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Embodied greenhouse gas emissions in structural materials for the German residential building stock — Quantification and mitigation scenarios

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ABSTRACT

Embodied emissions in construction materials make a relevant contribution to carbon emissions worldwide. While this has been broadly recognised, only little attention has been paid to the role of load-bearing structures in this regard, and if so, mainly limited to assessments of individual structures. For analysing the global warming impact of engineering structures in a wider context, dynamic material flow analysis is deployed in this study. The future stocks and flows of structural materials and their associated embodied emissions in German residential buildings are quantified based on a mass-balance consistent multi-layer model, which relates the stocks in use, their inputs, outputs and determinants, such as the building lifetime, the population or the useful building floor area per capita. A scenario analysis under combination of different emission mitigation measures is performed, among them a gradual replacement of the comparatively large masonry structure stock share by timber structures, and a general downsizing of structural material quantities. The results show that when applied to a realistic extent, such measures could contribute with about 4% to 8% to the German average target mitigation rate required for achieving emission neutrality in 2045.

1. Introduction

Constructions consume large amounts of non-renewable resources, arable land, and energy, produce huge quantities of waste, contribute to pollution of air, water, and soil as well as to emission of greenhouse gases and hence global warming [1]. The latter aspect is of specific importance. It has been early recognised that the climate goals can most likely not be reached without emission reductions within the construction sector [2], which is estimated to be responsible for more than 20% of the total $CO_{2,eq}$ emissions produced by global economic activities [3,4]. To get the sector on track to achieving a net-zero carbon emission balance by 2050 as demanded by the Paris Agreement on Climate Change, it has been agreed that *embodied carbon* emissions in constructions worldwide – referring to the emissions associated with the extraction and manufacturing of materials and components, on-site construction and transport activities, as well as maintenance and end-of-life processes – needs to be reduced by at least 40 percent by 2030 [5].

Achieving this ambitious goal requires commitments from all actors across the construction sector value chain, which includes not at least the structural engineering community. Load-bearing structures contribute between 30 and 80% to the total embodied emissions of buildings [6–9], and they are totally dominant in transport infrastructures such as bridges and tunnels [10–13]. Considering such a significant impact, and given the large number of structures being designed and erected every day all over the world, the opportunity for a significant reduction of their global warming potential should not be ignored.

A number of different strategies, methods, and tools for the sustainability assessment of buildings have been developed in the last decades, often related to Life Cycle Assessment (LCA). However, the scope of LCA is mainly limited to comparative studies of different decision alternatives on the level of particular buildings or parts of them, see e.g. [14–18]. When widening the scope from a building to the scale of a country, or region, dynamic material flow analysis (MFA) is a well-suited method to determine the time-dependent material flows and stocks of the built environment and their associated environmental impact [19]. Several studies in different countries have proven this. Müller developed a generic dynamic MFA model and applied it for the diffusion of concrete in the future Dutch dwelling stock [20]. Based on this model, Bergsdal et al. analysed the material flows of the Norwegian dwelling stock [21], while Holck Sandberg and Brattebø later enhanced the scope to the corresponding energy and carbon flows [22]. Tanikawa and Hashimoto established a methodology to make use of GIS data to

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analyse the evolution of material stocks and flows and applied it to urban areas of the UK and Japan [23]. GIS data was also employed in the MFA conducted by Lederer et al. who quantified the stocks and flows of materials in the building stock of Vienna (Austria) [24]. Schiller et al. integrated bottom-up and top-down approaches to quantify the anthropogenic material stock in Germany, which is dominated by materials consumed by buildings and infrastructure [25]. In another study, Schiller et al. used a continuous MFA approach to analyse a closed-loop material cycle of bulk nonmetallic mineral building materials by considering the use of recycled aggregates in building elements [26]. The estimation of the material stocks in wooden residential buildings in Finland was the objective of a bottom-up MFA study by Nasiri et al. [27], while Lausselet et al. combined MFA and LCA to determine the material flows and associated embodied carbon emissions of neighbourhood buildings stocks in Norway [19]. Such emissions were also in the focus of the recent study by Berril and Hertwich, who developed a housing stock model for the U.S. [28].

As a common denominator, none of the quoted studies explicitly addresses structural materials, i.e. materials used in the load-bearing structure of a building. Only two, very recent MFA studies have been identified with such a focus. In a comprehensive study, Arehart et al. investigated the structural material demand and the associated emissions of the U.S. building stock [29], while D'Amico et al. analysed the global emission saving potential of cross-laminated timber floor systems in comparison to composite steel and concrete floors [30]. Exhaustive MFA studies addressing overall structural material flows and stocks in the European built environment are not available to date. This is considered a significant gap since such studies could provide rational decision support for the design of structure-specific strategies for the mitigation of embodied greenhouse gas emissions in the context of the European climate goals.

With the aim to contribute to close this gap, the goal of the study is to support strategic decision making through a quantitative systems analysis of the residential building structure stock in Germany, the country with the by far largest CO_2 emissions from fossil fuel combustion for energy use within the EU [31]. Both the historical and near-future flows and stocks of useful floor area in such structures are quantified based on a dynamic MFA model approach adopted from [20], in connection with a bottom-up classification of structures constituting the German residential built environment. On these grounds, the expected structural material quantities and the corresponding embodied emissions, associated with buildings to be erected in the coming decades (until 2070), are estimated. Future projections are based on a scenario analysis, where the benefits of potential strategies for emission mitigation are quantified and contrasted with current practices. The scenario definition addresses two principle strategies [32]: (1) a generalised reduction of material use, e.g. by means of optimised structural design procedures or service life extensions of existing structures [33–35] and (2) the use of materials with a lower carbon footprint, e.g. through replacement of demolished concrete or masonry structures by functionally equivalent timber structures, e.g. [29,30], whenever such a replacement is technically feasible, i.e. where the properties of timber allow for a structural design in alignment with the requirements to structural safety, functionality and durability. The results of the scenario analysis provide a sound basis for the assessment of the efficacy of such strategies to contribute to the German climate protection goal of achieving carbon neutrality by 2045 [36] and to inform corresponding policies in the structural engineering sector.

2. Methods

This section describes the methodology applied, including a description of the MFA model (Section 2.1), the employed data, adopted assumptions (Section 2.2), strategies and scenarios (Section 2.3).

2.1. Model

2.1.1. System definition

A multi-layer MFA system based on an earlier study by Müller [20] is defined (Fig. 1). Three layers (sub-systems) are distinguished, (1) the useable floor area in German residential buildings (UFA), (2) the structural material quantities used in such buildings (SMQ), and (3) their associated embodied CO_2-equivalent emissions (ECE).

Each sub-system involves a single process (rectangles), which represents the time- (t) dependent stocks in use, K(t), and their derivatives, dK(t)/dt, i.e. stock changes ΔK(t). Each process has an inflow I(t) and an outflow O(t) (solid line arrows). The former represent the units of UFA, SMQ and ECE (depending on the layer considered) entering the system when a new building is constructed. The latter refer to the units leaving the system as a consequence of demolition/decommissioning at the end of a building structure's lifetime, LT. The model assumes identical LT for building structures and the totality of their constitutive structural components (beams, columns, etc.), i.e. the possibility of replacement of specific components within the lifetime of a structure is not accounted for.

The UFA layer is split into $i = 1,2, \ldots, n$ different *types of structures* (s_i), distinguished according to the *main* construction material, e.g. *reinforced concrete structures*. The SMQ and ECE layer, in turn, distinguish $j = 1,2, \ldots, k$ different types of *materials* (m_j) constituting these structures, e.g. *concrete* or *reinforcing steel* – note that certain material types m_j may be found in several structural types s_i – e.g. the material *concrete* is not only present in *reinforced concrete structures*, but also e.g. in *masonry structures* (in the foundations or floor slabs).

The inflows of the SMQ and UFA layer are linked via the structural material intensities (SMI) per unit of UFA of structural type s_i. The link between the inflows of SMQ and ECE is established by the embodied emission intensities (CEI) per unit weight of material type m_j. The model equations are defined below.

2.1.2. Modelling equations

Stocks K(t) and stock changes ΔK(t) are linked via the intrinsic model Eq. (1).

$$\frac{dK(t)}{dt} = \Delta K(t) = K(t) - K(t-1) \tag{1}$$

The balance Eq. (2), defines stock change ΔK(t) as the difference between the in- I(t) and outflows O(t).

$$\Delta K(t) = I(t) - O(t) \tag{2}$$

The unit for the discretisation of time (t) is "years" (y). The year of building construction y_c is referred to as "cohort". Buildings are decommissioned/demolished in year y_d, i.e. the sum of y_c and the building lifetime, L. The lifetime, which can depend on y_c (see Section 2.2.4), is represented by a specific probability distribution function and its first two moments, i.e. mean value (μ_{LT}) and standard deviation (σ_{LT}). Integration of this function over t delivers the probability of survival $P_{surv}(t)$, i.e. the probability that a particular unit is still in use in a specific year when entering the system at $t = y_c$. The expected value of "survived" units $K_c(t)$ is then defined by Eq. (3) as a function of $P_{surv}(t)$ and inflows $I(t = y_c)$:

$$K_c(t) = P_{surv}(t) I(t = y_c) \tag{3}$$

The outflows $O(t)$ are computed by summing the differences of survived units in two consecutive years over all n_c cohorts:

$$O(t) = \sum_{c=1}^{n_c} (K_c(t-1) - K_c(t)) \tag{4}$$

The UFA and SMQ layer are coupled by means of Eq. (5). In particular, the inflows $I_{SMQ,m_j}(t)$ corresponding to a particular structural material m_j are expressed as the sum of the individual contributions $I_{SMQ,m_j,s_i}(t)$ of this material to each of the $i = 1,2, \ldots, n$ structural

