

# Quantifying future post-demolition concrete in Germany: A multi-model projection until 2080

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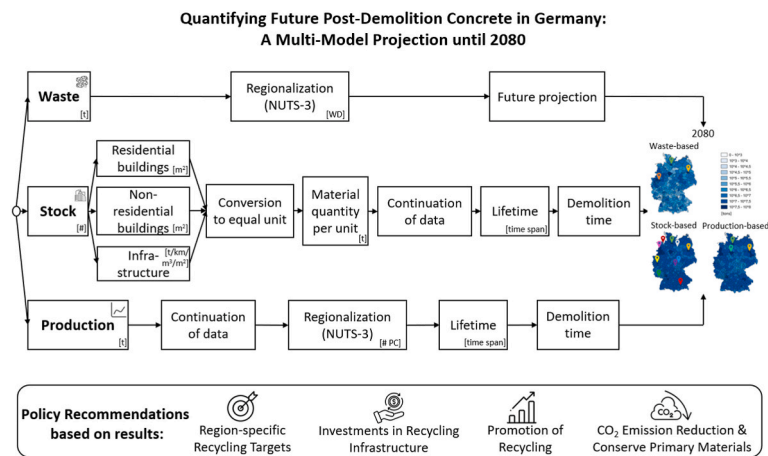
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## HIGHLIGHTS

- Development of a multi-model approach to determine post-demolition concrete volumes.
- Quantification approach combines waste statistics, stock data, and production statistics.
- Projection of post-demolition concrete volumes in Germany until 2080.
- > 50 million tons of post-demolition concrete predicted for 2040.
- Significant volumes arising primarily in urban areas in Germany.

## GRAPHICAL ABSTRACT



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## ABSTRACT

To meet climate targets, the environmental impacts of concrete production must be reduced, particularly those associated with cement manufacture. While recycled aggregates primarily contribute to resource conservation, secondary cementitious materials derived from recycling offer direct CO<sub>2</sub> mitigation potential. Post-demolition concrete (PDC) represents a critical secondary resource for both substitution pathways. Reliable projections for future availability are therefore essential for climate-oriented material and circular construction strategies.

This study aims to quantify and spatially resolve future availability of PDC in Germany at district level until 2080. A novel multi-model approach is applied, integrating concrete waste statistics, material stocks modelling of buildings and infrastructure, and historical concrete production data. Findings based on the production-based approach indicate that by 2040 approximately 50 million tons of PDC will become available as a secondary raw material, with the highest volumes concentrated in urban regions such as Hamburg and Berlin. Despite its considerable recycling potential, PDC is currently predominantly landfilled or used in low-value applications, indicating substantial underutilization. In parallel, landfill capacity is decreasing, while certain primary raw materials required for concrete production face increasing supply constraints.

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The projected PDC volumes provide a quantitative basis for assessing future substitution potentials in concrete production. Under the assumption of 35% replacement of primary aggregate and 30% substitution of Portland cement, the annual production of recycled concrete could reach up to 165 million tons annually by 2080. Overall, the results highlight the strategic relevance of PDC for advancing circular material cycles, reducing CO<sub>2</sub> emissions, and mitigating pressure on primary resources.

## 1. Introduction

The construction industry contributes significantly to CO<sub>2</sub> emissions – primarily due to cement production. To meet climate targets (e.g., the Paris Agreement's 1.5 °C limit and the EU's goal of climate neutrality by 2050), substantial emission reductions are required (Honegger et al., 2020). Recycling of construction and demolition waste (CDW) represents a key strategy for conserving resources, minimizing landfill use, and lowering CO<sub>2</sub> emissions. Demolished concrete serves as a secondary raw material for new production, aligning with circular economy principles (Kirchherr et al., 2017). These are supported by EU regulations (e.g., EU Waste Framework Directive, 2008/98/EC) and standards (e.g., DIN) (Deutsches Institut für Normung [DIN], 2024; European Commission, 2020; European Parliament and of the Council, 2008). When reuse is not feasible due to degradation, recycling remains the most effective mitigation option (Estévez et al., 2003; Zadeh et al., 2023).

Concrete is a valuable material used in various ways. After water, concrete is the second most consumed material in the world (Labaran et al., 2024) and ranks as the most extensively employed human-made material worldwide (Low, 2005; Naik, 2008). Cement accounts for 15–20% of the concrete volume, serves as a binding agent, and ensures the toughness of the final product (Neville and Brooks, 2010; Verein Deutscher Zementwerke e.V. [VDZ], 2022b). Production peaked in 2020 at 55.3 million m<sup>3</sup> in Germany, likely driven by population growth and increased housing demand (Statista, 2024a, 2024b, 2024c). Cement production, primarily based on limestone calcination at 1450 °C, results in substantial CO<sub>2</sub> emissions, ranging from 433 kg/t and 896 kg/t (ökobau.dat, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g), depending on factors such as energy source, temperature, and burning duration (Institut Bauen und Umwelt e.V. [IBU] & VDZ, 2017; VDZ, 2020).

Post-demolition concrete (PDC) yields fine sand (≤4 mm) and coarse aggregate (>4 mm) recyclable per DIN EN 12620 (BMUV, 2020; Müller, 2018a). Coarse aggregate can substitute natural aggregates, though higher porosity may affect strength (Höffgen et al., 2022; Rao et al., 2007). With proper treatment and mix design, recycled concrete can meet performance standards. Fine aggregate helps conserve resources, particularly in resource-constrained regions (Nedeljković et al., 2021). Aggregates, including both fine and coarse fractions, are also commonly used in road construction for high-load-bearing applications.

In Germany, PDC must be treated according to the waste hierarchy (European Parliament and of the Council, 2008). Existing literature highlights concrete recycling primarily for resource conservation, waste reduction, and CO<sub>2</sub> mitigation (Schiller et al., 2010). Methodologies describe how recycled building materials can replace aggregates in concrete (Deder, 2015; Haist et al., 2022; Maia Pederneiras et al., 2022; Müller, 2018b; Rübner et al., 2008), including applications such as aggregate, concrete additives, road base, or cement components. Since cement remains the most emission-intensive component, substituting it with low-impact alternatives is essential. Belit-based clinker, a possible cement substitute in RC<sup>2</sup>-concrete<sup>1</sup> production developed by Stemmermann et al. (2022), offers a promising mitigation pathway, as its lower CaO requirement reduces limestone demand and associated calcination emissions compared to ordinary Portland cement clinker

(Stemmermann et al., 2024). In addition, belite formation can occur at reduced kiln temperatures, lowering energy-related CO<sub>2</sub> emissions. When produced from crushed concrete sand (CCS), further emission reductions result from substituting primary raw materials. While research has focused on technical feasibility, a temporal and spatially resolved analysis of PDC at district-level (NUTS-3 level<sup>2</sup>) is still needed to enhance circularity.

While recycled concrete is increasingly regarded as a sustainable alternative in the construction sector, empirical data on PDC generation – especially with temporal depth and NUTS-3 level spatial resolution – remain scarce in the German context.

A spatially disaggregated analysis at the NUTS-3 level is valuable, as concrete is a heavy, low-value material, making long-distance transport economically and environmentally inefficient. Given that typically recycling catchment areas for PDC range between roughly 30 and 60 km in radius (Schultmann, 2000), the NUTS-3 scale provides a meaningful level of spatial resolution for assessing regional availability and recycling potential. Moreover, such regional representation enables a more precise alignment of supply and demand for recycled aggregates (RC-aggregate), facilitates the planning of decentralized recycling infrastructure, and supports the development of local circular economies in the construction sector.

This is essential for developing regional strategies for recycling PDC, enhancing sustainability in the construction industry. Additionally, it is unclear how much material is available for a meaningful cycle. Thus, the following two research questions are the focus of this study.

- i) How will PDC volumes evolve spatially and temporally across Germany until 2080, and what structural differences emerge between waste-, stock-, and production-based modeling approaches?
- ii) To what extent can projected PDC volumes be transformed into RC-aggregates and CCS, and how do these secondary material flows influence future concrete potential in Germany?

The projection horizon of 2080 was chosen because most concrete-based buildings and infrastructure components exhibit average lifetime of approximately 40–65 years, meaning that structures documented in the available post-2024 data will, on average, reach end-of-life within this timeframe, allowing their full demolition and recycling potential to be captured. Existing studies estimate future PDC primarily through building stock modeling. Marinova et al. (2020) and Deetman et al. (2020) project material inflows and outflows for residential buildings (RB) and non-residential buildings (NRB); however, infrastructure is not considered. This may, however, be due to the limited availability of reliable infrastructure data required for such projections. Earlier studies (Faist Emmenegger and Frischknecht, 2003; Fishman et al., 2015; Kapur et al., 2008; Lichtensteiger and Baccini, 2008; Tanikawa et al., 2015) focus on existing stock in industrialized countries but lack forward-looking projections. Further studies (Hashimoto et al., 2007; Kapur et al., 2008; Kohler and Hassler, 2002; Lanau et al., 2019) apply bottom-up or top-down methodologies to model building material stocks. A comprehensive study for Japan by Hashimoto et al. (2007) illustrates how national forecasts of material flows from the built

<sup>1</sup> RC<sup>2</sup>-concrete refers to a recycled concrete formulation using RC-aggregates and CCS, with partial cement substitution by belite-based clinker from CCS.

