynamics of the building stock was realized via a top-down modeling method based on gathered socioeconomic data. A prospective approach was applied because MFA aims to explore the “what-if scenario” of the future. As the waste flow was assumed to be determined by the change in stock, a stock-driven approach was used. Therefore, the MFA model applied to the Dutch case study presents a prospective, top-down, stock-driven model.

Müller (2006) developed a stock-driven model for estimating the diffusion of concrete in residential stock in the Netherlands from 1900 to 2100. Based on Müller’s modeling approach, we applied a three-layer stock dynamics model, as illustrated in Figure 5.1. The dwelling layer is the key layer for steering the turnover of the building stock. As part of the dwelling layer, data on population, floor area per capita, and building lifetime probability distribution were collected to calculate the construction, renovation, and demolition floor area for each year of study. Within the PCE layer, a geometry coefficient was used to determine the demand of PCE-new and PCE-refurbs per floor area of building construction and renovation. The outflow of the end-of-life (EoL) PCE was not considered because it is assumed to occur much later than the temporal scope of the accounting system. Finally, under the material layer, the waste intensity, material intensity, and recycling rate were investigated to understand the supply and demand conditions of secondary raw materials.

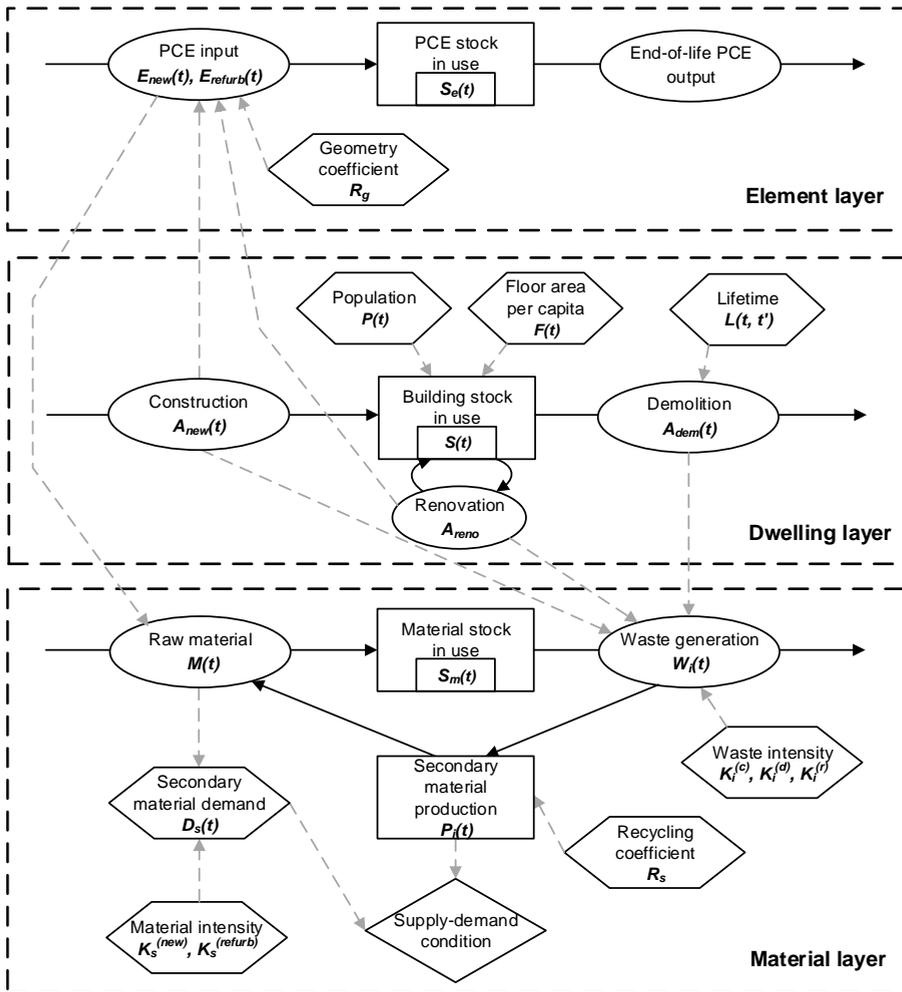


Figure 5.1 Conceptual framework of a three-layer dynamic material flow analysis model. Note: hexagons indicate drivers and determinants, rectangles represent processes, ovals with solid lines denote flows, and dashed lines with arrows denote influences between two variables.

5.3.2 Goal and scope definition

The goal of the MFA model was to estimate material inflows and outflows of the residential building stock of the Netherlands to support decision-making on the potential of material circularity in prefabrication-based building energy renovation. The geographical boundary of the assessment was the border of the Netherlands. The temporal scope of the assessment was from 2015 to 2050. Non-residential buildings, such as hospitals and schools, were excluded. The anthropogenic cycle of building

materials is generally considered to consist of five life phases, as shown in Figure 5.2; we focused on the recycling phase only, in which CDW was assumed to be reprocessed to manufacture secondary raw materials. For waste and materials to be tracked, we focused on the target CDW and secondary raw materials, as shown in the dotted box in Figure 5.2.

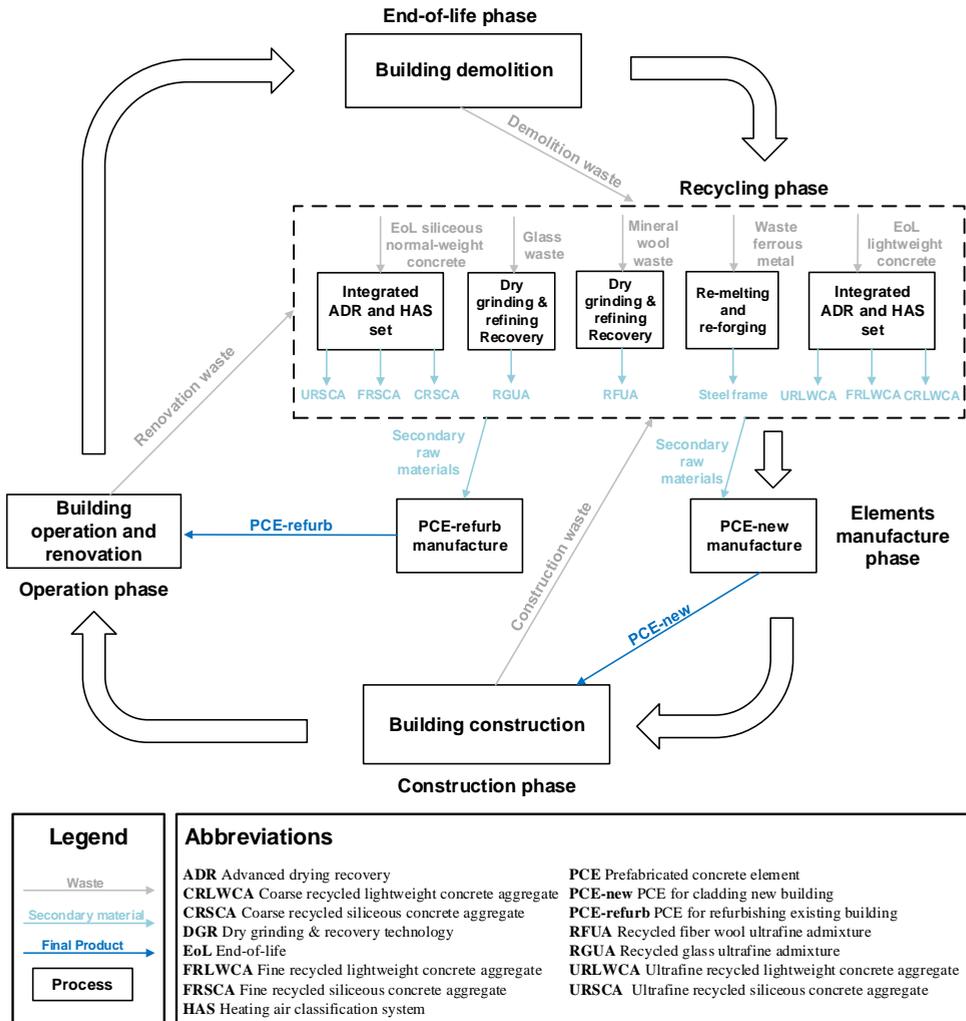


Figure 5.2 System boundary of the material flow analysis. Note: wastes and materials to be tracked in the system are shown in the dotted box

5.3.3 Characterization of parameters

Population

Historical population from 1900 to 2015 (CBS 2019a) and forecasted population from 2015 to 2050 (CBS 2019b) data were obtained for the Netherlands as shown in Figure 5.3(a).