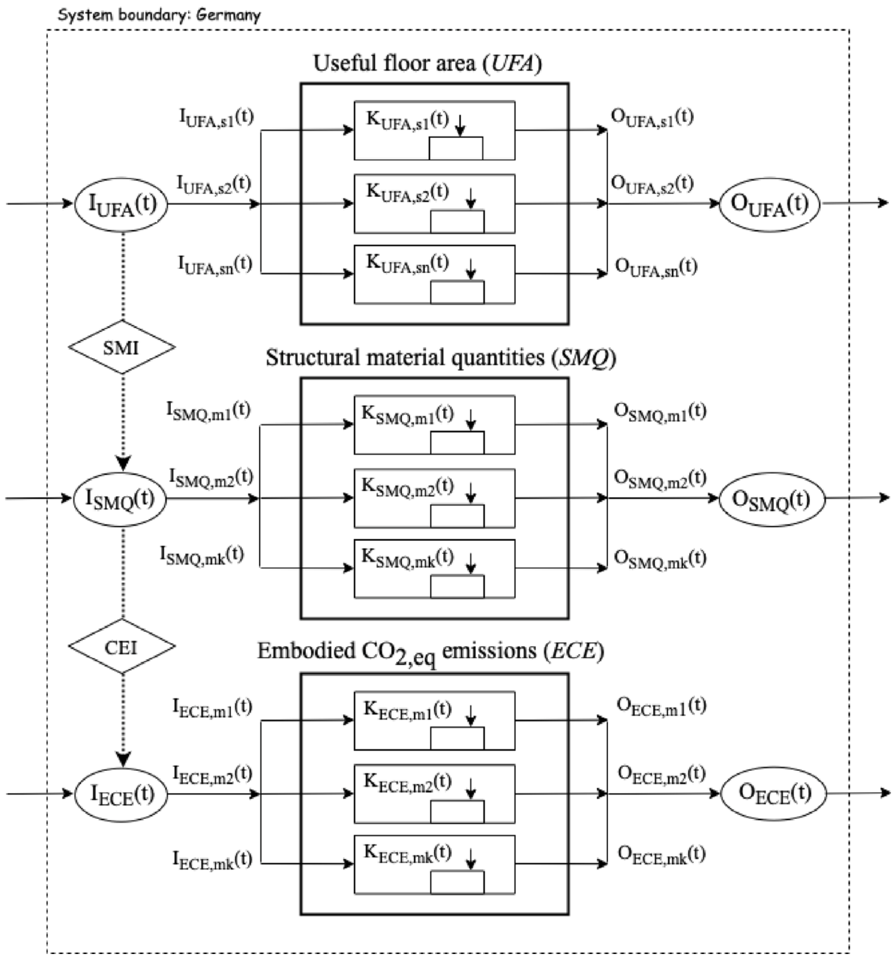

Fig. 1. MFA system definition.
Source: Adapted from [20]

types s_i included in the study. These individual contributions are given by the product of the inflows of useful floor area $I_{UFA,s_i}(t)$ of structural type s_i and the intensity SMI_{m_j,s_i} of material m_j per unit of UFA of s_i.

$$I_{SMQ,m_j}(t) = \sum_{i=1}^{n} I_{SMQ,m_j,s_i}(t) = \sum_{i=1}^{n}(I_{UFA,s_i}(t)SMI_{m_j,s_i}) \tag{5}$$

Finally, the link between the SMQ and the ECE layer is established through Eq. (6), which computes inflows of embodied carbon emissions of each of the $j = 1,2, \dots, k$ structural materials m_j by factoring the corresponding emission intensity CEI_{m_j} to the inflow $I_{SMQ,m_j}(t)$ of this material.

$$I_{ECE,m_j}(t) = I_{SMQ,m_j}(t)CEI_{m_j} \tag{6}$$

2.1.3. Drivers

Solving the previous set of equations requires knowledge (i.e. data) about the drivers of the system, usually the inflow I(t) or stock K(t). In this study, a combination of both approaches (inflow and stock-driven) is used as outlined below.

The availability of robust data on inflows of the UFA layer depending on the type of structure s_i, provides the basis for the inflow-driven approach adopted to quantify stocks and outflows for the historic observation period, from 1800 to 2021. However, this data is limited to the last 29 years of this period, namely 1993–2021. The inflows I(t) prior to 1993 are back-calculated based on Eq. (3) from the survived fractions $K_c(t = y^*)$ of the stock $K(t = y^*)$ in a specific year y^*.

The results of the inflow-driven model establish the grounds for the subsequently conducted stock-driven analysis to determine inflows and outflows for the future observation period, from 2022 to 2070. Following the approach in previous studies, e.g. [20–22], the expected stocks $K(t)$ are estimated as a function of the expected population $POP(t)$ and the expected average useful floor area per capita in German residential buildings, $(UFA/\text{CAP})(t)$, which both are time-dependent quantities.

$$K(t) = POP(t)(UFA/CAP)(t) \tag{7}$$

The data and assumptions underlying both approaches are described in Sections 2.2.2 and 2.2.3. Previously, Section 2.2.1 describes the split of layers UFA and SMQ/ECE into different types of structures s_i and structural materials m_j, respectively.

2.2. Data and assumptions

2.2.1. Structural types, components and materials

Structures of German residential buildings can be coarsely distinguished into $n = 3$ different main types (s_i): reinforced concrete structures (RCS), masonry structures (MS) and timber structures (TS). As shown further down, RCS and MS account for the vast majority of structures present in the current stock, while TS constitute a comparatively minor share. The contribution of other structural types, such as steel structures, to the German residential building stock is not significant, wherefore they are excluded from the study.

Fig. 2. Typical structural types for German residential buildings: Reinforced concrete structures (RCS); (b) Masonry structures (MS); (c) Timber structures (TS).

Building structures are constituted by different types of load-bearing components, among them *vertical* (e.g. columns, walls, cores) and *horizontal* (e.g. beams, slabs) components, in charge of transmitting the loads to the building *foundations*. A description of the principal components and their constitutive materials for the three distinguished structural types s_i is given below.

Reinforced concrete structures (RCS) are most frequently used for multi-storey buildings (Fig. 2a). They are mainly constituted by walls, columns and beams, supporting floor slabs and roof structure. In high-rise constructions, massive concrete cores accommodating elevator shafts and staircases may additionally be found to cope with lateral loads due to wind or earthquakes, see e.g. [37]. The principle materials used in RCS are concrete (C) and reinforcing steel (RS) — as a composite material referred to as reinforced concrete (RC).

Masonry structures (MS) are most often employed for the construction of single-family houses (Fig. 2b) although likewise used in low- and mid-rise multi-storey buildings. MS are characterised by load-bearing walls and columns made of bricks (B) (e.g. clay-based bricks, lime-sand bricks, pumice blocks, etc.) and mortar (M). However, basement walls in MS are often built in RC. While during many centuries executed in timber (T), RC is nowadays also the predominant material for floor systems in German MS (see Fig. 2b). However, as Fig. 2b shows, T is still frequently used for roof constructions of MS.

While timber structures (TS) have been applied for centuries in single-family houses in Germany, (Fig. 2c), their use in multifamily houses is gaining increasing attention. TS are constituted by solid or (cross- or glue-) laminated timber (T) components, including columns, beams, and slabs. In addition, RC is often employed for the erection of basement walls in TS. Steel quantities, e.g. used in connections or bracing systems of timber structures are comparatively small and will be neglected in this study.

Table 1 summarises the structural types s_i and their main constitutive materials m_j considered in this study, distinguished according to their use in vertical and horizontal structural components as well as the building foundations. Since the objective of the study is to quantify the future material and emission flows (Section 1), the classification disregards outdated construction methods and traditions. In this context it should be noted that historically, German residential buildings were mainly grounded on brick or stone foundations [38]. Nowadays, however, building foundations are normally made of RC, regardless of the main materials used for the erection of the above-ground structure.

2.2.2. Historical stock model

Data from the German Federal Statistical Office (DeStatis) on the annual values of the total useful floor area UFA_{tot} of new residential buildings between 1993 and 2021 is used [39], where subscript *tot* refers to the totality of residential buildings, i.e. the sum over all structural system types s_i. Only the living space ("Wohnfläche") is accounted for, i.e. areas for other types of use in residential buildings (e.g. a commercial area located at the ground floor) are disregarded and so are the corresponding materials. From a structural point of view such a distinction makes sense – the building use category determines the (imposed) load assumptions, which have a direct influence on the structural material quantities.

Table 1
Structural types s_i (RCS = Reinforced concrete structures, MS = Masonry structures, TS = Timber structures) and their main constitutive materials m_j (concrete (C), reinforcing steel (RS), brick (B), mortar (M), timber (T)).

Structural type s_i	*Vertical components*	*Horizontal components*	*Foundations*
RCS	C/RS	C/RS	C/RS
MS	B, M, C/RS[a]	C/RS[b], T[c]	C/RS
TS	T, C/RS[a]	T	C/RS

[a] Mainly in basement walls.
[b] Mainly in floor slabs.
[c] Mainly in the roof structure.

Table 2
Estimated survival fractions η [%] of the 1998 residential building stock distinguished into cohort periods cp (ranging from years y_{cps} to y_{cpe} with central value y_{cpc}) and structural types s_i (RCS = Reinforced concrete structures; MS = Masonry structures; TS = Timber structures).

y_{cps}	y_{cpe}	y_{cpc}	$\eta_{cp,RCS}$	$\eta_{cp,MS}$	$\eta_{cp,TS}$	$\eta_{cp,tot}$ [40]
1750[a]	1850	1800	0	3.1	1.3	16.0[b]
1851	1918	1885	0	11.0	0.7	
1919	1948	1934	1.2	12.2	0	13.4
1949	1978	1964	14.7	33.8	0	48.5
1979	1986	1983	1.4	8.2	1.2	10.8
1987	1998	1993	0.5	9.2	1.6	11.3
η_{tot,s_i}			17.8	77.4	4.7	100

[a] Assumes that the fraction of buildings in the 1998 stock constructed prior to 1750 is negligible.
[b] Fraction corresponding to cohorts <1918.