<sup>2</sup> The NUTS-3 level is the smallest level of regional classification in EU statistics and usually comprises rural districts or independent cities eurostart (2024).

environment can support resource planning – an approach that has been lacking in the German context to date. Given the special construction dynamics of the post-war period, the backlog of infrastructure renewal, and Germany's decentralized planning structure, a district-specific, spatially disaggregated assessment is necessary. For Germany, bottom-up approaches using representative building types and material coefficients are prominent (Deilmann et al., 2014; Ortlepp et al., 2016; Schiller et al., 2010, 2015), supported by data from microcensus, construction statistics, and the IÖR database (Leibniz-Institut für ökologische Raumentwicklung e. V., 2024). Yet most studies either focus on technical feasibility or on static stock estimates, without integrating multiple perspectives or long-term projections. While these approaches provide valuable insights into the composition and magnitude of the current stock, they generally do not predict the future waste flows that will arise once these materials reach the end of their life cycle through demolition. Although existing approaches shed light on current material stocks, they often lack forward-looking projections and rarely focus on Germany. Yet Germany's large aging building and infrastructure stock and policy commitments to climate neutrality highlight the need for national-scale waste flow projections to inform circular construction strategies.

Beyond existing concrete stocks, PDC generation and new concrete production are key parameters for evaluating recycling potential. While Destatis provides data on historical waste and production volumes, and studies such as Mostert et al. (2022) and Schiller et al. (2017) address material stock, a detailed forecast at NUTS-3 level is lacking. However, such spatially resolved projections are essential for advancing a circular concrete economy, particularly for reverse logistics planning and estimating resource and CO<sub>2</sub> savings.

The following sections outline the methodologies for quantifying the potential of RC-concrete in Germany, examine future circulation quantities, and discuss relevant limitations.

## 2. Methods

The three-fold approach (Fig. 1) was developed to assess the potential of PDC in Germany as a secondary raw material for concrete production. It integrates data from waste statistics, building and infrastructure stocks, and concrete production to ensure comparability of projected annual PDC volumes at NUTS-3 level and to increase robustness of the long-term projections. The model estimates the spatial and temporal distribution of PDC using historical data, construction activity, regionalization factors, and lifetime distributions of concrete

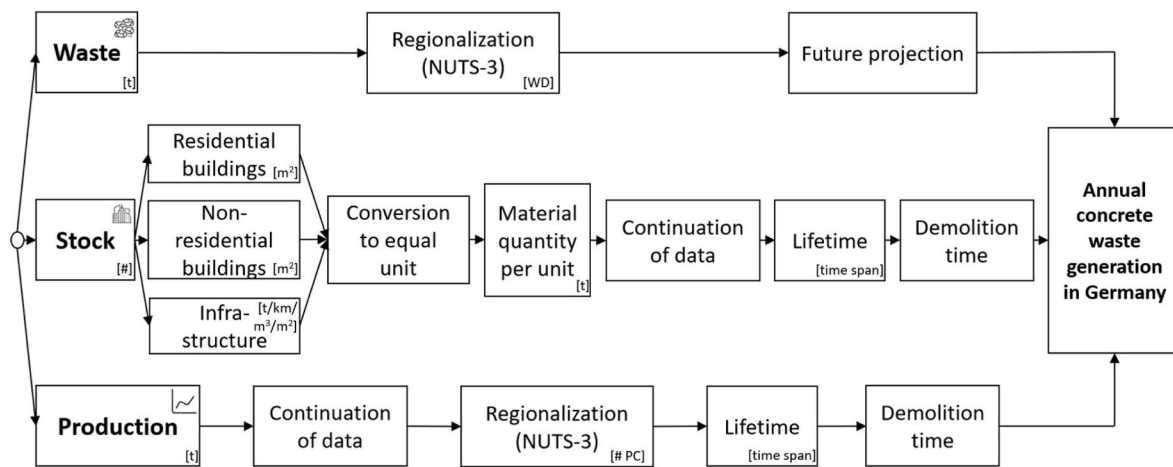
structures. Each model contributes unique temporal and spatial insights: waste data reflects recent demolition activity, stock data captures built environment dynamics, and production figures provide long-term historical trends. Their integration enables a more comprehensive quantification of PDC flows. By integrating waste, stock, and production perspectives, the overall approach captures the dominant system processes underlying construction material turnover, thus covering the key pathways through which PDC can be generated and observed. Current policy developments, including the Circular Economy Act and the Federal Government's Sustainability and Raw Material Strategy, are reflected through corresponding assumptions in the projections.

### 2.1. Waste

Waste statistics in Germany are structured according to standardized waste codes (Bundesministerium für Digitales und Verkehr [BMDV], 2008). Concrete-containing wastes are primarily recorded under the category 17 CDW (including excavated material from contaminated sites [see SI-1.1], as well as under category 1013 waste from the manufacture of cement, quicklime, gypsum and products made from these, which includes waste code 101314 concrete waste and concrete sludge (Bundesministerium der Justiz, 2001). Waste code 170106 was excluded, as the potential presence of hazardous constituents prevents high-quality recycling and reintegration into concrete production. For waste code 170107, German regulations do not specify the exact composition; however, classification practice indicates that this fraction contains no more than 50% concrete by mass. Higher concrete shares are typically assigned to waste code 170101. Consequently, a conservative assumption of up to 50% recyclable concrete content was applied for 170107. For waste codes 170101 and 101314, full material availability for potential recycling was assumed.

National waste statistics provided by the Federal Statistical Office (Destatis, 2021) report annual inputs to waste treatment and disposal facilities by waste code for the period 2017-2022. These data indicate that approximately 40 million tons of concrete waste are generated annually in Germany (see Fig. 2).

While waste data are available at national and federal state levels (Destatis, 2021), no district-level (NUTS-3) statistics exist for specific waste fractions. However, Destatis (2023) provides district-level information on total waste quantities disposed of or treated. To obtain a spatially resolved estimate of concrete waste, national concrete waste quantities were regionalized based on the relative share of total waste reported for each district and year.



PC = Permits for the construction of new residential buildings and flats in residential buildings by number of flats  
 WD = Volume of waste delivered to disposal and treatment facilities

Fig. 1. Graphical overview of the three-fold methodology of the quantification model.

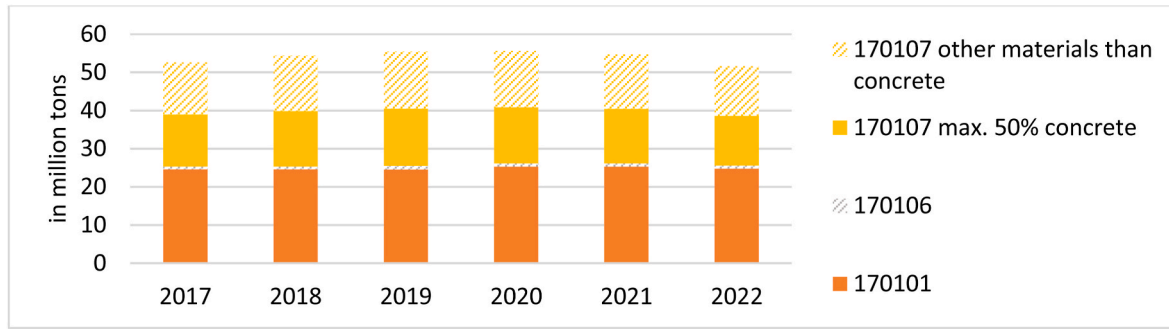


Fig. 2. National concrete-related waste statistics by the Federal Statistical Office for 2017-2022.

The NUTS-3 level concrete waste quantities were calculated as:

$$PDC_{d,y} = r_{d,y} * PDC_{d,y}^{DE}$$

$PDC_{d,y}$ : Concrete waste (input from waste disposal plants) in district  $d$  and year  $y$

$r_{d,y}$ : Weighting factor per district  $d$  and year  $y$  (where  $\sum_d r_{d,y} = 1$ )

$PDC_{d,y}^{DE}$ : Total PDC as input of waste disposal plants per year  $y$  in Germany

To project waste quantities until 2080, three continuation scenarios were applied. The first scenario assumes constant waste generation based on the mean value of the six-year observation period for each district. The second scenario reflects anticipated increases in renovation activities and lifetime-extension policies by applying a conservative annual reduction of 1% to the mean value (BMUV, 2024). The third scenario applies a linear extrapolation of the historical waste trends.

It should be acknowledged that the waste-based projection is derived from a relatively short six-year observation period, which limits the representation of long-term structural developments, cyclical variations, and potential policy-induced changes in waste generation. Accordingly, the continuation scenarios were deliberately formulated using simple and transparent assumptions, as the application of more complex statistical forecasting methods would not be warranted given the data limitations.

## 2.2. Stock

The stock approach estimates future recyclable concrete by combining current material stocks in RB, NRB, and infrastructure with lifetime assumptions to model demolition-based availability over time.

### 2.2.1. Buildings

In the RB sector, four building typologies are distinguished: single-family houses (SFH), terraced houses (TH), apartment blocks (AB), and large apartment blocks (LAB), based on the classification provided by the (Institut Wohnen und Umwelt GmbH [IWU], 2012). These typologies are defined by average net floor area sizes derived from available data for each construction age class at the NUTS-3 level. The TABULA database provides the number of buildings by construction period, enabling a cohort-based representation of the RB stock. Complementary to this, Leibniz-Institut für ökologische Raumentwicklung e. V (2024) provides material consumption data and material group compositions for RB and NRB across construction periods. The IÖR material classification reflects typical construction practices and material use patterns in Germany.