Residential floor area per capita

To the authors' knowledge, there are no statistics available on the historical and forecasted residential floor area per capita in the Netherlands. Müller simulated the floor area per capita in the Netherlands from 1900 to 2100 based on the United Nations' average value (Müller 2006). Here, we used the standard floor area per capita scenario from 1900 to 2050, as shown in Figure 5.3(b).

Construction, demolition, and renovation

Computation of the construction and demolition floor area was based on the concept of building stock dynamics in Figure 5.1 and an operable Python-based framework called the "Open Dynamic Material Systems Model (ODYM)" developed by Pauliuk and Heeren (2020). We extended the ODYM using an additional renovation function, where the residential building stock was calculated using Eq. (1):

$$S(t) = P(t)F(t) \quad (1),$$

where $S(t)$ is the gross residential floor area of year t (1900, 2050); $P(t)$ is the population of year t (1900, 2050); and $F(t)$ is the residential floor area per capita in year t (1900, 2050).

The newly constructed floor area for year t is given by Eq. (2):

$$A_{new}(t) = S(t) - S(t-1) + A_{dem}(t), \quad (2)$$

where $A_{new}(t)$ is the new construction floor area of year t (1900, 2050) and $A_{dem}(t)$ is the demolition floor area in year t (1900, 2050).

The annual demolition rate was modeled through Eqs. (3)–(6). $L(t, t')$ in Eq. (4) is a probability distribution function that presents the probability that buildings built in year $t' < t$ will be demolished in year t . The lifetime distributions of buildings are commonly estimated with normal, log-normal, and Weibull distributions, although no evidence is available to indicate which probability distribution is best suited for dynamic stock modeling (Müller 2006; Miatto et al. 2017b). Therefore, we used a modified Weibull statistical distribution to approximate the lifetime of residential buildings in the Netherlands. The Weibull random variables t and t' are characterized by the shape

parameter k and a scale parameter λ . The shape parameter $k = 2.95$ is specified according to the average level of buildings in Western Europe (Deetman et al. 2020). The scale parameter $\lambda = 134.48$ was determined as the average lifetime of Dutch residential buildings (E_{LF}), as shown in Eq. (5), in which $\Gamma(x)$ represents the gamma function as presented in Eq. (6). Müller (2006) compared different lifetimes for the Dutch building stock, specifically short (60 years), medium (90 years), and long (120 years). Deetman et al. (2020) found that estimations only match statistical data when a high average lifetime (130 years) of buildings in Western Europe is assumed. Thus, the average lifetime was assumed to be 120 years in our building stock modeling, as adopted by Sandberg et al. (2016). The resulting lifetime distribution of residential buildings in the Netherlands is shown in Figure 5.3(c).

$$A_{dem}(t) = \int_{t_0}^t A_{new}(t')L(t, t') dt', \quad (3)$$

$$L(t, t') = \begin{cases} k\lambda^{-k}(t - t')^{k-1}e^{-\frac{(t-t')^k}{\lambda^k}}, & t' < t, \\ 0, & t' \geq t \end{cases}, \quad (4)$$

$$\lambda = E_{LF}/\Gamma(1 + \frac{1}{k}), \quad (5)$$

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t} dt, \quad (6)$$

The assumptions for the renovation of obsolete buildings were as follows: 1) Renovation started from $t = 2015$ to 2050; 2) buildings to be retrofitted were constructed from $t' = 1900$ to 2014; buildings constructed after 2014 were not retrofitted; 3) buildings to be renovated were separated from those buildings to be demolished, i.e., buildings that are supposed to be demolished by 2050 will not be renovated; 4) renovation floor area per annum was calculated based on Eq. (7). The gross floor area for renovation was equally allocated to each year between 2015 and 2050, amounting to an approximately 17 million m^2 floor area to be renovated per annum; and 5) for those buildings to be renovated, older buildings were preferentially renovated. The simulation results of the construction inflow, demolition outflow, and floor area for the renovation of each year are shown in Figure 5.3(d), and the dynamics of the building stock specified by construction cohorts are presented in Figure 5.3(e). The renovation of buildings in different construction periods (cohorts) is shown in Figure 5.3(f).

$$A_{reno} = \frac{S(2050) - \sum_{t'=2015}^{2050} \{A_{new}(t') - \sum_{t=t'}^{t=2050} [\int_{t'}^t A_{new}(t') \cdot L(t, t') dt']\}}{(2050 - 2015) + 1}, \quad (7)$$

where A_{reno} is the renovation floor area in year t (2015, 2050).

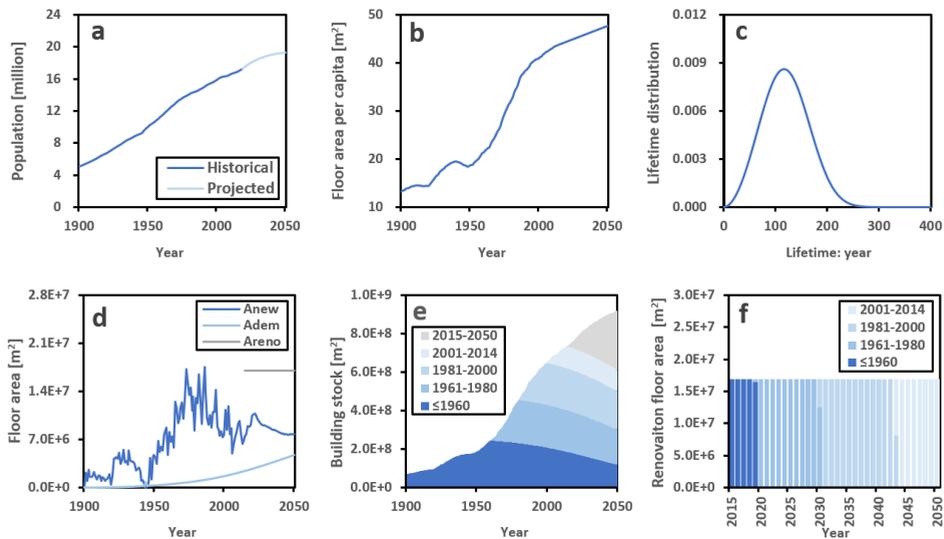


Figure 5.3 Estimation of parameter functions and simulation results for the Netherlands: (a) presents the historical and forecast population from 1900 to 2050; (b) demonstrates residential floor area per capita from 1900 to 2050; (c) shows the Weibull statistical distribution for modeling lifetime of dwellings; (d) presents construction, demolition, and renovation floor area of each year; (e) shows the dynamics of the building stock specified by construction cohorts; and (f) illustrates the vintage cohort of buildings to be renovated each year.

Demand of PCEs per floor area

The Agentschap NL of the Ministry of the Interior and Kingdom Relations in the Netherlands publishes data on the type and construction vintage of residential buildings. The Agentschap NL (2011) categorized the Dutch residential buildings into detached houses, semi-detached houses, terraced houses, maisonette houses, and apartments; and gave the number of homes and average floor area of each building type until 2005. The numbers of each type of house in different construction cohorts are presented in Table A5.1. The floor area of those examples is used to represent the average floor area of each type of house in the Netherlands as shown in Table A5.2. Based on the number (in Table A5.1) and average floor area (in Table A5.2) of each house, the stock share of each house (up to 2005) in gross residential stock share can be estimated, as shown in Table A5.3. The modified stock share of each building typology based on the Agentschap NL report is shown in Table 5.2. Details of the modifications are provided in the SI. We assumed that the share (m^2) of each housing category remains constant until 2050.