The annual inflows of the UFA layer split into structural types s_i, I_{UFA,s_i} (Fig. 1), are estimated by factoring the total area UFA_{tot} to the ratio of the annually constructed gross volume V_{s_i} of buildings of a specific type s_i, to the gross volume of the totality of residential buildings constructed in the same year (y_c), V_{tot}, see Eq. (8). Available data from DeStatis distinguishes V_{s_i} according to the "main material used in the load-bearing structure of the building" into RCS, MS, TS (Section 2.2.1), steel and "other" structures [39]. As mentioned above, due to lack of significance of the latter two, the present study only accounts for the former three. The UFA inflows corresponding to the period 1993 to 2021, estimated based on Eq. (8), are provided with the supplementary data to this publication (sheet A).

$$I_{UFA,s_i} = I_{UFA\_tot}(V_{s_i}/V_{tot}) \tag{8}$$

The inflows corresponding to the years 1800 to 1992 are obtained as follows:

Data from DeStatis [40] on the cohort-distribution of the German dwelling stock in year $y*$ =1998 is used, see last column in Table 2 — no such data prior to 1998 is available. The start and final year of the cohort-periods cp distinguished in [40] are denoted y_{cps} and y_{cpe}, respectively — see Table 2. As a representative value for these cohort periods, the central year, y_{cpc}, is provided.

The split of the 1998 stock into structural types s_i is inferred from data in Nemry et al. [38], where the dwelling stock of different EU countries, among them Germany, was represented by means of 24 representative building types. The classification considered a gross distinction of the main structural components and corresponding construction materials, the period of construction and the useful floor area (UFA). Based on this data, the survived fractions $\eta_{cp,s_i}(y^* = 1998)$ [%] of UFA in year $y^* = 1998$, corresponding to type s_i structures constructed in cohort period cp are estimated. The underlying calculations are provided in the supplementary data file (sheet B), submitted with this study. According to the results, displayed in Table 2, most of the buildings (almost 50%) among the 1998 stock are sustained by MS and RCS built between 1949 and 1978. With a total of approximately $\eta_{tot,MS} = 77\%$, MS constitute the by far highest fraction of the investigated stock, followed by RCS ($\eta_{tot,RCS} = 18\%$) and TS ($\eta_{tot,TS} = 5\%$).

Based on this stock classification, the inflows I_{UFA,s_i} corresponding to the cohorts 1800–1992 are determined as follows:

- The fractions η_{cp,s_i} shown in Table 2 are divided by the number of years constituting the corresponding cohort-period cp and linearly interpolated between the corresponding central year y_{cpc} of that period.
- The resulting annual average fractions η_{c,s_i} are scaled such that $\sum_{c=1750}^{1998} \eta_{c,s_i}$ equals the estimated 1998 stock share η_{tot,s_i} of the corresponding structural type $s_{(i)}$ (Table 2).
- The "survived" units $S_{c,s_i}(y^* = 1998)$ in the 1998 residential building stock are determined by factoring the annual average fractions η_{c,s_i} to the total useful floor area corresponding to that stock, $UFA_{tot,1998} = 3.089 \cdot 10^9 m^2$ [41].
- Based on the obtained $S_{c,s_i}(y^* = 1998)$, the inflows I_{c,s_i} corresponding to these cohorts are back-calculated by means of Eq. (3). The results of this procedure are presented in Section 3.1.

2.2.3. Population and floor area per capita

Fig. 3a shows observations of the German population (POP) between 1990 and 2022 in addition to different projections from 2023 to 2070 provided by DeStatis [42], depending on life expectancy, birth rate and migration balance (immigration–emigration). The three shown curves for the future period reflect projections based on "low", "moderate" and "high" expectations of these three parameters, respectively. In the present study, the "moderate" scenario will be adopted for the estimation of buildings stocks according to Eq. (7) between 2022 and 2070 (Section 3.2). The extreme scenarios will be used to analyse the sensitivity of the results with regard to population projections (Section 4.2).

The average useful floor area per capita (UFA/CAP), in German residential buildings between 1990 and 2022 is shown in Fig. 3b, calculated as the ratio of the total living space in a specific year (annual stock) to the corresponding population. A second order polynomial extrapolation of the observed (UFA/CAP) has been performed, which peaks in 2060 at a value of around 50 m^2/CAP, as shown in Fig. 3b - see [43] for a similar approach.

In addition to the POP and UFA projections, the stock-driven approach requires assumptions regarding the future split of the UFA layer into structural types s_i. These assumptions are defined in Section 2.3.

2.2.4. Lifetime

The building structure lifetime (LT) is a fundamental parameter in the present study. Long lifetimes will reduce the demand for new constructions and hence the use of primary resources and energy [21]. Previous studies have confirmed the sensitivity of the building stock evolution to the choice of the lifetime model, e.g. [44]. However, lifetimes of both buildings and their structures are still not fully understood [43]. The main reason for this are the manifold and interrelated influence parameters. Technical influences (e.g. type and properties of construction materials, the quality of building design and execution, exposure and loading conditions) play a major role, as do economical drivers and constraints [45–47]. Indeed, nowadays building lifetime is not seldom governed by financial obsolescence, i.e. in search for immediate economical profit, buildings are often replaced by new ones although their physical condition would still make lifetime extensions (e.g. through repair or maintenance) economically viable [48].

MFA models usually consider lifetime of buildings by means of a specific statistical distribution function and its parameters, e.g. [20,21,43]. In a stock-driven model for the analysis of energy reduction strategies in residential buildings in Germany, Vásquez et al. [43] varied the mean values μ_{LT} of the assumed normally distributed lifetime between 100 and 200 years, along with a coefficient of variation (CoV_{LT}) of 25%, to compute annual inflows in terms of UFA in such buildings. A comparison to observed inflows revealed the closest approximation for $\mu_{LT} = 150$ years, with only little differences within the interval 125 years < μ_{LT} < 175 years. The order of magnitude of these average lifetimes is consistent with the findings by Bohne et al. [49] for the Norwegian residential building stock. Evaluation of data on Norwegian buildings statistics led to $\mu_{LT} = 126$ years ($CoV_{LT} = 34\%$). However, buildings with a lifetime over 200 years were excluded from this evaluation.

In contrast to these results, typical ranges for *technical* lifetimes of different structural building components representative of constructions nowadays, given in [45], suggest lower average values. The provided data, which is indicated to depend on material quality and durability, different loading and exposure conditions of different structural building components and their execution quality and maintenance on site, allows for crude estimations of average values of approximately 100 years for concrete and brick components and 80 years for structural timber members. The CoV, which accounts for variability between different member types and exposure conditions, is of the order of 20%–34% (see supplementary data, sheet C). While, as stated above, actual lifetimes of building components are not exclusively influenced by technical factors, other studies offer certain evidence that the order of magnitude of the average values deduced from [45] appears to be a reasonable estimate of the μ_{LT} for recent constructions. Hassler and Kohler indicate an average lifetime of 80 to 100 years for constructions in Germany at the end of the 20th century [50]. Similarly, based on observed building service life data, Müller adopted in his study of the Dutch dwelling stock an average $\mu_{LT} = 90$ years for an assumed normally distributed LT ($CoV_{LT} = 22\%$) [20].

The previous considerations are supportive of a certain cohort-dependency of a building structure's LT, as discussed in previous studies. Bergsdal et al. [21], who studied the residential dwelling stock in Norway, assumed a decreasing lifetime of dwellings towards more recent cohorts, arguing that buildings constructed in the distant past were supposed to provide housing for several generations and thus designed for a longer functional lifetime than ones constructed today. Evidence for such decreasing lifetimes over time is provided by Kohler and Wang [51]. From their analysis of the survival functions of the German building stock, it appears that buildings of older cohorts have higher survival probabilities than comparatively more recent constructions. Also data on the average age of buildings at demolition in Zürich suggests time dependency of the building LT. Whereas an average age of more than 200 years was possible in the 19th century, the data suggested that the current average age at demolition is around 70 years [52].

Based on the described evidence, a decreasing μ_{LT} is adopted in the present study as shown in Fig. 4. The initial values (corresponding to the year 1800 for MS and TS; 1885 for RCS, i.e. shortly after RC had been invented and implemented in the German built environment [53]) characterising the assumed logistic function for μ_{LT}(t) are fixed to 175 years based on a sensitivity analysis presented in Section 4.2.3. The final values (for year 2070) are based on the provided data in [45], which are considered to give a realistic order of magnitude of average LT of today's constructions. As indicated above, $\mu_{LT,RCS} = \mu_{LT,MS} =$

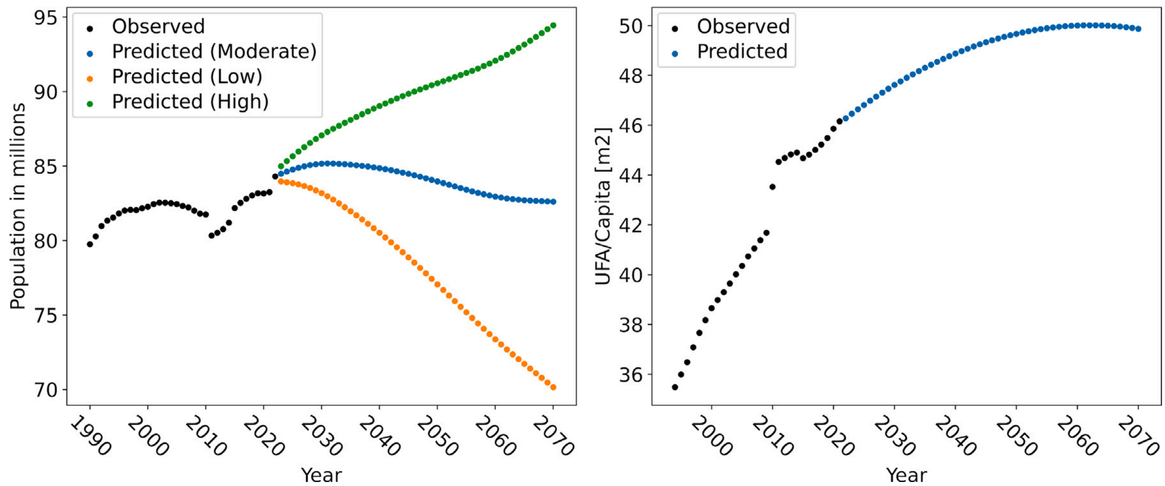

Fig. 3. Observations (1990–2022) and projections (2023–2070) of population (a) and UFA per capita (b) based on [42].