As IÖR defines broader age classes (e.g., pre-1918, 1919-1948, etc.), while TABULA provides more detailed intervals, material intensities were proportionally allocated when TABULA classes span multiple IÖR periods. Combining TABULA cohort data with IÖR material intensities allows the material matrix of the German building stock to be represented empirically. After the concrete material intensity is defined for each building type and age class, the material intensity per age class and

district is calculated (see SI-1.2).

Concrete inventory data for (N)RB are calculated at NUTS-3 level and projected up to 2080 using different forecasting methodologies (see Fig. 3).

Between 1949 and 1978, building construction rose sharply and fell again due to Germany's post-war reconstruction (Deutsche Digitale Bibliothek, 2025). Especially between 1958 and 1968, a very strong construction activity can be seen in AB (Wertheimer, 1958). Based on recent empirical trends and sustainability objectives, a 5% reduction in new building activity is assumed for periods after 2022 (BMUV, 2024; Bürger et al., 2016; Destatis, 2025a). Official statistics show a marked decline in RB permits since 2022 (Destatis, 2025a), following a relatively stable phase between 2016 and 2022 (Destatis, 2025c), indicating a structural adjustment rather than short-term cyclical variation. The 5% assumption, therefore, reflects a moderate long-term decline consistent with both observed developments and policy targets aimed at reducing land consumption and limiting further expansion of built-up area. To account for uncertainty, alternative reduction rates were examined in a structured sensitivity analysis.

$$(1) S_{d,y}^{RB} = S_{d,y-1}^{RB} * (1 - red_{RB})$$

$S_{d,y}^{RB}$ : Concrete stock in RB type in district  $d$  and year  $y$  [t]

$red_{RB}$ : Reduction rate (0.05 baseline)

The procedure for NRB mirrors that for RB, using a standardized average net building area (Leibniz-Institut für ökologische Raumentwicklung e. V, 2024) and the corresponding average concrete intensity per NRB and building class. In the first step, the concrete intensity per square meter of useable area in NRB is calculated using the same methodology as for RB. Due to the lack of detailed data, average concrete intensities for each building age class are applied (IWU, 2012) (see SI-1.2). In the next step, average concrete intensities are assigned to NRB by building age class and district. Multiplying these values by the number of buildings yields total concrete consumption.

As with RB, projections are extended to 2080, assuming a 5% decrease in new NRB per building age class. The concrete used in NWG for the different periods can be seen in Fig. 3.

$$(2) S_{d,y}^{NRB} = S_{d,y-1}^{NRB} * (1 - red_{NRB})$$

$S_{d,y}^{NRB}$ : Concrete stock in NRB type in district  $d$  and year  $y$  [t]

$red_{NRB}$ : Reduction rate (0.05 baseline)

As RB and NRB are reported in aggregated building age classes, construction volumes were uniformly distributed within these classes across the individual years in each period. Estimating PDC generation required assumptions about building infrastructure. Rather than adopting single average values, lifetime ranges were applied to better capture the variability and uncertainty inherent in demolition processes. The selective lifetime intervals were derived from a synthesis of literature sources reporting heterogeneous but broadly consistent estimates.

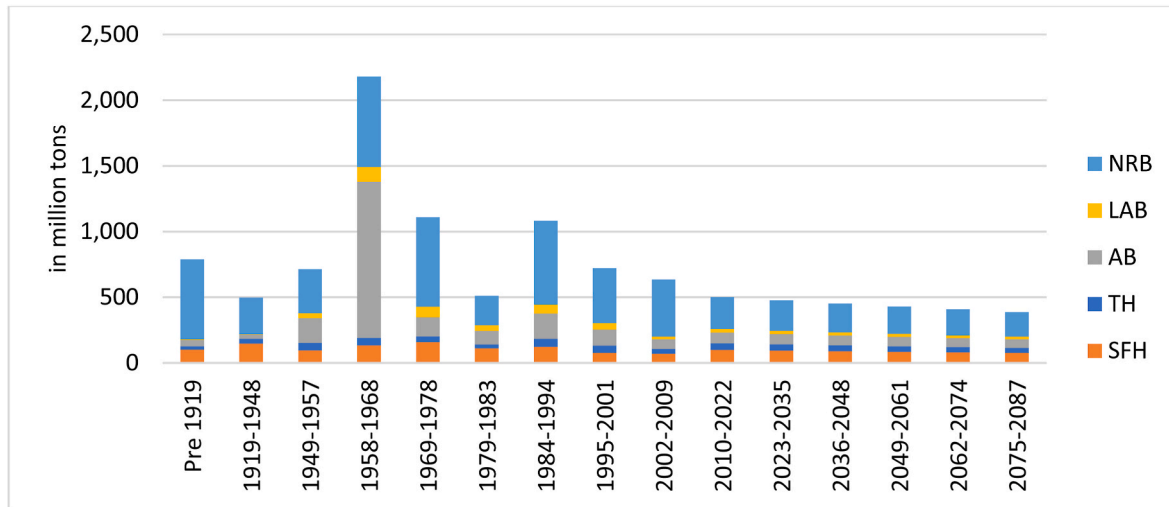


Fig. 3. Concrete stock [in million tons] in RB and NRB from pre-1919 to 2023 with a projection throughout 2087.

Reported average lifetimes typically range from 50 (Gehlen, 2010) to 60 (Huhn, 2019) to 90 years (Miller, 2020), while more differentiated analyses indicate substantial variability. Schmalwasser and Weber (2012) for example, report lifetimes of 40-95 years for RB and 15-113 years for NRB. Other lifetime distributions presented by Hossain and Ng (2018) further highlight the wide dispersion of demolition timing across building cohorts.

To remain consistent with these findings while avoiding over-precision, this study adopts conservative lifetime ranges of 35-95 years for RB and 20-100 years for NRB. These intervals reflect the lower and upper bounds reported in the literature and provide a pragmatic representation of building longevity suitable for long-term material flow modeling.

Lifetime sampling was conducted by generating building lifetimes using a Weibull distribution, which is commonly used to model probabilistic demolition processes and clustering of demolition events around characteristic lifetimes. The Weibull parameters were calibrated based on lifetime ranges reported in the literature (35-95 years for RB and 20-100 years for NRB). For the concrete volume of each building associated with each construction year, a lifetime value was drawn from respective Weibull distribution and added to the year of construction to estimate the expected demolition year. Accordingly, the concrete volume associated with each construction cohort was allocated to the corresponding demolition year as PDC. To account for uncertainty in lifetime assumptions, uniform distributions based on the same literature ranges were additionally evaluated as part of the sensitivity analysis. While this approach provides a probabilistic estimate for demolition timing, it cannot fully capture building-specific factors such as heritage protection, functional adaptation, or user-driven refurbishment cycles.

### 2.2.2. Infrastructure

Tunnels, bridges, roads, and railways were included to comprehensively assess concrete use across Germany's major infrastructure sectors.

**Tunnel** data from 1996 to 2017 (BMDV, 2019) shows a steady, though slowing, increase in tunnel kilometers. No data is available prior to 1996. A linear projection to 2080 estimates future tunnel lengths. Concrete stock in tunnels is derived from annual tunnel construction and material use per kilometer. The tunnel types are classified into two types: type one (10 m height, 20 m width) and type two (10 m height, 10 m width) (InformationsZentrum Beton GmbH, 2025). Based on STUVA (2022) 1% of concrete in the existing tunnels is assumed to be renewed annually, reflecting a 100-year lifetime, and 10% of the tunnel kilometers in 2022 will have to be renewed over the next 20 years (Sika, 2025). To assess uncertainty, sensitivity scenarios were modeled in

which 100%, 50%, and 25% of the assumed 1% annual renewal rate (see section 3.5) were considered to result in actual concrete removal and thus contribute to PDC generation. These projections extend to 2080 to estimate future PDC volumes. The following calculation is carried out.

$$(3) O_y^{tunnel} = S_{y-1}^{tunnel} * r_{tunnel} * \alpha_{tunnel}$$

$O_y^{tunnel}$ : PDC from tunnels per year  $y$  [t]

$S_{y-1}^{tunnel}$ : Cumulative concrete stock in tunnels at the end of year  $y - 1$  [t]

$r_{tunnel}$ : Annual renewal rate of the tunnels

$\alpha_{tunnel} \in (0,1]$ : Proportion of renewed tunnel concrete that is physically removed as demolition material

The Federal Highway Research Institute provides data on **bridge** surface area by material type in Germany from 1990 to 2018 (Bundesanstalt für Straßenbau [bast], 2018). These figures were linearly extrapolated up to 2080, while years before 1990 and after 2018 are excluded due to data unavailability. Since no detailed concrete quantity data exists for bridges differentiated by road type, and bridge design varies considerably in terms of span length, support configurations, and structural system (e.g., girders and piers) (Haack, 1979; InformationsZentrum Beton GmbH, 2025), a parametric highway bridge archetype model (see SI-1.3) with 4.5 m clearance (Bundesministerium für Verkehr, 2000) was developed to derive conservative yet structurally differentiated estimates. Material assumptions include 85% concrete for reinforced concrete and 80% for prestressed concrete, with a density of 2.3 t/m<sup>3</sup> used for volume-to-mass conversion.

Instead of applying a single standardized bridge geometry, three structural configurations were defined to reflect portfolio heterogeneity. These configurations vary in span length, pier volume, girder volume, and deck slab thickness, representing large/viaduct-type, average, and small bridge structures, respectively. As no reliable data on the distribution of bridge types is available at the national level, the average configuration was used for the main results, while smaller and larger bridge configurations were evaluated as sensitivity scenarios. The resulting concrete intensities range from 6.9 to 19.6 t/m<sup>2</sup> (see SI-1.4).