The required amount of PCEs (m^2) can be calculated based on the external wall surface and floor area of a building. To estimate the requirement of PCEs, we introduced a

geometry coefficient (R_g) to denote the ratio of the gross external wall surface compared to the gross floor area of a building. The TABULA database contains comprehensive information about the typology of residential buildings for 21 European states. Yang et al. (2020) used this database to measure the geometric information of buildings in Leiden, the Netherlands. Here, R_g data for the different types of buildings were collected from the TABULA database (2017), as shown in Table 5.2.

Table 5.2 Ratio of external wall surface and floor area for different types of houses in the Netherlands

Building type	Stock share ($R_{stock}^{(bt)}$)	Building demonstrator	Reference code in the TABULA database	Construction vintage	External wall surface [$S_{wall}^{(bt)}$] [m ²]	Floor area [$S_{floor}^{(bt)}$] [m ²]	Geometry coefficient ($R_g^{(bt)}$)
Detached house	15.98%		NL.N.SFH.03.Deta	1975–1991	144.00	169.00	0.85
Semi-detached house	11.39%		NL.N.SFH.01.Semi	Before 1964	97.80	121.00	0.81
Terraced house	33.60%		NL.N.TH.01.Mid1964	Before 1964	42.30	96.00	0.44
Maisonette	24.38%		NL.N.AB.02.Mai	1965–1974	598.40	1355.00	0.44
Apartment	14.65%		NL.N.AB.02.Por	1965–1974	951.40	1562.00	0.61

The weighted geometry coefficient of the Dutch building stock is $R_g = 0.57$, which was calculated using Eq. (8):

$$R_g = \sum \left[\left(\frac{S_{wall}^{(bt)}}{S_{floor}^{(bt)}} \right) R_{stock}^{(bt)} \right], \quad (8)$$

where R_g is the weighted geometry coefficient of the Dutch building stock, $S_{wall}^{(bt)}$ is the gross external wall surface of a certain type of reference building, $S_{floor}^{(bt)}$ is the gross floor area of a certain type of reference building, and $R_{stock}^{(bt)}$ is the gross stock of a certain building type.

Generation of CDW

According to statistics (Gámez-Martos et al. 2018), construction of per m² floor area of a new building generates from 18 to 33 kg of waste concrete and demolition of per m²

floor area of an obsolete building generates 840 kg of waste concrete. The median 26 kg is selected as the waste intensity coefficient for waste concrete for construction in the Netherlands ($K_{concrete}^{(c)}$). For demolition, from the global construction materials database developed by (Marinova et al. 2020), concrete intensity for different types of houses in Western Europe is in Table A5.4. Based on the stock share of each house type in the Netherlands in Table A5.3, the weighted concrete intensity is ($K_{concrete}^{(d)=}$) 902 kg per m² demolished floor area.

Zhang et al. (2020c) explored the composition of CDW generated in the Netherlands based on national waste flow statistic, share of concrete, ferrous metal, glass, and insulation in CDW by weight is 64.02%, 10.23%, 0.32%, and 0.07%. Thus the generation rate of glass and insulation per construction and demolition floor area can be calculated accordingly: $K_{ferrous}^{(c)} = 4.15 \text{ kg/m}^2$; $K_{glass}^{(c)} = 0.13 \text{ kg/m}^2$; $K_{insulation}^{(c)} = 0.03 \text{ kg/m}^2$; $K_{ferrous}^{(d)} = 144.08 \text{ kg/m}^2$; $K_{glass}^{(d)} = 4.51 \text{ kg/m}^2$; $K_{insulation}^{(d)} = 0.99 \text{ kg/m}^2$.

Waste from renovation is also considered in this study. Villoria Sáez (2018) estimated the ratio of renovation waste generation per renovation floor area for multiple retrofitting strategies. Amongst those strategies, the renovation by cladding system yields 30.62 kg of CDW per m² renovation floor area, and associated waste intensities are: $K_{ferrous}^{(r)} = 0/\text{m}^2$; $K_{glass}^{(r)} = 0/\text{m}^2$; $K_{insulation}^{(r)} = 0.04 \text{ kg/m}^2$; $K_{concrete}^{(r)} = 28.50 \text{ kg/m}^2$.

The thermal insulation market in Europe in 2014 is shown in Table A5.5 (Pavel and Blagoeva 2018). Based on the market share, we assumed the insulating mineral wool waste (glass wool and stone wool) account for 58% of the gross insulation waste by weight.

CDW yielded from construction, demolition, and renovation activities were estimated using Eq. (9):

$$W_i(t) = A_{new}(t)K_i^{(c)} + A_{dem}(t)K_i^{(d)} + A_{reno}(t)K_i^{(r)}, \quad (9)$$

where $W_i(t)$ is the waste i generated in year t ; $A_{new}(t)$ is the new construction floor area of year t ; $A_{dem}(t)$ is the demolition floor area in year t ; $A_{reno}(t)$ is the renovation floor area of year t ; $K_i^{(c)}/K_i^{(d)}/K_i^{(r)}$ is construction/demolition/renovation waste intensity coefficient: the amount of waste i generated per construction/demolition/renovation floor area.

As an emerging material, lightweight concrete is not yet widely used in Europe (Thienel et al. 2020). The average lifespan of buildings in the Netherlands was assumed to be 120 years, and buildings to be demolished were mainly constructed around the 1900s. Thus, most concrete waste in the CDW is normal-weight concrete waste. Therefore, we conservatively assumed that the gross concrete waste contained 1% lightweight concrete (by weight). According to the insulation material market in Europe, insulating mineral

wool accounts for 58% of the insulation material by weight (Pavel and Blagoeva 2018). Based on these assumptions, the estimated amounts of concrete waste, glass waste, ferrous waste, and insulation waste generated between 2015 and 2050 are presented in Figure 5.4.

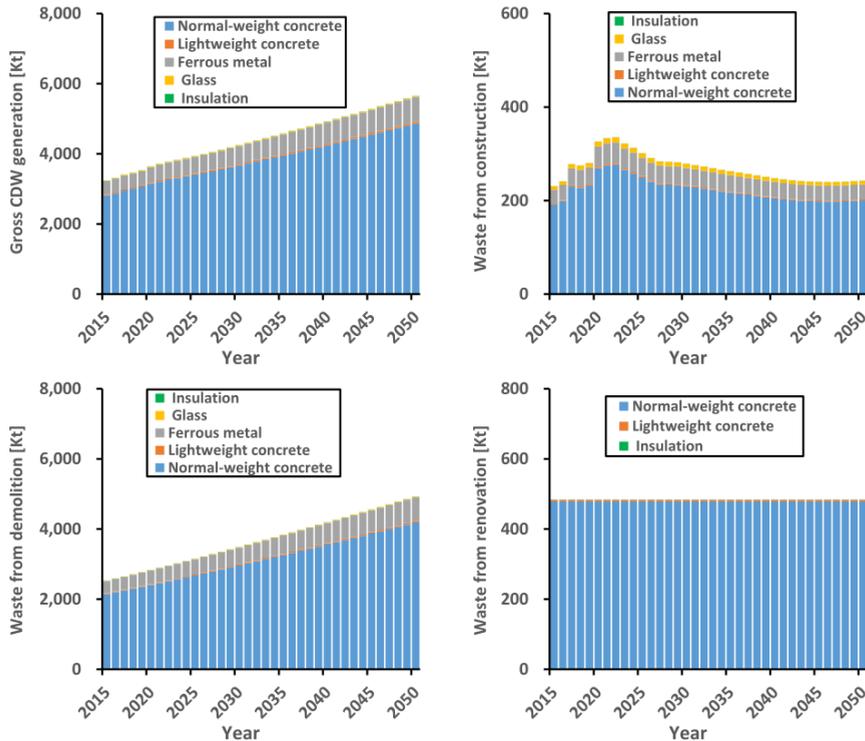


Figure 5.4 Estimated construction and demolition waste (CDW) generated from the construction, demolition, and renovation in the Netherlands for the period 2015–2050

Production of secondary raw materials

The recycling rate for steel is (R_{steel}) 90% (Ruukki 2011). The data on the mass balance of ADR and HAS to process siliceous normal-weight concrete waste and lightweight concrete waste were collected from Strukton’s CDW recycling site in Hoorn, the Netherlands. The siliceous concrete waste and lightweight concrete waste (around 14 tons for each type) were fed to the integrated ADR and HAS facility and the mass of the output streams were measured during experimental trials on site. The R_i for recycling siliceous normal-weight concrete waste are (Zhang et al. 2020a): R_{URSCA} =6.4%; R_{FRSCA}

= 25.6%; $R_{CRSCA} = 68\%$; R_s related to lightweight concrete recycling are (Zhang et al. 2021a): $R_{URLWCA} = 9.6\%$; $R_{FRLWCA} = 38.4\%$; $R_{CRLWCA} = 52\%$.