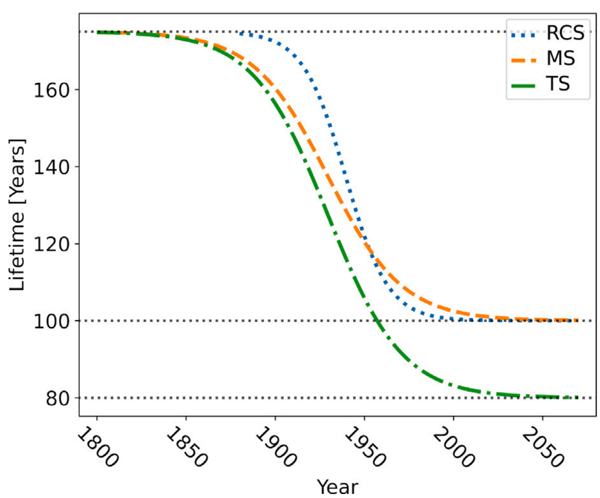

Fig. 4. Assumed distribution of average lifetimes μ_{LT} for masonry (MS), timber (TS) and reinforced concrete (RCS) structures.

100y, $\mu_{LT,TS}$ = 80y are adopted, thereby implicitly assuming a certain dependency of the LT on the type of construction material. As Fig. 4 shows, only scantly LT variations between the μ_{LT} for constructions nowadays and the year 2070 are assumed. The CoV_{LT} is kept constant (i.e. cohort-independent) at 25% throughout the study.

2.2.5. *Structural material intensities*

Material intensities (MI) specify the amount (weight) of a particular material per unit of area or volume of a specific reference system. The understanding of the reference system is of utmost importance for the purpose of a clear definition of MI and their interpretation. The reference system can obey to a very generic definition, such as "all buildings in a specific country", or to a rather specific one, such as "a multi-storey residential building with a RC frame structure". Likewise should the reference period be unequivocally indicated, since MI have been observed to be cohort-dependent, see e.g. [54], due to changes (over time) in construction technologies or standardisation procedures (e.g. structural safety and serviceability requirements), among others.

Another important aspect regarding the consideration of MI is their distinction into structural and non-structural contributions. Existing MI databases overlook such a distinction and provide overall material quantities, regardless of the technical function this material assumes within a building, e.g. [55–57]. However, such a distinction becomes relevant when the efficacy of structure-specific strategies for reduction of the environmental impact are to be assessed. While certain materials, such as e.g. concrete, fulfil primary structural functions in buildings [58], for others this assumption does not hold. Timber, for instance, is used for fabrication of structural members but also e.g. in claddings, floor planks, doors, windows and other building elements not regulated by structural design codes. The same applies to brick material, which may be found in both load-carrying and non-structural walls.

In this study, structural material intensities (SMI_{m_j,s_i}) in building structures of a specific structural type s_i (Section 2.2.1) are defined, e.g. the intensity C_{RCS} of concrete (C) in load-carrying members of a reinforced concrete structure (RCS); or the intensity C_{MS} of concrete (C) in load-bearing members of a masonry structure (MS), according to the distinction of structural materials m_j in Table 1. Table 3 offers an overview of material intensities (in *tons* of material per m^2 of UFA), adopted or inferred from different studies in European countries, that comply with such a definition. After their careful interpretation (see sheets D1–D5 in supplementary data file for further information on the background of the given values), the *best-estimate* values for SMI_{m_j,s_i} shown in the bottom line of Table 3 have been defined for use in the present study. These values should be understood as coarse, weighted averages for structures of all German residential building types (e.g. single-family houses, multi-family houses) as built nowadays, i.e. representative of *current practices*.

Table 3
Material intensities [t/m^2 of UFA] for concrete (C), brick (B), mortar (M), timber (T); RCS = Reinforced concrete structures, MS = Masonry structures, TS = Timber structures.

Study	*Country*	*RCS*	MS				TS	
		C	*B*	*M*	*C*	*T*	*T*	*C*
[59]	Central EU	1.44	0.61		0.94	–	–	–
[54]	Germany	1.48	–	–	–	0.06	–	–
[60][a]	Sweden	1.20	–	–	–	–	0.05	0.35
[23][a]	UK	–	0.50	0.21	–	0.07	–	–
[61][a]	UK	0.62[b]	–	–	–	–	0.12	–
SMI_{m_j,s_i}	Germany	1.4[c]	0.45	0.2	0.9[c]	0.06	0.10	0.35[c]

[a] An average conversion factor of UFA/GFA = 0.677, inferred from data in [62], has been used to convert material intensities based on the gross floor area (GFA) to the useful floor area (UFA).

[b] Only gravity load-resisting structure.

[c] An average reinforcing steel (RS) intensity of 9% of the concrete intensity is assumed based on data in [23,37,54,61].

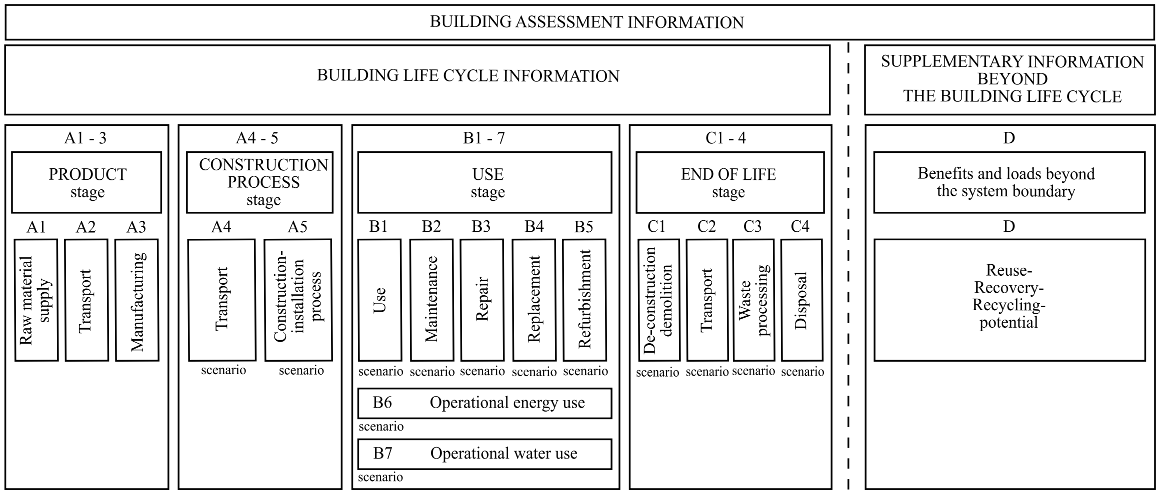

Fig. 5. Life cycle stages according to [63].

Table 4
Carbon emission intensities (CEI) [$kgCO_{2,eq}/kg$] used in this study.

Material	EPD	Life cycle stage	
		A1–A3	C3
Concrete (C)	[64]	0.102	0.001
Reinforcing steel (RS)	[65]	1.230	0.004
Timber (T)[a]	[66]	−1.265	1.613
Brick material (B)[b]	[67–70]	0.212	−0.004
Mortar (M)	[71]	0.073	N.D.[c]

[a] Cross-laminated timber.
[b] Weighted average for fired clay brick, sand-lime brick, aerated concrete and pumice blocks.
[c] Not declared in the EPD.

2.2.6. Embodied emission intensities

Embodied carbon emission intensities (CEI) of construction materials are usually determined based on LCA and specified in Environmental Product Declarations (EPD), see e.g. [34]. According to EN15978 [63], a construction work's life cycle (LC) can be divided into three principle stages, the product- and construction stage (module A), the use stage (module B) and the end-of-life (EoL) stage (module C), — see Fig. 5. Additionally, potential benefits and loads beyond the end of the construction's LC may be considered (module D).

The CEI used in this study are adopted from EPDs for materials representative of German construction sites (Table 4). The study accounts for the production stages A1–A3, and the EoL stage C3. Given their relative importance and the comparatively high certainty about the related CEI, the production stages should be in the focus of any carbon reduction efforts related to structures [34]. Emissions related to stage C3 are included to account for the re-emission into the atmosphere of biogenic carbon upon incineration of timber components following the end of structural service life – see Section 4.2.1 for a discussion of the temporal shifts between the actual and the modelled emissions, this assumption may imply. Loads and benefits from module C3 for other materials than T are insignificant (Table 4).

Emission intensities can change significantly over longer time periods (e.g. due to improvements of energy efficiency, a lower carbon intensity of the energy, etc.), e.g. [19]. However, making robust predictions about the evolution of the CEI up to 2070 is extremely difficult. For sake of simplicity, the study considers time-independent CEI. The implications of this assumption for the results and conclusions of this study are discussed in Section 4.2.2.