The following formula was applied to all bridges that were constructed in year  $y$  between 1990 and 2018 to estimate the respective concrete stock in these constructions.

$$(4) S_y^{bridge} = (ba_y * dt) * \rho + gm_y + pm_y$$

$S_y^{bridge}$ : Concrete stock in bridges in Germany per year  $y$  [t]

$ba$ : concrete bridge area [m<sup>2</sup>]

$dt$ : concrete deck thickness [m]

$\rho$ : density of standard concrete [ $t/m^3$ ]

$gm_y$ : total girder mass [t]

$pm_y$ : total concrete pier mass [t]

A linear continuation of the annual concrete stock in bridges was used to project this data until 2080. To calculate the resulting waste from renewal and/or demolition, the portfolio for each year from 2024 onwards is multiplied by a renewable rate. Currently, 50% of bridges in Germany are classified as in need of repair (Ganz, 2025; Puls, 2020). Given practical constraints on planning, financing, and construction capacity, a renewal rate of 3% was assumed as a pragmatic annual implementation rate for the period 2024–2041, followed by a reduced rate of 1.5% annually. These rates approximate a gradual reduction of the reported rehabilitation backlog over a multi-decade horizon, acknowledging practical limitations in planning and execution capacity. To assess uncertainty, sensitivity scenarios were modeled in which 100%, 50%, and 25% of the assumed 1% annual renewal rate were considered to result in actual concrete removal from bridges, as in reality, bridges typically undergo partial repairs and thus contribute partly to PDC generation.

$$(5) PDC_y^{bridge} = S_{y-1}^{bridge} * r_{bridge} * \alpha_{bridge}$$

$PDC_y^{bridge}$ : PDC from bridges per year  $y$  [t]

$S_{y-1}^{bridge}$ : Concrete stock in bridges in Germany per year  $y-1$  [t]

$r_{bridge}$ : Renewal rate of bridges

$\alpha_{bridge} \in (0,1]$ : Proportion of renewed bridge concrete that is physically removed as demolition material

The next step quantifies concrete stock in roads. According to data from the Bundesministerium für Digitales und Verkehr (BMDV) (2024a), federal roads and highways are built with a concrete layer. Material consumption is estimated using road length data by type (Statista, 2023b), assuming one lane per direction for federal roads and two for highways (see SI-1.5) (Deutscher Bundestag, 2009). Road area is calculated by multiplying length by total width, including lane and verge dimensions. Concrete in roads is estimated by assuming that 25% of highways and federal roads have a 0.25 m concrete layer (InformationsZentrum Beton GmbH, 2024). With a density of 2.3  $t/m^3$  and considering easier removal due to a separation layer (Eifert, 2007), the surface area is converted into concrete mass.

$$(6) S_y^{road} = (ra_y * pt) * \rho$$

$S_y^{road}$ : Concrete stock in roads in Germany per year  $y$  [t]

$ra_y$ : Road surface area with concrete pavement in year  $y$  [ $m^2$ ]

$pt$ : Concrete pavement thickness [m]

$\rho$ : Density of standard concrete [ $t/m^3$ ]

In 2023, concrete usage was estimated at 8,625 tons/m for federal roads and 13,225 tons/m for highways, in sections constructed with concrete.

Future road stock development includes 3500 km of new and extended federal roads and highways (BMDV, 2024b). Based on a 16% renovation demand, annual renewal rates of 2% (2024–2031) and 1% (from 2032 onwards) are assumed (Sackmann, 2024). The concrete consumption is multiplied by these rates to estimate PDC generation per year.

$$(7) PDC_y^{road} = S_{y-1}^{road} * r_{road}$$

$PDC_y^{road}$ : PDC from roads per year  $y$  [t]

$S_{y-1}^{road}$ : Concrete stock in roads in Germany per year  $y-1$  [t]

$r_{road}$ : Renewal rate of roads

The **railway** system is a relevant concrete-supported subsystem.

Track lengths of 39,200 km (2024) and 44,600 km (1994) in Germany form the basis for projections (Allianz pro Schiene e. V., 2024). It is assumed that 750 km will be added by 2030, 500 km between 2031 and 2035, and 2050 km from 2036 to 2045 (Knapp, 2024; Statista, 2023a), with length remaining constant through 2080. Due to limited data availability, a more granular breakdown was not possible.

Concrete consumption is estimated by dividing total track length by average sleeper spacing (0.65 m) to determine sleeper quantity (Bayrisches Landesamt für Umweltbundesamt, 2025; Deutscher Bundestag, 2021). Assuming 80% are B70 concrete sleepers (280–300 kg, 80% concrete content), total material use is calculated. Future post-demolition volumes are based on projected track renewals (Betonschwellenindustrie, 2017; Statista, 2023b, 2023c) Under this assumption, 13.5 million tons of concrete were installed in sleepers in 2024. The expected stock increase until 2080 is projected to be 2 million tons. To forecast the future PDC of the German rail network, data is used that indicates how many kilometers of track are to be refurbished by 2030 (~4100 km) (Statista, 2023a). From 2030 onwards, the average of the refurbishment projects from 2024 to 2030 is used (1% of the previous year's stock).

Additionally, railway bridges were considered due to their stock and high rehabilitation demand. The German rail network comprises approximately 25,000 bridges, with nearly 1000 refurbished between 2015 and 2019 (Deutsche Bahn AG, 2025a). Owing to a lack of detailed national inventory data, a parametric approach was applied, assuming an average bridge with a baseline concrete intensity of 8  $t/m^2$ , complemented by sensitivity scenarios of 5  $t/m^2$  (high masonry/steel share) and 12  $t/m^2$  (concrete-dominated assumption) (BMDV, 2023).

Based on announced rehabilitation programs, 200 bridges per year are assumed to be renewed through 2029, and 100 thereafter (Deutsche Bahn AG, 2025b). PDC was calculated by multiplying the renewed bridge area by the assumed concrete intensity. Additional sensitivity scenarios considered that 100%, 50%, and 25% of the renewed concrete quantities generate post-demolition material.

$$(8) PDC_y^{rail network} = S_{y-1}^{rail track} * r_{rail track} + S_{y-1}^{rail bridge} * r_{rail bridge} * \alpha_{rail bridge}$$

$PDC_y^{rail network}$ : PDC from railway per year  $y$  [t]

$S_{y-1}^{rail track}$ : Concrete stock in railway track per year  $y-1$  [t]

$r_{rail track}$ : Renewal rate of railway track

$S_{y-1}^{rail bridge}$ : Concrete stock in railway bridges in Germany per year  $y-1$  [t]

$r_{rail bridge}$ : Renewal rate of railway bridge

$\alpha_{rail bridge} \in (0,1]$ : Proportion of renewed railway bridge concrete that is physically removed as demolition material

Then, the PDC amounts from the main infrastructure categories are aggregated.

$$(9) PDC_y^{infra} = PDC_y^{tunnel} + PDC_y^{bridge} + PDC_y^{road} + PDC_y^{rail network}$$

$PDC_y^{infra}$ : PDC from infrastructure per year  $y$

Finally, the PDC of the infrastructure, RB, and NRB are summed up to the annually expected PDC until 2080.

As infrastructure-related data is only available nationally, spatial disaggregation was required to ensure consistency and comparability across the waste-, stock-, and production-based approach. Nationally reported quantities were therefore allocated to NUTS-3 districts using regionally available statistical indicators.

The allocation assumes that infrastructure development, production quantities, and material accumulation are systematically linked to regional construction dynamics. Accordingly, multiple indicators derived from population and construction statistics were evaluated as potential spatial proxies (see SI-1.6 & SI-1.7), including demographic variables, construction completions, and approvals. Their suitability

was assessed using Pearson correlation analysis with national concrete production. The indicator “total approvals for dwellings in RB and NRB (including construction work on existing buildings)” showed the strongest correlation ( $r = 0.91$ ) and was selected for spatial allocation (Destatis, 2022). Approvals reflect planned construction activity and can therefore be used as a proxy for regional building dynamics associated with infrastructure development and material flows. However, this proxy primarily captures new construction dynamics and may therefore introduce a bias towards rapidly growing suburban districts, while potentially underrepresenting dense urban areas where demolition activities and associated PDC generation can be comparatively higher, particularly in the absence of spatially resolved demolition data.

Based on this proxy, district-level weighting factors were calculated to distribute national infrastructure quantities across NUTS-3 regions.

### 2.3. Production

The third approach analyzes concrete production data from national statistics to identify component types and standardize units by converting all values into tons using reference sources (bausep, 2025; Ott Betonwerke, 2025). Concrete production data in Germany is available from 1950 to 2018 (Destatis, 2018), with Betonservice data extending to 2022, shown in Fig. 4. To align units, data transformations were applied.

In overlapping periods (2008–2018), Betonservice reports concrete production volumes that are approximately 34–43% higher than those published by Destatis (Betonservice, 2023). To quantify this discrepancy, annual correction factors were calculated as the ratio between Betonservice and Destatis production values for each overlapping year. The resulting correction factors ranged between 1.34 and 1.43. Due to its higher granularity, particularly the availability of product-specific categories, the Destatis data was used as the primary input for the analysis. As the underlying reason for the level discrepancy could not be

conclusively identified (e.g., potential differences in reporting coverage or system boundaries), Destatis was retained as the reference dataset to ensure consistency with official national statistics. To continue the categorised Destatis data beyond 2018, the following approach was applied: First, the annual share of each product category in total concrete production was calculated based on the final available Destatis year (2018). Next, the total annual production values for 2019–2022 were taken from Betonservice. To ensure consistency, these were adjusted using an average correction factor derived from the overlapping years. To avoid systematic overestimation of production volumes and subsequent PDC projections, the lower bound of the observed correction range (1.34) was applied as a conservative adjustment.