The data on the mass balance of the DGR system was collected from experimental trials in Helsinki, Finland. The input mass of glass waste and insulating mineral wool waste (100 Kg for each) and the output mass of secondary raw materials were measured. The residue contained in the RGUA and RFUA is less than 1% by weight. Thus the recycling coefficient for RGUA and RFUA is assumed 100%, which means $R_{RGUA} = 100\%$ and $R_{RFUA} = 100\%$.

The production of secondary raw materials was calculated according to Eq. (10):

$$P_s(t) = W_i(t)R_s, \quad (10)$$

where $P_s(t)$ represents the amount of secondary raw material made from waste i in year t , and R_s denotes the recycling coefficient of production of secondary raw material from waste. The potential productive capability of secondary raw materials via recycling waste is presented in Figure 5.5.

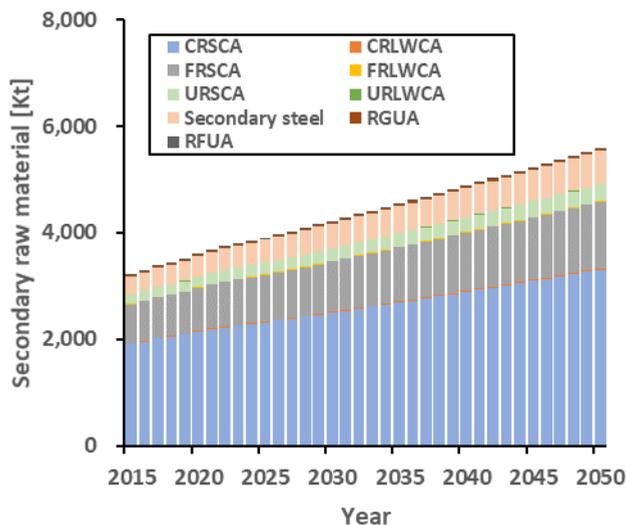


Figure 5.5 Potential productive capability of secondary raw materials in the Netherlands for the period 2015–2050

Demand for secondary raw materials

Based on the formulation of green concrete and aerogel, secondary raw materials used in green normal-weight and lightweight concrete, green aerogel, and steel frame for the

PCE-new and PCE-refurb are listed in Table A5.6. Due to commercially confidential concerns, the detailed recipes for concrete and aerogel is not disclosed.

Based on the formulation of VEEP PCE-new and PCE-refurb in Table A5.6 and the weighted geometry coefficient, the secondary raw materials demanded per m² construction and renovation floor area are presented in Table A5.7.

The secondary raw material demand of PCE-new and PCE-refurbs were computed using Eq. (11):

$$D_s(t) = A_{new}(t)K_s^{(new)} + A_{reno}K_s^{(refurb)}, \quad (11)$$

where $D_s(t)$ is the secondary raw material demand in year t , $A_{new}(t)$ is the construction floor area of year t , A_{reno} is the renovation floor area of each year, $K_s^{(new)}$ is the secondary raw material demand of PCE-new per construction floor area; and $K_s^{(refurb)}$ is the secondary raw material demand of PCE-refurbs per renovation floor area. The data sources for each parameter are presented in the SI. Based on these calculations, the total secondary raw materials required for the implementation of the PCE-new and PCE-refurbs are presented in Figure 5.6.

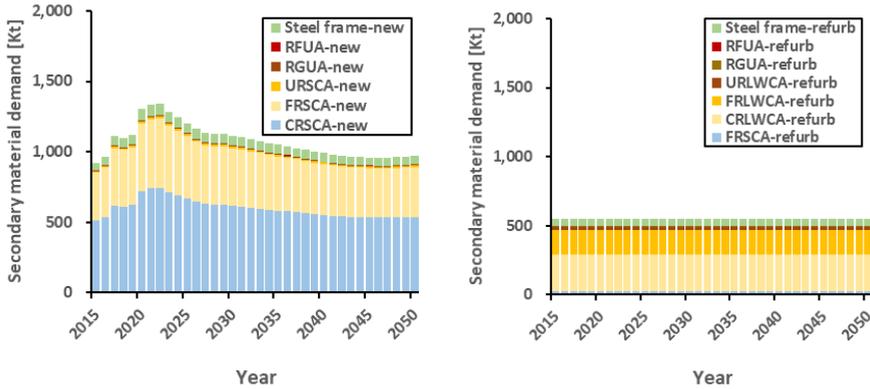


Figure 5.6 Secondary raw material demand for the manufacture of PCE-new (left) and PCE-refurb (right) in the Netherlands for the period 2015–2050

5.4 Results and discussion

5.4.1 Supply-demand analysis

Based on the potential supply of secondary raw materials (see Figure 5.5) and the demand for secondary raw materials for construction and renovation (see Figure 5.6), the supply and demand balance of each secondary raw material is presented in Figure

5.7. Based on this, the secondary raw materials (CRSCA, FRSCA, and URSCA) for PCE-new can be supplied in sufficient quantities, even with surplus quantities. The demand for steel frames, RGUA, and RFUA can also be fully met.

The CRLWCA, FRLWCA, and URLWCA for the production of PCE-refurbs are inadequate, however, to support significant refurbishment efforts. The deficit portion of these materials could be complemented by using virgin materials (e.g., expanded clay, sand, and cement) or by importing lightweight concrete waste from neighboring countries such as Germany or Belgium, although this is unlikely due to high transportation costs.

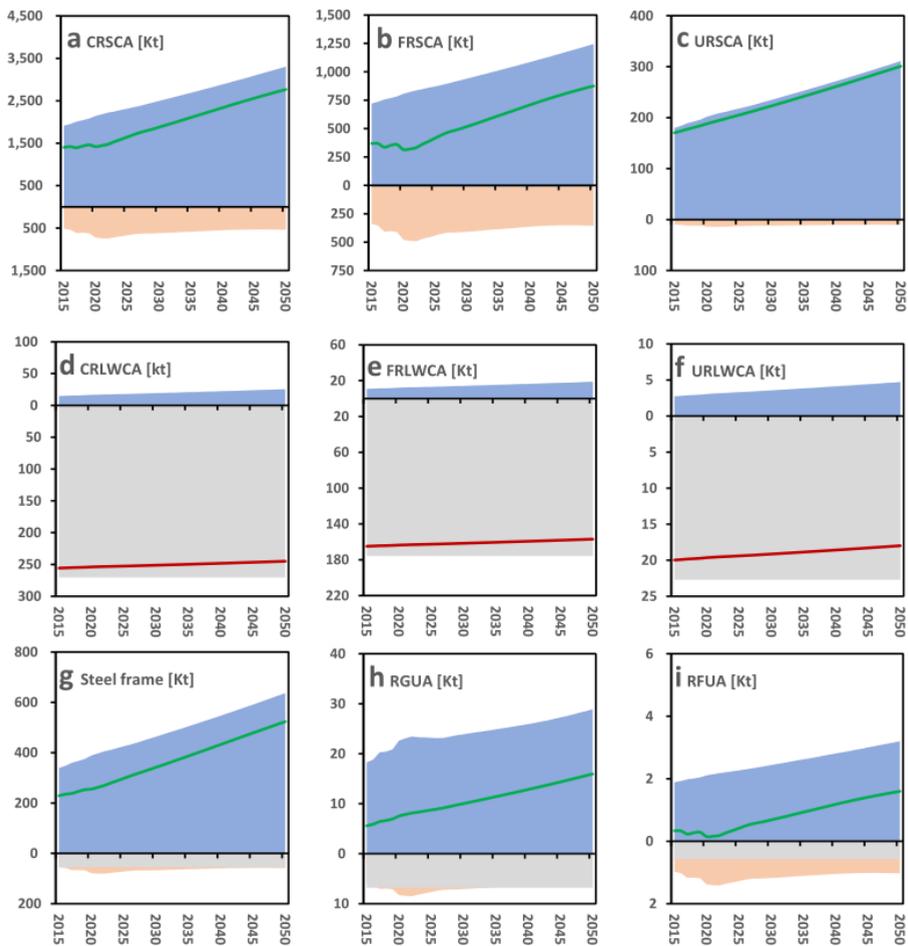


Figure 5.7 Supply-demand condition of secondary raw materials. Note: 1) zone (in blue) above 0 represents the supply of secondary raw materials, zone below 0 represents the demand of secondary

raw materials for building construction (in salmon) and building renovation (in grey); 2) curves in red indicate the deficient amount of secondary raw materials, curves in green indicate the surplus amount of secondary raw materials.