2.3. Strategies and scenarios

2.3.1. Strategies

Measures for the mitigation of embodied greenhouse-gas emissions in structures can be generally classified into one out of two main strategies [32]: (1) to use structural materials with a lower environmental footprint as compared to those employed in current practice; (2) to reduce the (structural) material quantities (SMQ):

- Substitution of pollutant materials (Replacement — RP)
  The replacement of structural materials with a large CO_2 footprint can be principally achieved in two different ways. One is the replacement by materials of the same type, but with improved environmental properties, such as e.g. the design of low-carbon concretes, e.g. [72]. The other possibility is the substitution by different materials. Several studies have identified clear environmental benefits of timber in comparison to other structural materials [16,30,73–76]. The present study explores the substitution of masonry structures (MS) by timber structures (TS). MS are the preferable substitution object not only because they constitute the by far largest share among the structural types of German residential buildings. Also their common use for single family or low-rise multi-family houses (Fig. 2), makes MS ideal objects for replacement with TS.
- Reduction of SMQ (Downsizing — DS)
  Different opportunities for achieving a reduction of the SMQ in buildings exist, a strategy also referred to as “downsizing” or “lightweight design” [33,57,77]. Significant scope for savings of emissions is given in the conceptual design stage of structures through an optimised system geometry and choice of constitutive structural components [34]. Additional potential is provided by optimisation of the detailed structural design (i.e. dimensioning of components and their cross-sections), e.g. in form of adaptations of cross-section geometries to the flow of internal forces [77] or the application of enhanced, risk and reliability-based structural design methods [32,35]. Such methods can also efficiently contribute to lifetime extensions of existing structures. Also the reuse of individual structural components in new structures, provides opportunities for reduction of SMQ, see e.g. [78,79].

2.3.2. Scenarios

The pathways of three hypothetical scenarios regarding future policy actions in the structural engineering sector are defined and evaluated in this study:

- Baseline scenario: Current practice (CP)
In current structural engineering practice, decisions on the sustainability performance of constructions are in many cases at the mercy of the client [80]. The client's interests, in turn, are mainly governed by cost-efficiency, usually pursuing short-term profit by minimising the initial investment (construction costs). Environmental concerns are seldom accommodated in such thinking [48]. Although methodologies and procedures for quantifying the environmental impact of structures are by now available, mostly related to LCA, these are far from a broad and efficient implementation in daily structural design procedures [81]. The baseline scenario represents this description of "Current practice".
- Moderate Action (MA)
The moderate action scenario assumes that the current German climate protection plan to move towards a carbon-neutral society [81] will translate into coordinated, although "moderate measures", affecting the structural engineering sector. Given the strong evidence of the environmental benefit of timber as primary structural material 2.3.1, one of these measures consists of a gradual replacement of the inflows (UFA) of MS by functionally equivalent TS, varying from 0 in 2022 (last year of historical observation period) to 40% in 2070 (measure *RP40*. In addition, a 10% average downsizing of structural members is assumed, i.e. a general reduction of the SMQ with respect to CP levels, regardless of the material type (measure *DS10*). Since procedures and technologies that would enable such a reduction are already available 2.3.1, an immediate implementation of this measure is assumed.
- Strong Action (SA)
In a more optimistic scenario it is assumed that the urgency for climate action in the structural engineering sector is fully recognised among decision-makers. This will trigger the release of strong environmental policies, which are reflected in: a substitution of up to 80% of new MS by functionally equivalent TS by 2070, assuming a linearly increasing substitution rate between 2022 and 2070 (measure *RP80*), plus an immediate 20% average downsizing of SMQ with respect to CP levels (measure *DS20*). A substitution of 80% of the MS inflows in favour of TS entails a potentially strong impact on the material industry (see Section 4.1.2), wherefore larger substitution rates are considered unrealistic. The 20% SMQ reduction is considered to be within the limitations of technical feasibility, e.g. [34,82].

3. Results

The results of the study are presented separately for the historic- (Section 3.1) and future observation period 3.2.

3.1. Historic observation period

Fig. 6a shows the historical inflows I_{UFA,s_i} versus time. The dashed lines represent the back-calculated inflows for the period 1800–1992 (Section 2.2.2). In line with the results given in Table 2, MS make the highest contribution to the total inflows, followed by RCS and TS. The inflow of RCS starts with a smooth increase by the end of the 19th century, just after this composite material had been implemented in Germany [53]. At this time, the construction of MS experiences a significant increase, what is in line with the start of industrialised brick production in the second half of the 19th century [83]. The most significant increase in the historical inflows of both MS and RCS starts in the 1930's, peaks in the 1960's, followed by a continuous decline until the 90's. TS, on the contrary, do not experience notable inflows until the 1960's, reaching a peak around two decades years later.

The continuous lines in Fig. 6a reflect the inflows I_{UFA,s_i} between 1993 and 2021, based on official data provided by DeStatis (Section 2.2.2). Note that the 1993 inflows are of the same order of magnitude as the back-calculated 1992 values. The differences between both are within the order of magnitude of the visible short-term oscillations affecting the observed values.

Fig. 6b displays the evolution of the stocks K_{UFA,s_i} between 1800 and 2021. A continuously increasing stock since 1800 can be observed, what is in line with the stock-driven model results by Vásquez et al. [43]. Until the 1940's, MS constituted up to 90% of the total stock. At that time, significant stocks of RCS started to accumulate, progressively reducing the share of MS to approximately 78% in 2021. The stock of TS did experience comparatively slight changes only. By 2021, it accounted for less than 5% of the total. A comparison of the modelled total stocks to data from DeStatis [41] for years 1993 yo 2021 (red stars) reveals a good agreement, especially until 2010. Note that in the mentioned year, the DeStatis data displays a significant and abrupt stock change. The origin of this could not be clarified but it is believed to correspond to some kind of procedural change in the DeStatis estimation of existing dwellings and/or their corresponding UFA. The likewise relatively strong increase of the observed inflows in 2010 (Fig. 6a) does not fully explain this abrupt change in the stocks.

3.2. Scenario analysis

3.2.1. Baseline scenario

In consequence of the mismatch between the observed and modelled stocks at the end of the inflow-driven assessment of the historic evaluation period (2021) – see Fig. 6b – the first year of the subsequent stock-driven analysis (2022) is unavoidably characterised by a large, unrealistic stock change. The results for the subsequent years 2023 to 2070 are not significantly affected by this, however. These are shown in Fig. 7. Fig. 7b shows the evolution of the UFA stock (K_{UFA,s_i}), assuming current practice conditions (baseline scenario CP). Only slight stock-changes can be observed, with a maximum stock accumulation of approximately 4170 Mm^2 of UFA at around 2050. The corresponding inflows, in turn, shown in Fig. 7a, reflect a declining demand for new constructions in the coming decade, followed by around two decades of almost constant total inflows of the order of 27 Mm^2/year. Towards the end of the evaluation period, the demand for new residential constructions experiences a considerable increase, with expected total UFA inflows of approximately 38 Mm^2 in 2070.

The expected SMQ corresponding to new residential constructions (I_{SMQ,m_j}) in the period 2023–2070 according to the baseline scenario (CP) are depicted in Fig. 8a. With an accumulated amount of approximately 605 Mt from 2023 to 2045 (Table 5) – period of interest with regard to German climate goals (see Section 4.1.1) – concrete (C) makes the highest contribution to the SMQ, in spite of the comparatively low share of RCS among the total inflows of the UFA layer (Fig. 7a). This can be attributed to the relatively high SMI for C (Table 3) and to the significant amounts of C used in floor systems, basement walls and foundations of MS, see Sections 2.2.1 and 2.2.5. Since MS have the by far highest share among new constructions (Fig. 7a), substantial inflows of brick material (B) (222 Mt from 2023 to 2045) and mortar (M) (98 Mt) are also expected. In contrast to this, reinforcing steel (RS) and timber (T) have a comparatively low share among the total SMQ. Altogether, the model predicts a need for 1012 Mt of structural materials for the construction of new residential buildings between 2023 and 2045 (Table 5).

Fig. 8b shows the inflows of embodied carbon emissions (ECE), I_{ECE,m_j}, which are expected if current practices are extended until 2070. While in 2023 the total emissions amount to almost 11 Mt/year $CO_{2,eq}$, they are foreseen to fall to approximately 8 Mt/year at the end of the coming decade. In the second half of this century, ECE are expected to increase substantially, until reaching a maximum value of nearly 12 Mt/year $CO_{2,eq}$ at the end of the evaluation period in 2070. Altogether, approximately 194 Mt $CO_{2,eq}$ of mainly production-related ECE are expected to be embodied in structural materials of German residential buildings between 2023 and 2045 (Table 5). In spite of its

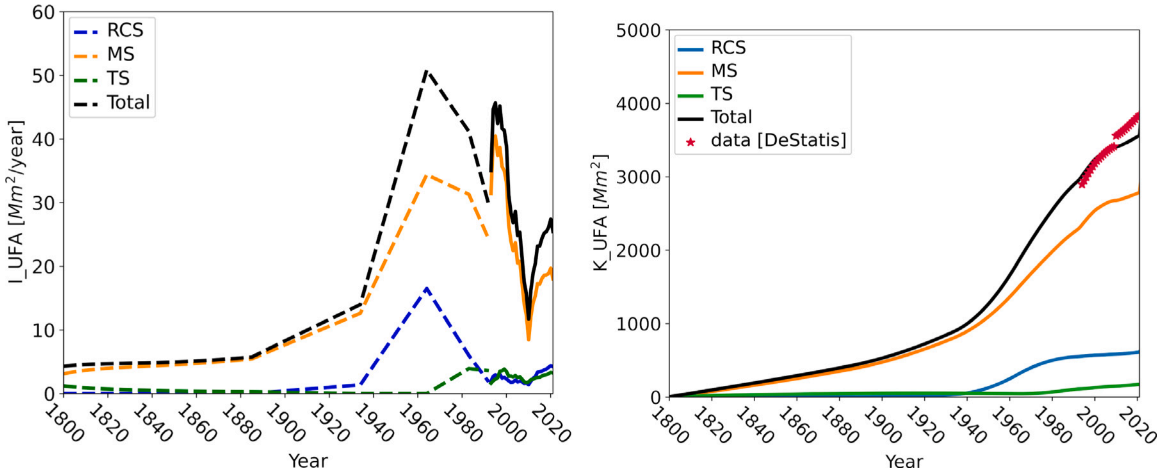

Fig. 6. (a) Inflows I_{UFA,s_i} (left) and (b) Stock K_{UFA,s_i} (right) of UFA for period 1800–2021; RCS = Reinforced concrete structures, MS = Masonry structures, TS = Timber structures.