Finally, the category shares from 2018 were multiplied by the corrected total Betonservice volumes to approximate product-specific values for 2019–2022. The method allows for a consistent extension of the product-level time series, despite the absence of detailed category data after 2018.

Fig. 4 illustrates official concrete production statistics within Germany up to 2022 (orange). For 2019–2022, data sourced from Betonservice were used and adjusted using the derived correction factor (1.34–1.43). Despite the absolute level differences, both data sets exhibit highly consistent temporal trends during the overlapping period, suggesting that the discrepancy is primarily due to systematic differences in reporting rather than structural shifts in production. The blue curve shows cement production in Germany from 1993 to 2022 (Bundesverband der Deutschen Zementindustrie [BDZ], 2021; VDZ, 2023), with notable peaks in 1991, 1992, and 2011. It serves as a benchmark to assess whether variations in concrete production align with cement production trends.

The production statistics and their categories (see SI-1.8) are filtered for standard concrete. Lightweight concrete was excluded as already examined by Steins (2024). Heavy concrete (2600–5900 kg/m<sup>3</sup>),

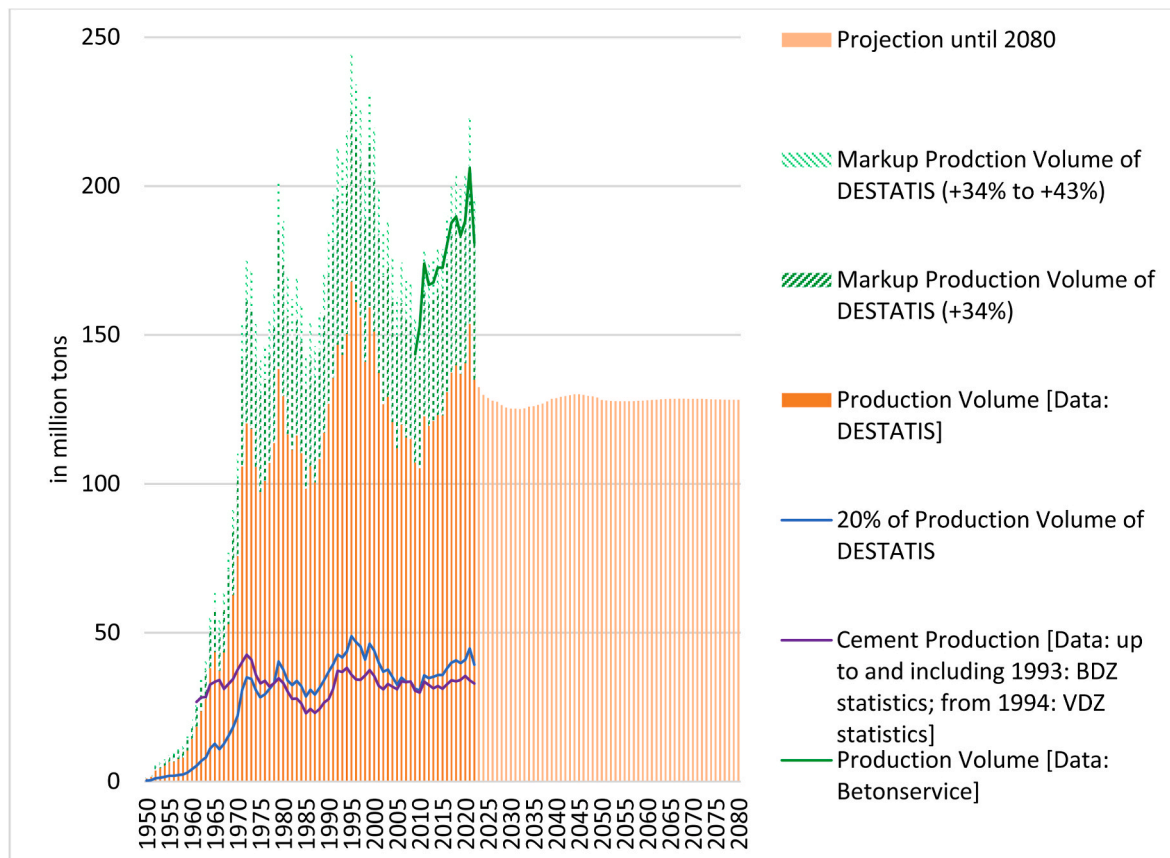


Fig. 4. Concrete and cement production volumes [in million tons] in Germany from 1950 to 2022 and projection until 2080.

requiring more complex processing and higher crushing forces, was likewise not considered (Deutscher Ausschluß für Stahlbeton [DAfStb], 2010; Grübl and Rühl, 2005).

For forecasts beyond 2022, the time series for product categories was extended using a rolling historical mean with a constant window length. As product classifications in the Destatis dataset remained consistent from 1995 onward, this year was selected as the starting point for projection calculations. For 2023, the average production value of each production category was calculated for the period 1995-2022. For 2024, the average over 1996-2023 was used, and so forth, thereby shifting the time window forward while maintaining a constant time span.

The rolling-window approach preserves long-term structural production levels while smoothing short-term volatility and avoiding artificial drift that could result from a progressively shrinking historical basis. To assess robustness, two alternative projection methods were additionally evaluated: (i) continuation of the rolling historical mean with an imposed 1% annual decline, and (ii) linear extrapolation based on recent trends. These alternative approaches provide uncertainty bounds for long-term production development (see SI-1.9).

To enable consistent comparisons, production data were downscaled to NUTS-3 level using the same methodology as for infrastructure: each district's share of total registrations was multiplied by the annual production volume per category.

$$(10) P_{d,y,k} = A_d \cdot P_{y,k}^{DE}$$

$P_{d,y,k}$ : Concrete production mass per district  $d$ , year  $y$ , and product category  $k$

$A_d$ : Relative share of total approvals for RB and NRB in Germany per district  $d$

$P_{y,k}^{DE}$ : Total concrete production mass per year  $y$  and product category  $k$

To project PDC volumes through 2080, a lifetime sampling approach was applied, assuming production and use occur in the same year. For each district, category, and year, a value from the Weibull lifetime distribution applied in the stock-based approach was added to the production year to estimate the demolition year. Expanded production data were then aggregated by category to calculate annual PDC volumes at the NUTS-3 level from 2024 to 2080.

## 2.4. Saving potential

This study uses an RC<sup>2</sup>-concrete formulation, which enables low-CO<sub>2</sub> belite clinker production from CCS, as researched by the Institute of Technical Chemistry at KIT. PDC is assumed to consist of ~10% fines for belite clinker and ~70% coarse material for RC-aggregate, with up to 20% processing losses. Although some sources suggest a 20:80 CCS-to-aggregate ratio (Höffgen et al., 2022), a conservative estimate is applied in this study. Fine fractions (<2 mm) could be used as secondary raw materials in the cement production process, either as supplementary cementitious material or as a reactive component (Steins, 2024; Stemmermann et al., 2024). Additionally, producing 1 m<sup>3</sup> RC<sup>2</sup>-concrete requires 1960 kg/m<sup>3</sup> RC-aggregate, 96 kg/m<sup>3</sup> belite clinker (as substitute for Portland cement in 320 kg/m<sup>3</sup> composite cement), which in turn is produced using 48.82 kg/m<sup>3</sup> of CCS (Stemmermann et al., 2023). With that, 30% of the Portland cement could be replaced with belite clinker. According to the current regulations, RC-aggregate >2 mm from CCS (concrete chippings, type 1) can be used in new concrete up to a proportion of 45% by volume or from mixed construction waste (building chippings, type 2) up to a proportion of 35% by volume (DAfStb, 2010). According to the new version of DIN 1045-2 from 2023, aggregates (type 1) ≤ 2 mm (CCS) may also be officially allowed to be used in concrete to a limited extent in the future (VDZ, 2022a). In other countries, like Switzerland, up to 100% of the aggregates are recycled in concrete production (BETONSUISSE, 2022; Schweizerischer Ingenieur-und

Architektenverein [SIA], 2005, 2019). Therefore, three scenarios were considered: substitution of 35, 45, and 100% primary aggregates (Table 1) at a 30% substitution of Portland cement with belite clinker from PDC.

## 3. Results

### 3.1. Waste

Due to limited data, the projected waste volumes depend heavily on the forecasting method and the underlying assumptions. Based on the mean value, waste volumes of 39.02 million tonnes are expected for 2080. Assuming that concrete waste decreases by 1% annually from 2024 to 2080 due to the goal of demolishing fewer buildings and renovating most of them, the waste is expected to decrease to 32.88 million tonnes by 2080. Based on a linear continuation of the data, the forecast for 2080 is 38.02 million tonnes. However, the relatively short time series for concrete waste does not allow for a reliable waste forecast.

### 3.2. Stock

#### 3.2.1. Buildings

The projected quantity of PDC from the stock in Germany is shown in Fig. 5. National volumes from RB are expected to peak at 64.05 million tons in 2032, followed by a decline to 56.13 million tons in 2030, 42.84 million tons in 2060 and 25.62 million tons in 2080. In Germany, the largest volume among the categories is expected to originate from AB in 2032, totaling 39.75 million tons, while the lowest volume is projected for LAB in 2080, with 2.81 million tons. Nationally, the PDC of NRB shows an annual peak of 54.19 million tons for 2031, followed by a declining trend beginning around 2065. During the analysis timeframe, the NRB stock share ranges from 40 to 56%.