5.4.2 Comparison of secondary material surplus and primary material imports

The surplus or deficit of each secondary raw material was compared to the net import of the corresponding virgin raw material. The associated import and export data were collected from the UN Comtrade Database (2020). Because the data on iron and steel are presented as monetary values in the database, the comparison of these materials with reformed steel was excluded. For the comparison of gravel and CRSCA in Figure 5.8(a), the median trend of gravel net imports is approximately five times that of CRSCA since 2018; however, under conservative (lower confidence limit) conditions, the surplus of CRSCA can substitute all gravel imports from 2040 onwards. Concerning the net import of expanded clay in Figure 5.8(b), the overall volume is considerably smaller than that of gravel, fluctuating from 5 to 100 Kt between 1992 and 2018, and probably continuing to decrease to 2050. The deficit of CRLWCA stabilizes at approximately 180 Kt, which may cause the import of expanded clay to increase in the future.

For virgin sand imports in Figure 5.8(c), compared to the other raw materials, sand relies less on imports according to the trend of historical net imports, although with a large uncertainty range. The surplus of FRSCA and the deficit of FRLWCA are insignificant compared to the large uncertainty in net imports. In the case of the cement import in Figure 5.8(d), as with the net import trend of gravel, the Netherlands is and will be largely dependent on imports. The amounts of RGUA and URSCA surpluses and the URLWCA deficit are negligible compared to imports. Lastly, as shown in Figure 5.8(e), the net import of limestone follows an increasing trend. As insulation waste only accounts for less than 0.1% of the total CDW, the RFUA produced from insulation waste has an almost negligible effect on the import of limestone.

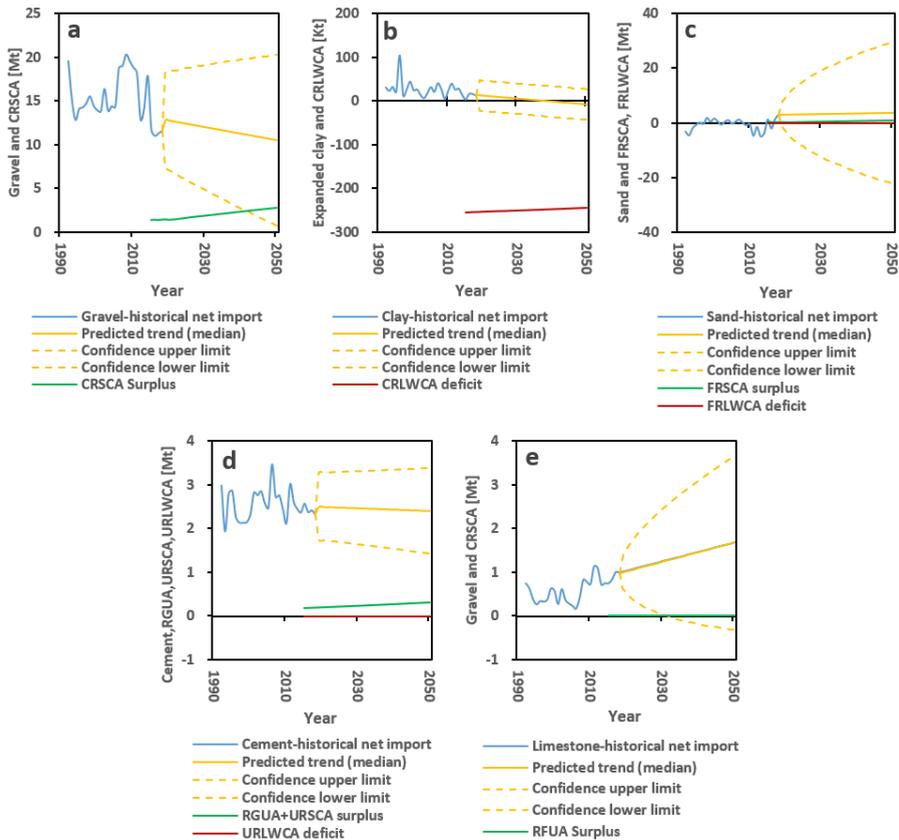


Figure 5.8 Comparison between virgin raw material net import (import subtracts export) and secondary raw material deficit and surplus in the Netherlands for the period 1990–2050: (a) represents the comparison of gravel net import and CRSCA surplus; (b) denotes comparison of expanded clays net import and CRLWCA deficit; (c) compares sand net import, and FRSCA surplus, and FRLWCA deficit; (d) compares cement net import, RFUA+URSCA surplus, and URLWCA deficit; and (e) compares limestone net import and RFUA surplus. Data were collected from the UN Comtrade database (2020). The predicted trends were obtained via linear regression with a 95% confidence interval.

5.4.3 Validation and uncertainty

The dynamic MFA model is based on multiple parameters, and the fluctuations of each parameter will, therefore, affect the final supply and demand balance. Owing to the lack of a valid reference for the fluctuation range of each parameter, it is impossible to conduct a full uncertainty analysis. Nevertheless, an examination of the uncertainty was performed based on those factors with a relatively strong influence on the results. Thus, we deem that the biggest uncertainties lie in the estimation of (i) annual construction,

demolition, and renovation floor area; (ii) concrete waste intensity; and (iii) the share of lightweight concrete waste in gross concrete waste.

5.4.3.1 Annual construction, demolition, and renovation

The annual construction, demolition, and renovation floor area in this study were validated in reference to other data sources, the Environmental Assessment Agency (Staniaszek 2015), the ZEBRA2020 Data Tool (2020), Sandberg et al. (2016), and Statistics Netherlands (2020). Some of these sources measured the turnover of the building stock based on the number of dwellings instead of floor area, which makes their results incomparable. Therefore, we used relative indexes, namely construction rate, demolition rate, and renovation rate, to unify the comparison. Based on Figure 5.9(a), all of the construction rates present a decreasing trend from approximately 1.5% to 1%, while in Figure 5.9(b), demolition rates show a gradually increasing trend from approximately 0.3% to 0.5%. These renovation rates from the different sources demonstrate a notable disparity. Overall, the construction and demolition rates we applied in this study are in general accordance with these other sources.

As shown in Figure 5.9(c), the average historical renovation rate from Statistics Netherlands is approximately 0.5% while the renovation rates of other sources are much higher. To achieve the carbon-neutral goal by 2050, of the 7.5 million dwellings, 170,000 need to be renovated per annum in the Netherlands (Staniaszek 2015). Based on this, the equivalent renovation rate was set at 2.3% in 2015, amounting to approximately 17 million m² per annum.

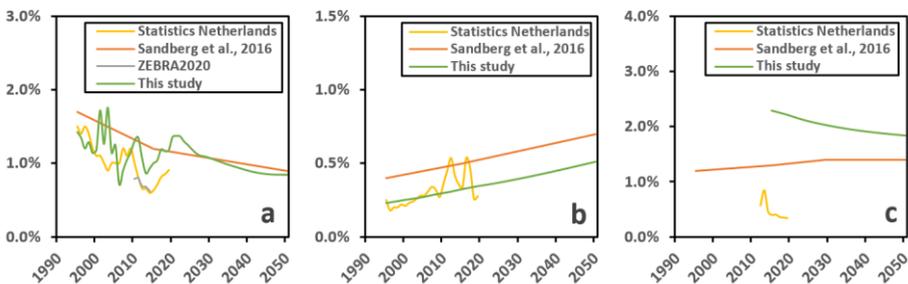


Figure 5.9 Comparison of (a) construction rate, (b) demolition rate, and (c) renovation rate for the Netherlands based on a range of sources

5.4.3.2 Concrete waste intensity

Concrete waste was the focal waste stream of our CDW estimates. The concrete waste intensity for demolition ($K_{concrete}^{(d)} = 902 \text{ kg/m}^2$) has a far greater contribution to gross concrete waste generation than construction ($K_{concrete}^{(c)} = 26 \text{ kg/m}^2$) and renovation

($K_{concrete}^{(r)} = 28.5 \text{ kg/m}^2$). Therefore, the uncertainty in waste concrete generation from building demolition ($K_{concrete}^{(c)}$) is discussed further in this section.