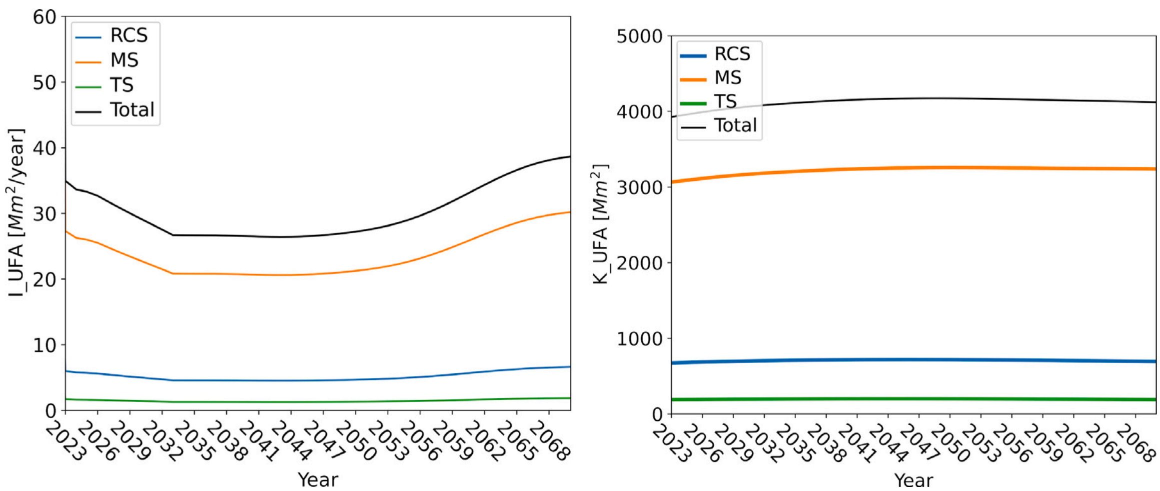

Fig. 7. (a) Inflows I_{UFA,s_i} (left) and Stocks K_{UFA,s_i} (right) for period 2023–2070; RCS = Reinforced concrete structures, MS = Masonry structures, TS = Timber structures; CP scenario.

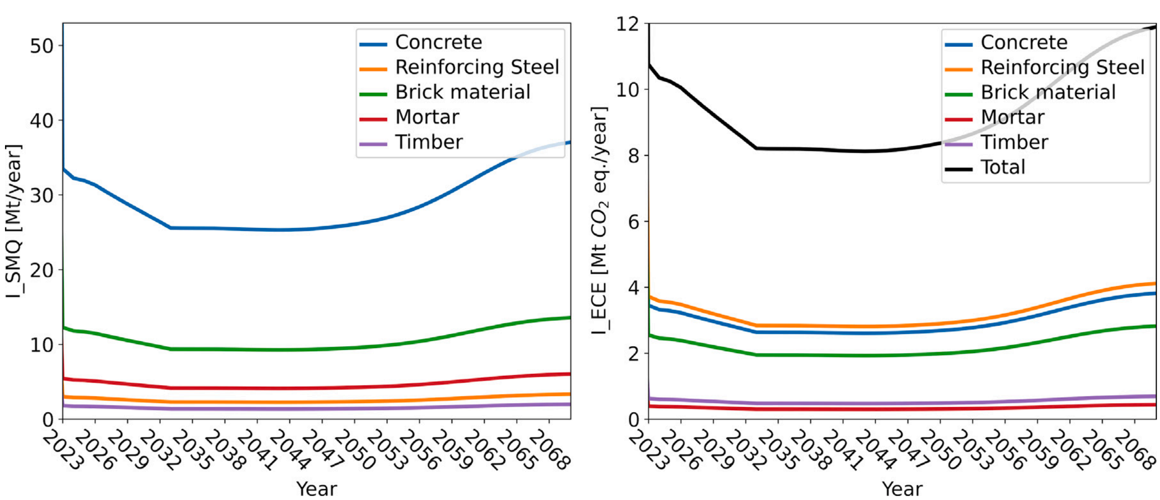

Fig. 8. (a) Inflows I_{SMQ,m_j} (left) and (b) Inflows I_{ECE,m_j} (right) for period 2023–2070; CP scenario.

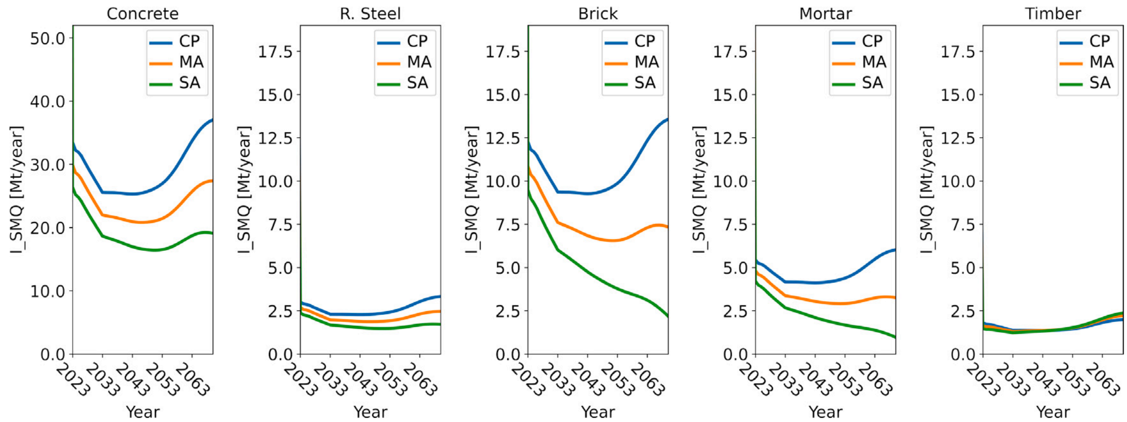

Fig. 9. Inflows I_{SMQ,m_j} for period 2023–2070; Scenarios: CP = "Current practice" (baseline), MA = "Moderate Action", SA = "Strong Action".

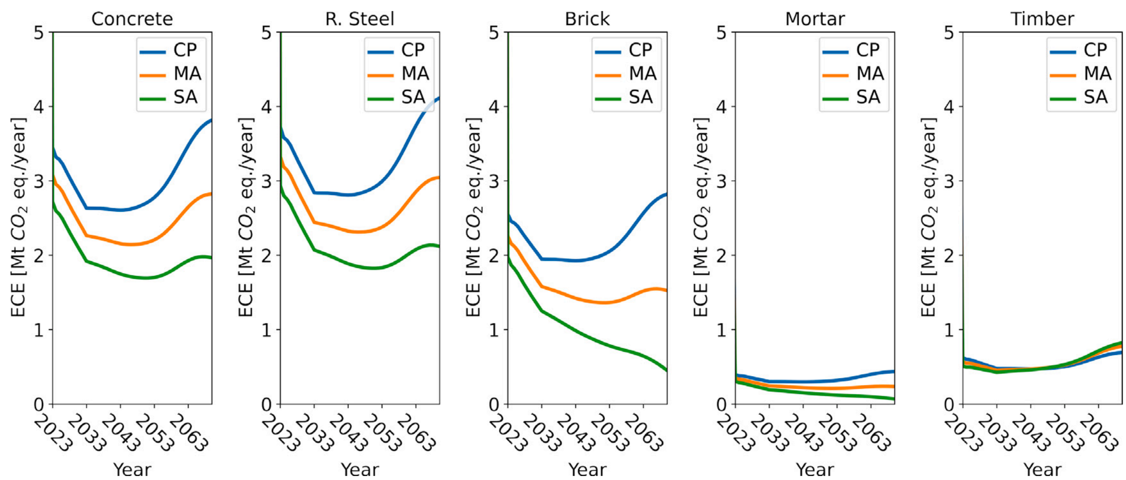

Fig. 10. Inflows I_{ECE,m_j} for period 2023–2070; Scenarios: CP = "Current practice" (baseline), MA = "Moderate Action", SA = "Strong Action".