#### 3.2.2. Infrastructure

The largest share of PDC from the analyzed infrastructure sectors is generated by bridges, reaching up to 3.95 million tons annually, whereas tunnels contribute the smallest portion, with a maximum of 0.24 million tons per year (Fig. 5).

For tunnels in 2030, 0.27 million tons of PDC are projected, increasing to 0.52 million tons by 2080. The share of tunnel-related PDC in total infrastructure waste rises from 4% (2030) to 10% (2080). For bridges, 3.61 million tons (2030) and 2.57 million tons (2080) are expected for PDC from renovation and renewal activities. The share of PDC from roads decreases from 38 to 32% by 2080, amounting to 3.20 million tons. Railway-related PDC is estimated to range between 0.47 million tons (2030) and 0.39 million tons (2080) per year. Infrastructure contributes only 4-9% of total volumes and is thus comparable to tunnels.

Fig. 5 shows that the total PDC ranges from 100 to 123 million tons annually until approximately 2055, likely due to reduced new construction in RB and NRB from 2024 onward. Given assumed minimum lifetimes (35 years for RB, 20 years for NRB), the decline begins approximately 20 years later. Beyond 2055, a steady decrease suggests a long-term reduction in PDC.

### 3.3. Production

Based on production data, PDC is expected to increase continuously until 2080 (Fig. 6). The largest share originated from ready-mix concrete (dark grey), followed by pre-cast concrete parts (green), roof tiles, paving slabs, and paving stones (orange), as well as concrete products for civil engineering and road construction (dark blue). The annual PDC from ready-mix concrete ranges between 13.97 and 88.20 million tons over the years. During 2024 and 2080, the share of ready-mix concrete of the total mass is the highest in 2075 with 70%.

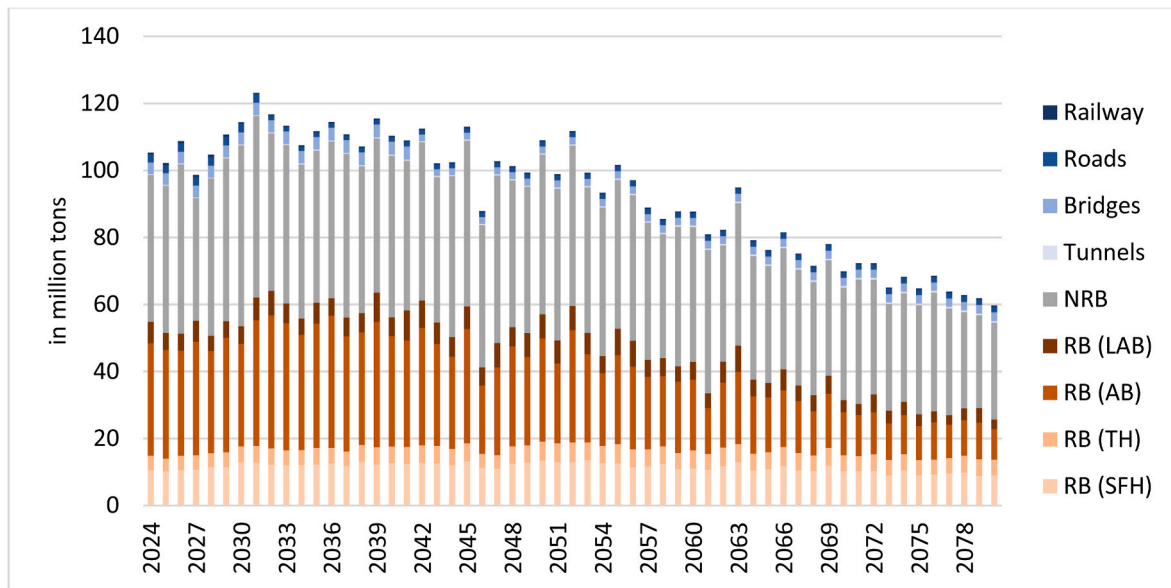


Fig. 5. PDC forecast based on stock-based approach differentiated by RB, NRB, and infrastructure components until 2080.

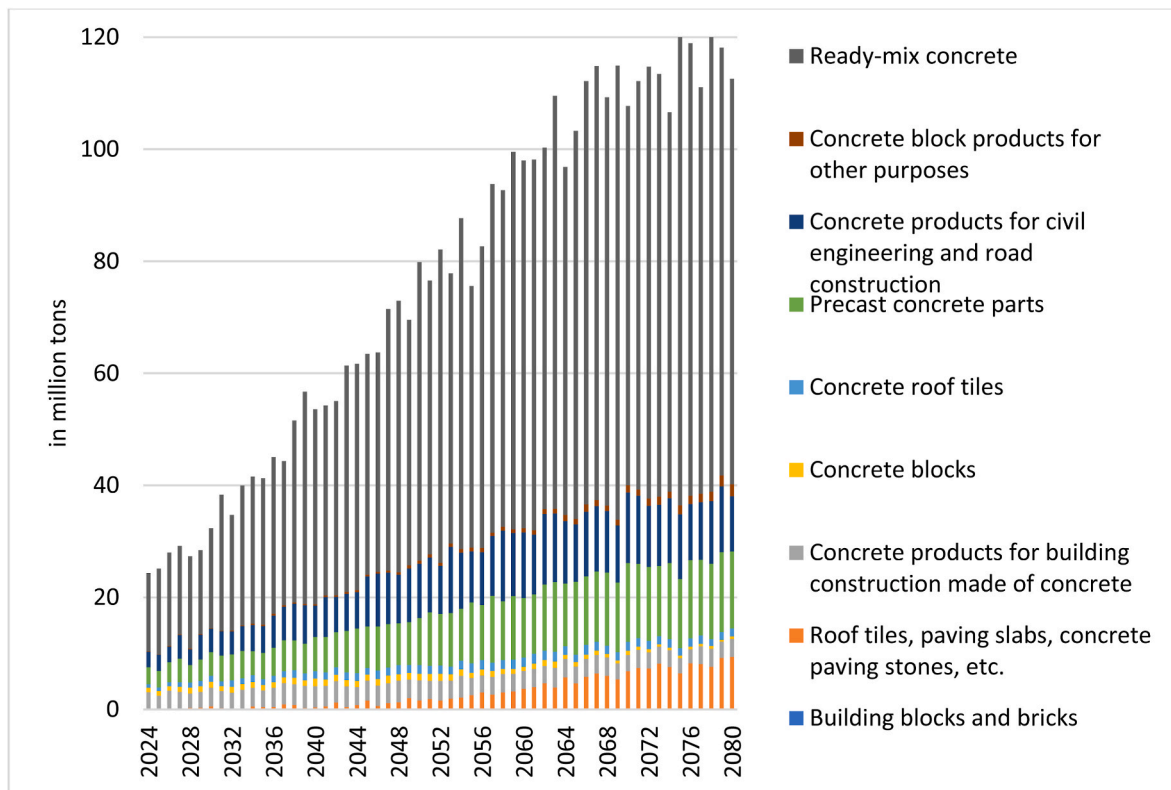


Fig. 6. PDC forecast based on production-based approach differentiated by concrete production categories in Germany until 2080.

### 3.4. Integrated findings

The analyzed approaches yield divergent projections for PDC in Germany (Fig. 7).

Due to limited input data, the waste-based projections show the least variation through 2080. In 2024, the stock-based approach already forecasts three times as much PDC as the production-based approach. This discrepancy is primarily due to missing production data for Eastern Germany, resulting in lower estimated quantities, especially in the

earlier decades.

The higher PDC estimates from the stock-based approach in the early decades may result from overly high renewal rates and the lack of differentiated data for (N)RB built before 1919. While the stock-based forecast shows a declining trend, the production-based forecast increases through 2080. From 2025 onward, both projections exceed waste-based estimates in over 85% of the year. In 2060, stock and production projections converge at approximately 95 million tons. Overall, the multi-model approach yields an annual PDC range (see grey

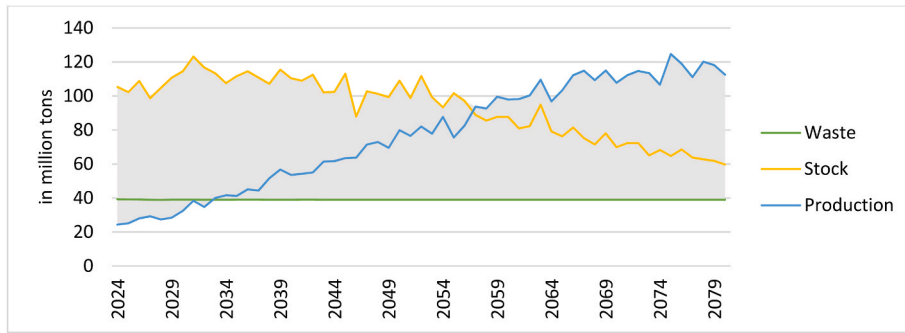


Fig. 7. Comparison of the three quantification approaches for forecasting PDC in Germany until 2080.

area in Fig. 7) of 39.06-114.43 (2030), 39.02-110.34 (2040), 39.02-108.98 (2050), and 39.02-112.58 million tons (2080), likely capturing the actual values.