Concrete waste is commonly generated from four sectors: (i) the residential building sector, (ii) the non-residential building sector, (iii) civil engineering, and (iv) the building materials industry. Concrete waste produced from the residential sector accounts for approximately 30% of the gross concrete waste in the Netherlands (Zhang et al. 2020b), and the Environmental Data Compendium of the Netherlands (CLO) (2020) reported the generation of CDW between 1985 and 2016. Based on this, we estimated the concrete waste generated from residential buildings, as shown in Figure 5.10. These data show that the concrete waste released from residential buildings has stabilized at approximately 4,500 Kt per annum since 2000.

Notably, the concrete waste intensity varies for different types of buildings. For example, a timber-structured building generates up to 300 kg/m^2 of concrete waste (Gámez-Martos et al. 2018). For concrete structure buildings, relevant data from a demolition project located on the de Kempkensberg in Groningen in the Netherlands (Hu et al. 2012) were collected to estimate the concrete waste intensity. This concrete high-rise building had 14 stories and a $6,174 \text{ m}^2$ of useful floor area, from which a total of 12,357 tons of concrete waste was generated during demolition, amounting to 2 tons of concrete per m^2 of floor area. This is in accordance with the medium-level concrete waste intensity of 2.1 t/m^2 in Müller's stock dynamics modeling (Müller 2006). The amounts of concrete waste based on different concrete intensities (300 kg/m^2 , 902 kg/m^2 , and $2,000 \text{ kg/m}^2$) were compared, as shown in Figure 5.10. If $K_{concrete}^{(d)}$ increases to $2,000 \text{ kg/m}^2$, gross concrete waste shows a sharply increasing trend. In contrast, at 300 kg/m^2 , this trend is less than half of the historically probable trend. The selected median value (902 kg/m^2) was also lower than the actual trend. Therefore, the estimation of concrete waste in this study was relatively low compared to the reality. This may be because we assumed a high lifetime for residential buildings, leading to less generation of demolition waste. Moreover, we used static concrete waste intensity, whereas waste intensity is likely to increase over time.

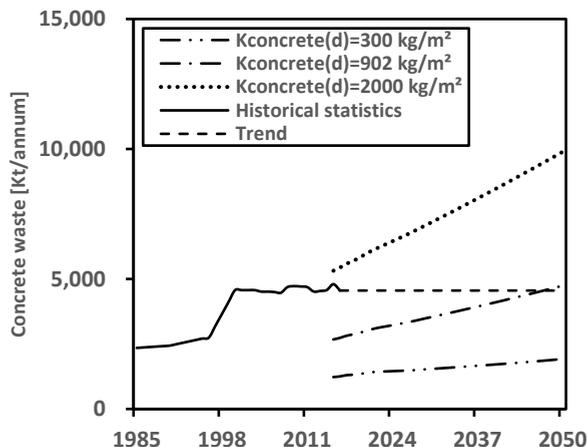


Figure 5.10 Concrete waste generation from the residential building sector in the Netherlands under different waste intensities. Note: $K_{concrete}$ denotes the waste concrete waste intensity for demolition.

5.4.3.3 Share of lightweight concrete waste

According to the Report and Data (2020), the global lightweight aggregate concrete market was valued at 37.2 billion USD in 2018 and is expected to reach 56.7 billion USD by 2026. In Europe, the lightweight aggregate concrete market is forecasted to increase from 23 million USD in 2018 to 40 million USD in 2026 (Reports and Data 2020). The share of lightweight concrete waste compared to gross concrete waste is assumed to remain stable at 1% until 2050. Quantification of the variations in this share can provide a more comprehensive assessment of the supply-demand connection. Therefore, we examined the level of uncertainty by modeling several scenarios in which the share of lightweight concrete waste would increase at different rates over time. The share was modeled starting with different initial values (1%, 3%, and 5%) and then increased linearly to 8%, 12%, and 20% between 2015 and 2050.

The results of the uncertainty simulation are shown in Figure 5.11. Under all conditions, the URLWCA is likely to be sufficiently supplied. For CRLWCA and FRLWCA, when the initial share is 1%, even though it increases to 8% by 2050, production barely meets the demand for widespread renovation until 2050. In this case, a large amount of virgin expanded clay and sand is produced or imported to replenish the CRLWCA and FRLWCA feedstock. If the initial share increases to 3%, the CRLWCA and FRLWCA supplies can sufficiently support building renovations with PCE-refurbs up to approximately 2045 with a high increase speed. If the share is started at 5% in 2015, the supply of FRLWCA and CRLWCA reach the break-even point by 2035. Finally, the production of URLWCA is barely able to sustain consumption under any of the

assumptions. Primary sand and expandable clay are, therefore, needed to complement FRLWCA and CRLWCA by 2035 at the latest.

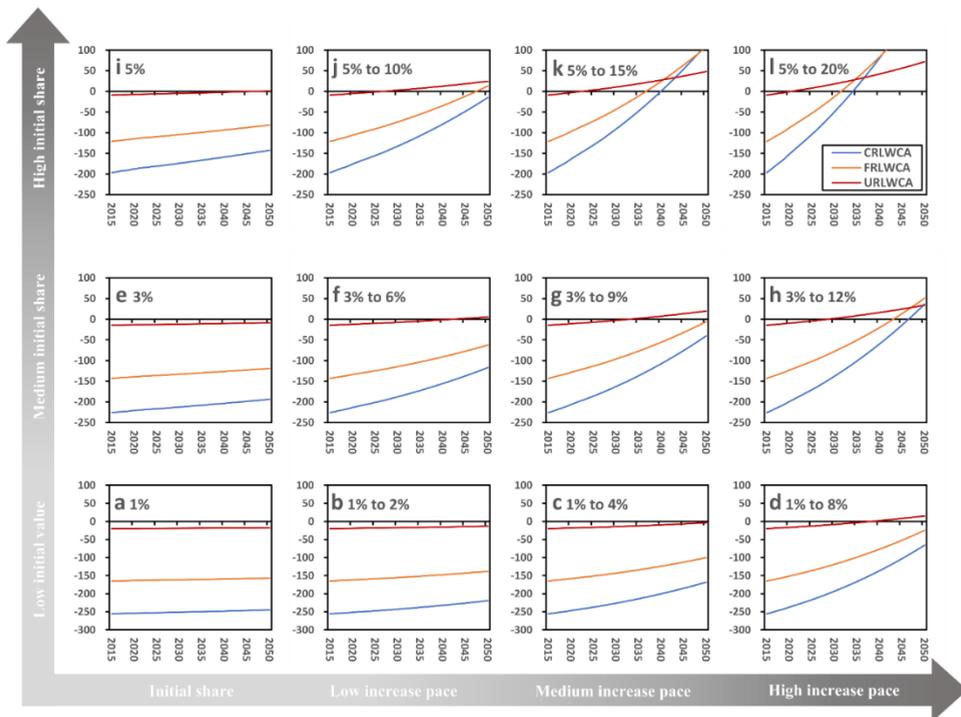


Figure 5.11 Supply-demand condition of CRLWCA, FRLWCA, and URLWCA in Kt. Note: (a) “initial share” means “initial value of the share of lightweight concrete waste to the total concrete waste remains at 1%, 3%, and 5% from 2015 to 2050; in Panel b, “1% to 2%” represents a linear share increase from 1% in 2015 to 2% in 2050. (b) zones above represent the amount of the surplus of secondary raw materials, zones below 0 represent the amount of the deficit of secondary raw materials.