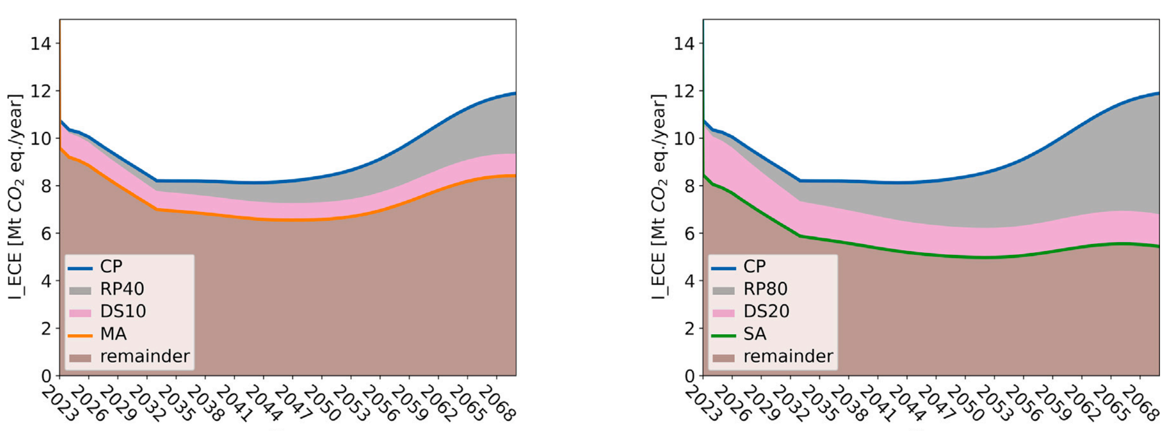

Fig. 11. Inflows $I_{ECE,tot}$ for period 2023–2070; Comparison of CP = "Current practice" (baseline) scenario to (a) MA = "Moderate action scenario" (left) and to (b) SA = "Strong action scenario" (right); Replacement measures RP40/80 = gradual replacement of 40%/80% of new MS by TS; Downsizing measures DS10/20 = general material intensity reduction of 10%/20% for all materials.

rather small share among the SMQ (Fig. 8b), RS (67 Mt) assumes the largest contribution (approximately 35%), what is attributable to the relatively high carbon emission intensities of this material (Table 4). With respectively 32% and 24%, C and B likewise represent significant shares among the total ECE embodied between 2023 and 2045, whereas the contribution of T (6%) and M (4%) is far less important.

3.2.2. Mitigation scenarios

Inflows for SMQ (I_{SMQ,m_j}) and associated ECE (I_{ECE,m_j}) corresponding to the CP, MA and SA scenarios (Section 2.3.2) are compared in Figs. 9 and 10 for each of the analysed materials m_j. As expected, the SMQ and ECE of all materials, except T, decrease in consequence of the assumed emission mitigation measures characterising the MA and

Table 5
Sum over inflows of expected structural material quantities (I_{SMQ,m_j}) and corresponding production-related carbon emissions (I_{ECE,m_j}) in years 2023–2045; Scenarios: CP = "Current practice" (baseline), MA = "Moderate action scenario", SA = "Strong action scenario".

Material	I_{SMQ,m_j} [$10^6 t$]			I_{ECE,m_j} [$10^6 tCO_{2,eq}$]		
	CP	MA	SA	CP	MA	SA
C	605	521	442	62	54	45
RS	54	47	40	67	58	49
B	222	180	143	46	37	30
M	98	80	63	7	6	5
T	33	31	29	11	11	10
Total	1012	858	717	194	165	139

SA scenario. With approximately 19% (MA) and 35% (SA), the decrease of the accumulated SMQ and associated ECE between 2023 and 2045 with respect to the CP scenario is most significant for B and M, followed by C and RS with reductions of the order of 13% (MA) and 27%) (SA) — absolute numbers are given in Table 5. Contrarily, T quantities and emissions are only scantly affected by the implementation of the mitigation scenarios, attributable to the opposite effects of downsizing (DS) and replacement (RP) measures — in contrast to the latter, the former diminishes the amount of T.

Fig. 11 compares the total emissions $I_{ECE,tot}$ (sum over all materials) for the CP scenario to those corresponding to the MA (a) and SA (b) scenario. The underlying mitigation measures lead to a decline of ECE accumulated between 2023 and 2045 of approximately 14.7% (MA) and 28.4% (SA). In addition, the figure offers insight into the contributions of the individual mitigation measures. Gradually replacing the MS inflows by functionally equivalent TS until 2070, as assumed under the MA/SA scenario (measures RP40/RP80), entails overall emission reductions between 2023 and 2045 of approximately 5.2%/10.5%, significantly below the approximately 9.5%/17.9% reductions obtained through the downsizing measures (DS10/DS20). Note that the DS reductions remain slightly below the nominally envisaged 10%/20%, given that the downsizing of the SMQ is performed *after* applying the RP measures. Fig. 11 also clearly shows that towards the end of the evaluation period the RP measures gain substantially in importance with respect to the time-independent DS measures.

4. Discussion

The discussion of the results is divided into an evaluation of potential policy implications (Section 4.1) and an analysis of the uncertainties and limitations characterising the study (Section 4.2).

4.1. Policy implications

4.1.1. Emission mitigation potential in the context of german climate goals

The results of the scenario analysis presented in the previous section suggest a generally significant potential for the mitigation of ECE in structures of German residential buildings. To put the presented numbers into a broader perspective, their comparison to the total carbon emissions in Germany and to the emission mitigation goals put forward by the German authorities is necessary. According to the latest climate protection report issued by the German government [36], Germany emitted in 2021 around 762 Mt $CO_{2,eq}$. Although tendentiously German emissions are diminishing over time, the cited report stresses the need for a significantly increased mitigation rate compared to current practices, if the main climate goals, which are in line with the Paris agreement, are to be achieved: emission neutrality until 2045 and negative emissions beyond 2050.

Taking the German 2021 emissions (762 Mt) as a basis, achieving climate neutrality until 2045 would require an annual average mitigation rate of around 30.5 Mt$CO_{2,eq}$/year. This figure can be related to the findings of the present study. With average mitigation rates of approximately 1.3 and 2.4 Mt$CO_{2,eq}$/year (calculated on the basis of the accumulated emissions between 2023 and 2045 shown in Table 5), the herein analysed MA and SA scenarios would contribute with respectively around 4.1% and 7.8% to this requirement. Taking into account the manifold opportunities for $CO_{2,eq}$ emission reduction across different sectors (energy, traffic, building, industry, agriculture, etc.), these potential contributions are to be judged as significant. Further opportunities for enhancing these numbers is given by widening the scope of structural ECE mitigation measures to non-residential buildings, which, in terms of UFA, have been estimated to account for approximately 45% of the total German building stock (in 2010) [84], and to other types of engineering structures, such as e.g. transport or energy-infrastructure, etc. Available statistics, which show an almost equal use of cement quantities in these three sectors (residential, non-residential, other civil engineering infrastructure) [85], suggests that such a scope extension would increment ECE from structural concrete substantially with respect to the findings of the present study. In addition, it would account for the comparatively large ECE mitigation potential in steel and composite (steel and concrete) structures, which account for a substantial share among both non-residential building structures [84] and bridges [13].

4.1.2. Required actions and corresponding challenges

Among the manifold emission mitigation measures implemented or proposed in the German climate protection plan, resource efficiency and -substitution, new construction techniques and materials as well as the sustainable use of wood is promoted (see measures 3.4.4.3, 3.4.4.4, 3.4.7.4 in [36]). Yet it is unclear and too early to judge to which extent these measures will change current practices in the structural engineering sector and what will be their efficacy.

Fundamental to a broad and systematic implementation of any measure, however, is their appropriate standardisation. The design and assessment of structures is regulated by normalised and compulsory applied decision rules in structural codes and standards, such as the Eurocodes, which largely regulate the use of structural materials and their corresponding quantities. Sustainability objectives have not been explicitly considered in the conception of these rules. Achieving a substantial downsizing (DS) of SMQ at a systemic level, as supposed in the analysed mitigation scenarios (SA/MA) calls for appropriate modifications to these rules, e.g. through an optimisation of the safety factors used in daily structural design or by enabling the use of performance-based design approaches and advanced structural safety concepts [35]. In addition, the scope of the decision rules should be extended from the detailed structural design stage (i.e. dimensioning of components) to the conceptual structural design stage, which includes also the choice of the main structural materials, in the present study addressed in form of the replacement measures (RP), which do not require any technological development nor upskilling of current practices, thus making it an immediately viable solution to accelerate decarbonisation [30]. Any efforts in this direction should be preferably aligned with existing standards for LCA of constructions, e.g. [63]. Given that standardisation procedures in the structural engineering sector are generally long-lasting and tedious, authorities are advised to accelerate such procedures while providing additional (economic) incentives for the adoption of climate-friendly solutions in daily structural engineering practice. In the absence of such actions, a substantial, short-term emission mitigation is considered unlikely to be achieved.

The implementation of structure-specific measures implies also important challenges for the industry. Material production quantities, which even under the baseline (CP) scenario are expected to suffer a considerable decrease in the coming decade followed by a stagnating period until mid-century (Fig. 9), would be substantially altered. For the herein defined MA and SA scenarios, the brick material industry would be necessarily the most affected. Under the SA scenario, for example, the production of this material would experience a maximum decrease with respect to the CP scenario of approximately 84% in 2070. Contrarily, the timber industry would benefit from increased production quantities, although limited to a maximum of about 20% (SA scenario, in 2070). Generally, increased demands for timber might compete with limited wood resources, see e.g. [86]. Wood resources are becoming popular for all kinds of climate mitigation strategies, including carbon sequestration in forests (harvesting less), in buildings, in soil (biochar), to replace fossil energy carriers, and to substitute for coke as a reduction agent in the processing industry. An efficient and sustainable management of such resources is therefore of crucial importance, see e.g. [87]. In addition, other climate-friendly structural materials than timber should be promoted as replacement options for conventional brick or concrete structures. The use of unfired bricks is a good example thereof. The recent release of the new DIN 18940 standard, which is compatible with Eurocode 6, enables for the first time a standardised design of load-bearing masonry structures with such low-carbon footprint bricks of up to 4 storeys [88].