The discrepancies primarily arise from the different modeling logics of the three approaches and illustrate how data limitations can affect the results in different ways. The waste-based approach reflects short-term, historically observed post-demolition volumes and therefore exhibits only limited temporal variability. In contrast, the stock-based approach derives demolition flows from the cumulative building and infrastructure stock, along with assumptions about lifetimes and renewal rates, which can yield higher estimates in the initial phase, when structures are expected to remain in use longer. The production-based approach links historical production volumes with assumed lifetime distribution. As production and installation are assumed to occur in the same year, potential time lags between production and actual use are not captured, potentially leading to deviations in the timing of demolition flows.

The stock-based model is based on assumptions about lifetimes and renewal rates, which might overestimate concrete volumes when

buildings and infrastructure are longer in use of the future and which leads to higher initial values.

The spatial distribution of projected PDC at NUTS-3 level shows clear regional differences up to 2080 (Fig. 8).

The waste-based approach indicates that the highest cumulative amount of PDC will occur in Unna followed by the urban areas Hamburg and Berlin. The generally lighter shading of individual districts highlights the lower projected PDC amounts under the waste-based approach.

The highest cumulative PDC concentrations from RB are anticipated in major cities such as Berlin, Hamburg, Munich, and Cologne, driven by continued urbanization and population growth. The lowest cumulative amounts over the period are anticipated in the districts of Zweibrücken, Suhl, and Lüchow-Dannenberg. For NRB, for 2024 and 2080, the highest cumulative volume is expected in the Emsland district, totaling 30.56 million tons. The highest annual volume per district (2.33 million tons) is likewise projected from Emsland in 2041. Between 2024 and 2080, the highest cumulative amounts of PDC from infrastructure are

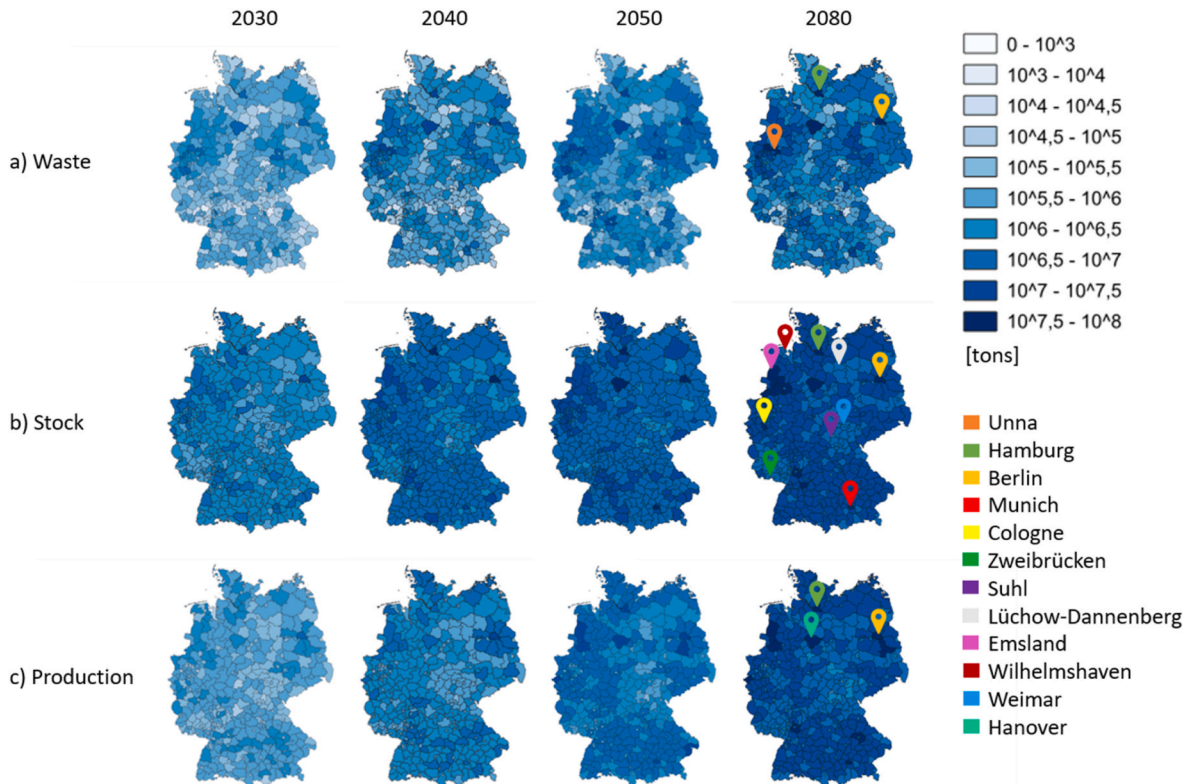


Fig. 8. Projected cumulative PDC [tons] based on the three approaches a) waste-based, b) stock-based, and c) production-based for the years 2030, 2040, 2050, and 2080 in Germany.

**Table 1**

Potential RC<sup>2</sup>-concrete quantities [million tons] under different aggregate substitution rates and 30% Portland cement substitution using PDC based on waste-, production-, and stock-based approaches.

	With 100% substitution of primary aggregate [%] (acc. to practice in Switzerland/SIA, 2030)	With 45% substitution of primary aggregate [%] (acc. to DIN 1045-2:2023)	With 35% substitution of primary aggregate [%] (acc. to DIN 1045-2)	With 30% substitution of Portland cement [%] (acc. to URBAN project)
<b>2024</b>				
Waste	32.17	71.48	91.91	184.51
Production	20.02	44.48	57.19	114.81
Stock	84.50	192.22	247.14	496.13
<i>Average</i>	<i>45.56</i>	<i>102.73</i>	<i>132.08</i>	<i>265.15</i>
<b>2030</b>				
Waste	32.08	71.29	91.66	184.01
Production	26.58	59.07	75.95	152.25
Stock	94.00	208.89	268.57	539.17
<i>Average</i>	<i>50.89</i>	<i>113.08</i>	<i>145.39</i>	<i>291.81</i>
<b>2040</b>				
Waste	32.05	71.22	91.57	183.83
Production	44.00	97.79	125.72	252.40
Stock	90.64	201.42	258.97	519.90
<i>Average</i>	<i>55.56</i>	<i>123.48</i>	<i>158.75</i>	<i>318.71</i>
<b>2050</b>				
Waste	32.05	71.22	91.57	183.84
Production	65.61	145.79	187.44	376.30
Stock	89.52	198.94	255.78	513.49
<i>Average</i>	<i>62.39</i>	<i>138.65</i>	<i>178.26</i>	<i>357.88</i>
<b>2080</b>				
Waste	32.05	71.22	91.57	183.84
Production	92.48	205.50	264.22	530.43
Stock	49.01	108.92	140.04	281.13
<i>Average</i>	<i>57.85</i>	<i>128.55</i>	<i>165.28</i>	<i>331.80</i>

generated in Berlin, Hamburg, and the Emsland region, each exceeding 3 million tons per year. By contrast, the lowest cumulative volumes are recorded in Wilhelmshaven and Weimar (between 0.03 and 0.04 million tons).

The **production**-based approach also shows and supports that the most PDC will be generated in the urban areas such as Berlin, Hamburg, and Hannover. For these districts, projected volumes over the entire study period range between 50.22 and 70.76 million tons.

Based on the stated assumptions, a total of 22.65-80.10 million tons of RC-aggregate and 3.24-11.44 million tons of CCS are projected for 2030. In 2080, the projected amounts are expected to be 27.31-78.81 million tons of RC-aggregate and 3.90-11.25 million tons of CCS. These forecasts and regional patterns offer a valuable basis for developing strategies to manage high PDC volumes locally and support the planning of optimized logistics networks for efficient use in recycled cement and concrete production.

**Table 1** presents the potential RC<sup>2</sup>-concrete production volumes achievable under individual strategies: aggregate substitution using RC-aggregate from PDC at varying replacement rates and Portland cement substitution using 30% belite clinker. The annual concrete quantities producible with 30% belite clinker substitution consistently exceed those achievable with any level of aggregate replacement. This indicates that the available volume of CCS suffices for belite production (Stemmermann et al., 2024) without limiting the use of coarse RC-aggregate for aggregate substitution, as both utilize different particle fractions of PDC.

With a 35 (45)% substitution rate, approximately 145.39 (113.08) million tons of RC<sup>2</sup>-concrete could be produced in 2030 using the available RC-aggregates. If future regulations allow 100% substitution, 57.85 million tons could be produced in 2080 based on the projected PDC volumes. Replacing 30% of Portland cement would enable the production of 291.81 million tons in 2030 and 331.80 million tons in 2080. Depending on the assumed substitution rates, the generated PDC could supply large amounts of RC-aggregate and CCS, enabling significant production of recycled concrete and providing a potential resource

base for circular supply chains in the German construction sector.

### 3.5. Sensitivity analysis

The sensitivity analysis focused on parameters based on assumptions due to the limited availability of data. These include lifetimes, renewal rates, infrastructure characteristics, and assumed reduction of new construction.