5.5 Implications of this study

5.5.1 Constraints and opportunities of CDW management in the Netherlands

The EU has enacted a series of relevant directives on CDW management and energy efficiency. For example, the Waste Framework Directive (2008/98/EC) sets a 70% target for CWD recovery for EU member states (EC 2008a); the COM (2011) 571 aims to promote resource efficiency during the construction and renovation of buildings (EC 2011b); and the Energy Performance of Buildings Directive (EPBD, 2002/91/EC) (EC 2002) and Energy Efficiency Directive (EED, 2012/27/EU) (EC 2012b) request member

states to employ cost-effective energy renovation measures to promote the energy performance of new and old buildings.

The residential building stock in the Netherlands has poor insulation level and is obsolete; approximately half the building stock was constructed between the 1950s and the 1970s—before minimum energy performance requirements were introduced in 1995 (Staniaszek 2015). In the Energy Agreement for Sustainable Growth (SER 2013), the Netherlands committed to achieving the ambitious goal of a carbon-neutral built environment by 2050. To support the EU's response to the Paris Climate Agreement, the Government of the Netherlands (2019) enacted a national climate agreement to achieve a 49% mitigation in national carbon emissions by 2030. Thus, an additional reduction of 3.4 Mt of greenhouse gas is required by 2030, and the Netherlands even called for increasing the European target to 55% by 2030. By 2050, the Netherlands is expected to achieve carbon-neutral status (EZK 2019), setting up a significantly limited carbon budget for the building sector.

For decades, the Netherlands has exceeded the EU target of 70% CDW management but upgrading the practice of road backfilling to high value-added recycling is urgently needed. Due to the topography of the Netherlands, domestic extraction of large quantities of stony mineral resources is not possible. Raw materials for the production of concrete, such as sand and gravel, are, therefore, must be imported and—in the future—recycled domestically. The Dutch government has outlined the goal for a circular economy in the Netherlands by 2050 (Dijksma and Kamp 2016), involving a 50% reduction in raw material use by 2030 and a fully circular economy by 2050. Therefore, to transition to a fully circular built environment, it is crucial to close the loop of the construction material supply chain, especially emerging materials used in energy renovation.

Prefabrication has been identified as a reliable solution for reducing CDW (Tam et al. 2006); waste concrete can be reduced by 52% to 60% as prefabricated products are cast off-site (Tam et al. 2005). Prefabrication also contributes to other on-site benefits, such as improved quality control, tidier and safer working environments, and improved environmental performance (Jaillon et al. 2009). According to the estimation of our model, approximately 8 million m² and 17 million m² of dwellings are to be constructed and renovated per annum. Therefore, the proposed PCE system presents a promising solution to upgrading the treatment of CDW, waste reduction, and energy renovation. The practice of prefabricating buildings is well established in the Netherlands, with prefabricated elements used in over half (55%) of all Dutch construction projects in 2016 (de Gruijl 2018). This lays a solid technical foundation for the implementation of the PCE system.

5.5.2 Influence of the density and typology of concrete on mass estimation

Concrete production is the main engine for rapid urbanization. The EU directive of resource efficiency opportunities in the building sector (COM/2014/0445) suggests that concrete waste should be a focal point for CDW management (EC 2014d). Indeed, the literature review in Table 5.1 shows that concrete waste management is a significant topic for MFA studies.

In general, the concrete in MFA studies is modeled as normal-weight concrete. In this study, normal-weight siliceous concrete and lightweight aggregate concrete were considered to represent normal-weight concrete and lightweight concrete, respectively. The normal-weight concrete includes other types of concrete, such as limestone concrete, which employs different formulations compared to siliceous concrete. Lightweight concrete can be categorized as lightweight aggregate concrete, foamed concrete, and autoclaved aerated concrete. Despite this diverse typology, the density of concrete is the key factor that could influence MFA because material flows are derived from physical mass data. A concrete waste intensity $K_{concrete}^{(d)} = 902 \text{ kg/m}^2$ was applied to estimate the generation of normal-weight concrete. Because the waste intensity for lightweight concrete is unavailable, we simplified the estimation of lightweight concrete waste by assuming a share of 1%.

The densities of normal-weight concrete and lightweight concrete used in our analysis were $2,089 \text{ kg/m}^3$ and $1,963 \text{ kg/m}^3$, respectively. Assuming 1% of lightweight concrete waste by weight, the difference in the mass of gross concrete waste is approximately 2 Kt by 2030; if concrete waste comprises 1% of ultra-lightweight concrete (500 kg/m^3), the mass difference is 28 Kt over the same timeframe. With the gradual prevalence of lightweight concrete in building energy renovation practices, MFA studies should consider the effect of lightweight concrete on mass estimation.

5.5.3 Whether or not to consider renovation waste

The measurement of the composition and generation of CDW is a longstanding dilemma for MFA studies. The generation of renovation waste, in particular, is relatively difficult to estimate due to diverse retrofitting options, such as external insulation systems, cladding systems, and ventilated façade systems (Villoria Sáez et al. 2018) as well as different levels of renovation, i.e., minor, moderate, deep, and nearly zero-energy building levels (Economidou 2011). Thus, most of the MFA studies summarized in Table 5.1 do not consider waste from building renovation. Table 5.3 provides some examples of waste intensity for the renovation of residential buildings in different regions. In more developed areas, the amount of renovation waste is growing rapidly (Cheng and Ma 2013). For instance, renovation waste accounts for 29% of the gross CDW by weight in

Norway (Bergsdal et al. 2008), and its intensity can reach up to 300 kg/m², which considerably exceeds the intensity of construction waste (41 kg/m² in this study). In developing countries such as China, renovation waste amounts to less than 1% of gross CDW (Ding et al. 2019b), and intensity could be lowered to 20 kg/m². The estimation of renovation waste based on the construction area, living area, and useful area can also yield differing results (Coelho and De Brito 2011).

Table 5.3 Examples of waste intensity for the renovation of residential buildings

Literature	Location	Amount [kg/m ²]	Remark
(Bergsdal et al. 2008)	Norway	60.13–89.47	Residential building
(Villoria Sáez et al. 2018; Thorpe 2008)	UK	147.84	Residential building, estimation based on volume (m ³) of waste generated per 100 m ²
(Villoria Sáez et al. 2018)	Spain	2.46–65.24	Residential building
(Coelho and De Brito 2011)	Portugal	347.3	Residential building, estimation based on a gross construction area
(Máia et al. 2013)	Portugal	28–397	Residential building
(Cochran et al. 2007)	USA	43.70–82.00	Residential building
(Ding et al. 2019a)	China	15.65–25.98	Residential building
(Ding et al. 2019b)	China	21.05	Residential building

We assumed that the Netherlands will undergo large-scale renovation, with more than 50% of the current stock (based on 2015 data) to be refurbished. Therefore, renovation waste was considered in the MFA model. The amounts of construction waste, demolition waste, and renovation are presented in Figure 5.12. Overall, the amount of renovation waste exceeds the amount of construction waste. It is noteworthy that we only estimated the renovation waste from the implementation of the proposed PCE cladding technology; deeper renovation is expected to yield more renovation waste. Moreover, we only estimated the wastes that can be incorporated into the PCEs, namely concrete, insulation, glass, and steel, which account for 77% of CDW by weight (Zhang et al. 2020b); minor waste streams, such as wood, plastic, and paper, are not included. Given the fact that building energy renovation has become a primary pathway towards a carbon-neutral built environment, considering renovation waste in MFA studies offers a more comprehensive means of CDW management.



Figure 5.12 Generation of construction waste, demolition waste, and renovation waste estimated in the Netherlands for the period 2015-2050. Note: construction waste and demolition waste are estimated based on the share of concrete waste in CDW and the concrete waste intensity

5.6 Conclusions

The building sector is considered one of the main drivers of material depletion, waste generation, energy use, and greenhouse gas emissions. It is highly important and urgent, therefore, to accelerate the transition toward a carbon-neutral and circular built environment. Ongoing building energy renovation is accompanied by emerging materials such as mineral wool insulation and lightweight concrete, triggering new problems of disposal. This makes it harder to close supply chains in the building sector. The proposed PCE system delivers a potential solution by incorporating CDW into building energy renovations. Here, we constructed a prospective top-down stock-driven MFA model to explore the supply-demand condition of associated secondary raw materials for the PCE system for new building construction and existing building renovation in the Netherlands for the period 2015–2050. Compared to previous MFA studies, our model considers the recycling of glass, lightweight concrete, and insulation mineral wool in CDW through an on-site innovative recycling technological system in the context of building energy renovation in the Netherlands.