In the stock-based approach, varying assumed lifetime spans significantly influenced the temporal distribution of PDC (see SI-1.10). A uniform distribution rather than the Weibull lifetime distribution was used. The results show that both lifetime distributions yield a similar overall trend in the projections. In the early projection period until around 2050, slightly lower PDC volumes are observed, while somewhat higher values occur in later decades. This reflects the tendency of the Weibull distribution to concentrate demolition events around characteristic lifetimes rather than distributing them evenly across the entire lifetime range. Shifting the entire lifetime span range upwards (by 10%) led to lower annual PDC in the near term and slightly higher values by 2080, compared to the baseline scenario. Conversely, shifting the range downwards (by 10%) resulted in temporarily increased annual volumes, followed by lower quantities in the long term. In addition, the assumed 5% reduction in new construction per building age class was tested. A greater reduction slightly increased total PDC by 2080, while a lower reduction slightly decreased it. However, both effects remain minor. The infrastructure sensitivity analysis indicated that the projected PDC volumes are most strongly influenced by assumptions regarding bridge characteristics. Variations in bridge concrete intensity account for the largest differences in annual demolition volumes, reflecting high material intensity of bridges (around 50%) compared to other infrastructure components. Overall, variations in infrastructure parameters have a comparatively limited impact on total PDC projections, as infrastructure represents a smaller share (<10%) of the total PDC projection per year under the stock approach.

In general, **Fig. 9 (a)** shows on the left the sensitivity corridor of the

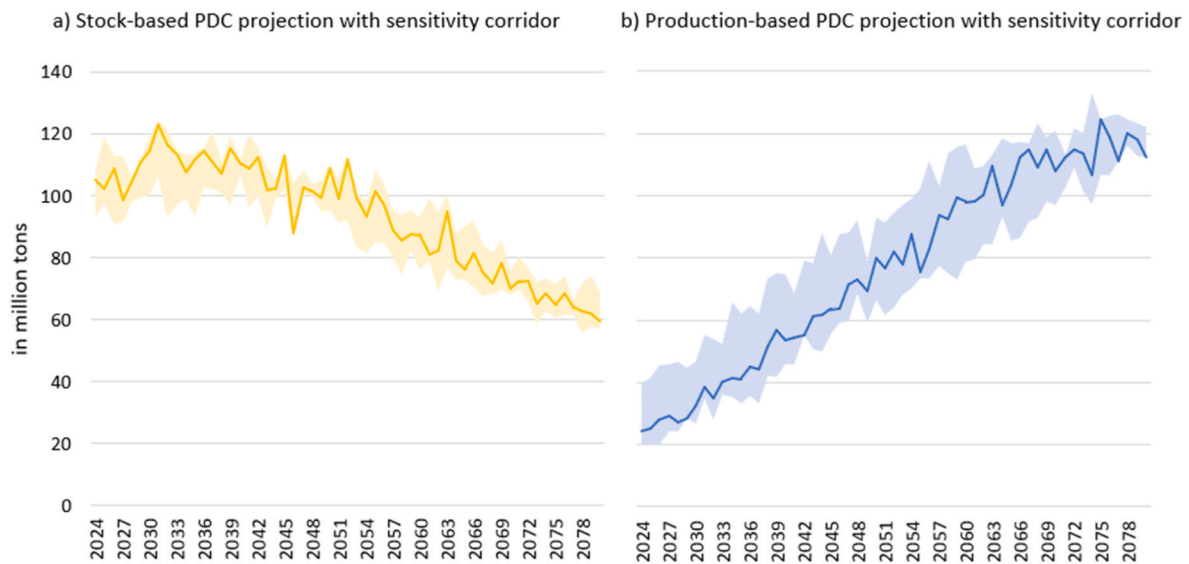


Fig. 9. PDC projections based on stock- and production-approach with sensitivity corridor.

minimal and maximal variations of the stock-approach, based on the analyzed parameters. This corridor shows  $\pm 20\%$  of the baseline scenario.

For the production-based approach (see Fig. 9 (b)), varying lifetime assumptions lead to comparable results (see SI-1.11). In the first decade of the projection period, lifetime variations can increase the estimated PDC by up to 50%. In subsequent years, the deviations remain significant, with variations of roughly  $\pm 20\%$  around the baseline scenario. These results highlight that lifetime assumptions have a substantial influence on both the absolute quantity and the temporal distribution of projected PDC flows.

#### 4. Discussion and limitations

Although national RC-concrete use remains limited, regional developments indicate growing potential (Staatsministerium Baden-Württemberg, 2023). In 2022, 75.3 million tons of recycled aggregates were used in Germany, covering 13.3% of total aggregate demand (Kreislaufwirtschaft Bau [KWB], 2024). This corresponds well with the projected RC-aggregate range for the study's focused time horizon, suggesting that the modeled PDC volumes are market-relevant. A projected 12% rise in available recyclate by 2040 is predicted (Schwarzopp et al., 2022). Similarly, the present analysis forecasts a minimum increase of 13% in RC-aggregate availability from 2024 to 2040, aligning with external projections such as the estimated 17% rise reported by Schwarzopp et al. (2022). Recent studies have also begun to assess the economic implications of using belit clinker for circular recycling pathways for specific construction materials, for example, in the case of autoclaved aerated concrete (Steins et al., 2026), highlighting the growing relevance of economic considerations for implementing circular construction strategies.

For contextual validation, approximately 191 million tons of non-hazardous CDW were generated in 2023 (Destatis, 2025b; Umweltbundesamt, 2025). Although these figures include broader mineral fractions, modeled 2024 PDC volumes fall within a plausible magnitude relative to national CDW flows.

Despite robust projections, key data gaps remain. Priority needs include harmonized infrastructure inventories, demolition registries, forensically referenced building stock data, and consistent district-level material flow reporting. Improved traceability tools such as digital material passports and mandatory demolition reporting would enhance planning reliability.

Spatial concentration of future PDC requires differentiated

strategies. High-volume regions (e.g., Hamburg, Berlin) may justify expanded stationary recycling capacity and recycled-content procurement policies, while lower-volume regions may benefit from shared logistics systems or mobile processing units.

In addition to quantity, material quality must also be considered. While the predicted substitution potential suggests significant material savings, strategies for circular concrete must consider potential compromises in mechanical properties, durability, and thermal behavior. An increased RC-aggregate content can affect strength development, modulus of elasticity, porosity, and long-term structural resistance, while alternative binders such as belite clinker can influence early-stage strength development and hydration heat. Circular construction must therefore strike a balance between material substitution and structural performance, durability requirements, and life cycle aspects, which requires performance-based mix design and strict quality controls to ensure safety and lifetime.

Long-term circularity is further constrained by multi-cycle degradation. Future PDC will partly consist of previously recycled concrete. Although secondary recycling is technically feasible, repeated processing may reduce material quality. While the present analysis implicitly assumes a one-to-one substitution of primary material, repeated recycling can lead to yield losses and quality-related limitations, thereby reducing the effective availability of high-quality recycled materials. Future research should therefore examine cascading use, multi-cycle LCA modeling, and quality-preserving recycling strategies.

#### 5. Conclusion

This study employed a multi-model approach combining waste, stock (including buildings and infrastructure), and production data to estimate future concrete waste generation at the NUTS-3 level in Germany until 2080. By integrating three complementary modeling logics, the approach captures structural uncertainties and provides spatially explicit projections of PDC availability. Overall, the waste-based approach is best understood as an empirically grounded lower-bound reference that reveals persistent limitations in available waste statistics, whereas the stock-based and production-based approaches are the primary basis for long-term strategic planning due to their greater structural and temporal resolution.

Annual PDC availability is projected to range between 37 and 109 million tons by 2030 and 33 and 117 million tons by 2080. Assuming a substitution rate of 35 (45)% of natural aggregate with RC-aggregate, up to 143 (112) million tons of RC<sup>2</sup>-concrete could be produced annually.

The available fine fraction would further enable partial cement substitution using 30% belite clinker, highlighting the material's relevance for both aggregate and binder replacement.

This study highlights the future availability of PDC as a secondary raw material, underscoring its potential to replace primary aggregates and Portland cement, conserve resources, and reduce CO<sub>2</sub> emissions. In particular, the spatially resolved PDC projections at NUTS-3 level offer a crucial basis for designing efficient and regionally optimized recycling logistics networks.

The spatially explicit results reveal strong concentration of projected PDC volumes. Metropolitan areas and infrastructure-intensive regions such as Hamburg and Berlin, and transport corridors like Emsland exhibit disproportionately high future PDC volumes. These regions may require early expansion of stationary recycling capacities, investment in advanced sorting and processing technologies, and stronger integration of recycled aggregates into local public procurement and construction markets. In contrast, regions with lower projected PDC volumes may benefit more from interregional cooperation, shared treatment facilities, and optimized transport logistics rather than large-scale permanent plants. Furthermore, projected temporal peaks suggest that flexible or mobile processing units could complement stationary infrastructure in regions with fluctuating demolition activity.

The results provide a quantitative basis for regionally differentiated investment planning, targeted recycling infrastructure development, and logistic optimization, thereby supporting strategic implementation of circular economy policies in the construction sector.

Despite the robustness of the multi-model approach, data gaps and structural uncertainties remain, particularly regarding lifetime assumptions, renewal rates, and regional allocation. Improved transparency and harmonization of national construction and demolition data are essential to enhance forecasting precision. Future research should refine lifetime modeling, integrate economic and policy dynamics, assess material flow conflicts, and further explore region-specific circular construction strategies.

### CRedit authorship contribution statement

**Antonia L.C. Frank:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rebekka Volk:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Rafael Bischof:** Writing – review & editing, Data curation. **Frank Schultmann:** Writing – review & editing, Supervision.

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used “OpenAI ChatGPT 5.1” to improve the formulation of English text and to condense selected sections of the text. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Antonia Frank reports financial support was provided by Federal

Ministry for Economic Affairs and Energy. Rebekka Volk reports financial support was provided by Federal Ministry for Research, Technology and Space. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2026.148446>.

### Data availability

Data will be available for download.

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