Our results show that secondary raw materials recycled from normal-weight concrete waste, namely CRSCA, FRSCA, and URSCA, can be sufficiently supplied, even with a large surplus. The reformed steel frames, RGUA, and RFUA required for building construction and renovation can also be sufficiently supplied. However, under the condition that lightweight concrete waste was assumed to account for only 1% of the gross concrete waste, the secondary raw materials CRLWCA, FRLWCA, and URLWCA for new lightweight concrete production are inadequate for supporting manufacturing of

the PCE-refurb system. The deficit could be replenished using virgin materials or by importing lightweight concrete waste from neighboring countries. Based on a comparison of the surpluses/deficits of recycled materials to the net import of corresponding virgin materials, we found that the demand for main mineral resources in the Netherlands is highly dependent on imports. Only CRSCA shows potential for offsetting gravel imports assuming conservative imports. The other secondary raw materials do not appear to reduce the import of associated virgin materials.

Using uncertainty analysis, we quantified the influence of variations in (1) construction, demolition, and renovation floor area of each year; (2) concrete waste intensity; and (3) the share of lightweight concrete waste. We used construction, demolition, and renovation rates to compare the uncertainties of construction, demolition, and renovation activities each year from different sources. The results show that the construction and demolition rates are harmonized with historical statistics. The renovation rate is assumed to track the prospective energy renovation planning of the Netherlands and is, therefore, higher than the actual value. Regarding concrete waste intensity, owing to a conservative assumption of concrete waste intensity, the forecast waste concrete stream is relatively lower than the current statistics. Lightweight concrete was modeled with different initial shares in gross concrete waste with an increasing pace, starting from 1%, 3%, and 5% in 2015 and increasing linearly to 8%, 12%, and 20% by 2050, respectively. We found that the production of URLWCA can barely meet the demand under any of these cases, whereas primary sand and cement are still needed for the substitution of FRLWCA and CRLWCA until 2027.

This study has investigated the physical mass link between CDW recycling and secondary material demands in the context of building energy renovation in the Netherlands. However, the associated environmental and financial implications remain unknown. Our previous studies investigated the life-cycle carbon emissions and costs of the PCE system at the building level (Zhang et al. 2020a, 2021a). In the future, we aim to scale up the life cycle environmental and economic benefits of the proposed PCE system for energy renovation at a regional level.

Acknowledgements

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Appendix

Table A5.1 Numbers of each type of house in different construction cohorts

	Up to 1945	Up to 1964	1965-1974	1975-1991	1992-2005
Detached house	/	441,000	119,000	221,000	178,000
Semi-detached house	/	285,000	142,000	224,000	173,000
Row house	523,000	478,000	606,000	879,000	353,000
Maisonette house	/	2,266,000	22,000	94,000	40,000
Apartment-gallery	/	69,000	174,000	109,000	113,000
Apartment-porch	256,000	267,000	112,000	142,000	70,000
Apartment-other	/	99,000	125,000	125,000	136,000

Table A5.2 Average floor area of each type of house by building typology and construction cohort

	Up to 1945	Up to 1964	1965-1974	1975-1991	1992-2005
Detached house	/	130	144	154	172
Semi-detached house	/	110	123	123	132
Row house	102	87	106	106	114
Maisonette house	/	88	88	80	84
Apartment-gallery	/	72	82	68	79
Apartment-porch	59	66	71	70	74
Apartment-other	/	67	77	70	82

Table A5.3 Gross floor area of houses by building typology and construction cohort, and stock share

	Up to 1945	Up to 1964	1965-1974	1975-1991	1992-2005	Up to 2005	Stock share
Detached house	/	57,330,000	17,136,000	34,034,000	30,616,000	139,116,000	15.98%
Semi-detached house	/	31,350,000	17,466,000	27,552,000	22,836,000	99,204,000	11.39%
Row house	53,346,000	41,586,000	64,236,000	93,174,000	40,242,000	292,584,000	33.60%
Maisonette house	/	199,408,000	1,936,000	7,520,000	3,360,000	212,224,000	24.38%
Apartment-gallery, porch, other	15,104,000	29,223,000	31,845,000	26,102,000	25,259,000	870,661,000	14.65%

Table A5.4 Concrete intensity for different types of houses in Western Europe

	Concrete intensity (kg /m ²)
Detached house	1507.04
Semi-detached house	1507.04
Row house	796.02

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Maisonette house	567.99
Apartment	567.99

Table A5.5 Share of insulation material in Europe

Insulation material	Share
Glass wool	36%
Expanded polystyrene	27%
Stone wool	22%
Polyurethanes	8%
Extruded polystyrene	6%
Other	1%

Table A5.6 Formulation of secondary raw materials used for VEEP PCE-new and PCE-refurb

VEEP PCE	Component of PCE	Weight [Kg] per unit of PCE	Remarks
VEEP PCE-new (length 3.6 m, width 2.4 m)	Green normal-weight concrete	2658.41	URSCA used for per m ³ of concrete: 16.75 kg/m ³ FRSCA used for per m ³ of concrete: 566 kg/m ³ CRSCA used for per m ³ of concrete: 880 kg/m ³ RGUA used for per m ³ of concrete: 10.05 kg/m ³ RFUA used for per m ³ of concrete: 1.675 kg/m ³
	Green Aerogel	42.35	FRSCA used for per 0.01m ³ of aerogel: 0.31 kg/m ³
	Expanded polystyrene	13.50	/
	Rebar cages & welded nets	117.10	Steel frame for per unit of PCE: 117.10 kg/PCE
VEEP PCE-refurb (length 2 m, width 2 m)	Green lightweight concrete	374.80	URLWCA used for per m ³ of concrete: 47 kg/m ³ FRLWCA used for per m ³ of concrete: 364 kg/m ³ CRLWCA used for per m ³ of concrete: 560 kg/m ³ RGUA used for per m ³ of concrete: 14.1 kg/m ³ RFUA used for per m ³ of concrete: 1.2 kg/m ³
	Green Aerogel	19.60	FRSCA used for per 0.01m ³ of aerogel: 0.31 kg/m ³
	Steel beams & welded nets	23.72	Steel frame for per unit of PCE: 23.72 kg/PCE

Table A5.7 Secondary raw material demanded per 1 m² construction and renovation floor area

	Coefficient of secondary raw material demand	Value (kg/m ²)
K _{URSCA(new)}	Ultrafine recycled siliceous concrete aggregate (URSCA) for PCE-new	1.269
K _{FRSCA(new)}	Fine recycled siliceous concrete aggregate (FRSCA) for PCE-new	44.070
K _{CRSCA(new)}	Coarse recycled siliceous concrete aggregate (CRSCA) for PCE-new	66.662
K _{RGUA(new)}	Recycled glass ultrafine admixture (RGUA) for PCE-new	0.761
K _{RFUA(new)}	Recycled fiber wool ultrafine admixture (RFUA) for PCE-new	0.127
K _{SF(new)}	Steel frame for PCE-new	7.450
K _{URSCA(refurb)}	Ultrafine recycled lightweight concrete aggregate (ULWSCA) for PCE-refurb	1.293
K _{FRSCA(refurb)}	Fine recycled siliceous concrete aggregate (FRSCA) for PCE-refurb	1.194
K _{FRLWCA(refurb)}	Fine recycled lightweight concrete aggregate (FRLWCA) for PCE-refurb	10.010
K _{CRLWCA(refurb)}	Coarse recycled lightweight concrete aggregate (CRLWCA) for PCE-refurb	15.400
K _{RGUA(refurb)}	Recycled glass ultrafine admixture (RGUA) for PCE-refurb	0.388
K _{RFUA(refurb)}	Recycled fiber wool ultrafine admixture (RFUA) for PCE-refurb	0.033
K _{SF(refurb)}	Steel frame for PCE- refurb	3.260