4.2. Uncertainties and limitations

4.2.1. Model definition

Model uncertainties involve those related to the definition of the MFA model (Section 2.1.1). Certain simplifications have been introduced in this regard. For instance, the model neglects the possibility of material recycling and energetic recovery. Concrete, for instance, can be recycled for the purpose of road constructions while the incineration of timber at the end of a structural life-cycle generates heat and power, thus contributes to climate change abatement through substitution of fossil fuels. Also the possibility of reuse of specific structural components has been disregarded in this study, with potentially high environmental benefits due to a reduced need for new materials and products, see e.g. [89–91]. For capturing such benefits with certain accuracy, explicit modelling of EoL processes and flows would seem crucial. Only then we could determine embodied emissions when and where they occur. Allocating the benefits or costs for consequences that are appearing in different time frames to the place and time of construction (i.e. the inflows) only, by considering module D carbon emission intensities (see Section 2.2.6), would lead to an inaccurate temporal emission profile of only little meaningfulness for the design of climate change mitigation policies.

An expansion of the system boundaries of the MFA would also allow for a representation of carbon sequestration in timber, and to a minor extent also in carbonated concrete [92]. The CO_2 is absorbed by trees (biogenic carbon uptake) several decades or even centuries before it is released to the atmosphere after building demolition. In this sense, the assumption of a zero biogenic carbon balance, through allocation of this release to the inflows (via the CEI corresponding to LC stage C3, see Table 4), is a simplifying and conservative approach, i.e. emission savings of the RP measures would be expected to be larger than shown in Fig. 11 if the temporary profile of biogenic carbon effects would be modelled with a higher degree of accuracy. However, in addition to a clear allocation of emissions to, respectively, in- and outflows of timber constructions, such modelling would also require the consideration of forestry dynamics and policies within the scenario analysis (see e.g. [87]), what exceeds the scope of this study. We need to cut emissions by 2050 and the herein found results clearly show that replacement of structural brick material and concrete by timber can be an efficient measure for achieving this goal, even when neglecting the benefits of carbon sequestration in timber (and concrete). The results of other dynamic stock models with focus on structural materials confirm this finding [29,30].

The fact that our study focuses on structural materials is innovative and pretends to contribute to the establishment of a sound scientific argumentation basis for convincing decision makers of the benefits of implementing specific measures to cut down material consumption and embodied emissions in structural design procedures. But at the same time, the scope limitation to structural materials can be perceived as a lack of comprehensiveness that might distort the comparison of materials consumed and their associated emissions between different structural types. For example, the herein determined benefits of using timber frame structures might be even larger if also non-structural building envelopes including their insulation materials would be accounted for in the comparison. Prefabricated straw-bale walls with load-bearing structural timber components, for instance, have shown to dispose of a high carbon storage potential over relatively long lifetimes, see e.g. [93,94]. This example underlines that the influence of non-structural building components is to be kept in mind when the aim is to obtain a more holistic comparison of the embodied carbon in buildings with different structural types and materials.

4.2.2. Structural systems and their material/emission intensities

The representation of the MFA model parameters constitute another source of uncertainty. Among them are e.g. a simplified representation of structural system types s_i (Section 2.2.1) and the quantification of the constitutive material quantities based on SMI (Section 2.2.5). Although carefully selected, the choice of the SMI, built on the grounds of previous studies (Table 3), is affected by doubts on the degree of representativity of the data sets analysed in these studies for modelling of structural typologies characterising German residential buildings. Future studies could address the reduction of such uncertainties by means of a specific bottom-up definition and design of a more detailed representation of *structural* prototypes for such buildings.

As the SMI, the emission intensities CEI are key parameters to the estimation of the ECE. While the chosen values (Table 4) are considered to be representative of materials used in German residential building structures, this affirmation is not entirely free from subjectivity, considering e.g. the lack of data on the actual distribution of specific material types and grades in such structures. Also the disregarded time-dependent evolution of the CEI should be highlighted. As stated in Section 2.2.6, the CEI might be expected to decrease over time. Consequently, the emissions estimated in the CP scenario have most likely been overestimated, while also possibly overestimating the reduction potential of the assumed mitigation measures to certain degree. This is especially true for the RP measures, since cement and possibly also brick production have a higher decarbonisation potential than cutting emissions involved in manufacturing of timber components. However, due to the generally large uncertainties involved in the future evolution of CEI, any quantification of the degree of such overestimation would only be possible within very wide bounds and has been omitted herein.

In an attempt to quantify the overall error associated with the estimation of ECE involving SMQ and CEI (disregarding the described time-dependent effects), the annual German cement production emissions of around 20Mt/year (in 2019) [72] are taken as a reference, which account for approximately 2.5% of the total national emissions, i.e. far below the worldwide 6%–8% contribution of cement production emissions to total global emissions [33]. When considering the German export and import balance for cement, and the fact that only around 1/3 of the total cement production in Germany is used in residential buildings [85], the corresponding emissions reduce from 20Mt/year to around 5.6Mt/year. Excluding from these a 30% share for cement used in materials such as screed, plaster or mortar (estimation based on data in [54]), leads to estimated 2019 emissions embodied in *concrete* for German residential building structures of around 3.9 Mt. From these, a roughly estimated 0.5Mt can be attributed to cement-based brick material, such as aerated concrete and pumice blocks (see footnote to Table 4). The remainder, around 3.4Mt, still exceeds the herein determined concrete emissions in 2019 of about 2.4 Mt $CO_{2,eq}$ in approximately 40%. However, it must be considered that the present study includes only the living space in residential buildings, while excluding the UFA designated to other uses in such buildings, as for

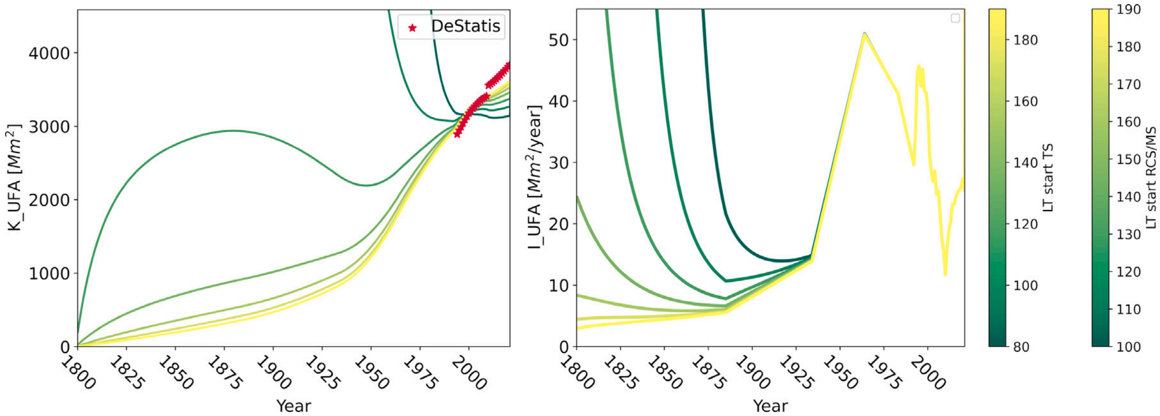

Fig. 12. (a) Stocks K_{UFA,s_i} (left) and (b) Inflows I_{ECE,s_i} (right) for period 1800–2021 under varying μ_{LT} corresponding to the start year of the observation period (year 1800 for MS and TS, and 1885 for RCS).

example office or commercial areas (Section 2.2.2). In 2019, such non-living spaces accounted for approximately 20% of the total UFA in German residential buildings. When accounting for this circumstance in the comparison, the difference between observed and modelled concrete emissions in 2019 reduces to less than 15%, which would be reasonably explained by the uncertainties in the defined SMI and CEI.

4.2.3. Lifetime

Another key-parameter of this study, subject to significant uncertainty, is the building lifetime, LT (Section 2.2.4). Fig. 12a shows the stocks $K_{UFA,tot}$ for the historical observation period (1800–2021) obtained under the assumption of different average LT (μ_{LT}) corresponding to the start year of the observation period (year 1800 for MS and TS, and 1885 for RCS). In this representation, the μ_{LT} have been varied in arrays of size seven between a maximum of 190 years and a minimum of, respectively, 100 years (MS and RCS) and 80 years (TS). As the comparison shows, reasonable results, characterised by initially smoothly increasing stocks, are only obtained for μ_{LT} = 150 years or higher. In addition, as Fig. 12b shows, the adoption of a μ_{LT} lower than about 170 years leads to initially strongly decreasing inflows $I_{UFA,tot}$, what is unlikely given the evidence for a progressively increasing population at the beginning of the 19th century [95]. These observations led to the final choice of μ_{LT} = 175 years in the start year of the observation period.

The reason for the unrealistically high stocks and inflows at the beginning of the observation period, obtained for comparatively low μ_{LT}, is to be sought in the relatively high share of old buildings (<1918) among the 1998 stock used for reconstruction of the historical inflows, see Table 2. In combination with the assumption of a normal distribution and relatively low μ_{LT}, high survival fractions of old buildings cause correspondingly large (back-calculated) inflows (and hence stocks). This might suggest that the adoption of a right-skewed distribution, with a comparatively lower μ_{LT} than adopted in this study, might be more appropriate for a realistic representation of the LT. While we have tested. that the estimated ECE appear to be only slightly sensitive to the choice of μ_{LT} in the start year – for example, in comparison to the μ_{LT} = 175 year model (for the start year), the obtained accumulated ECE in the period 2023–2045 decrease in only approximately 2% (CP scenario), when μ_{LT} is decreased to 160 years – future studies should envisage to further improve and analyse the LT model since several previous studies have detected a relatively large sensitivity of their results to the choice of this model [29,43,44].

4.2.4. Population and useful floor area

The future evolution of the population is fraught with uncertainties. Fig. 13 compares the evolution of ECE corresponding to the CP scenario, based on respectively, mean, lower and upper bound projections

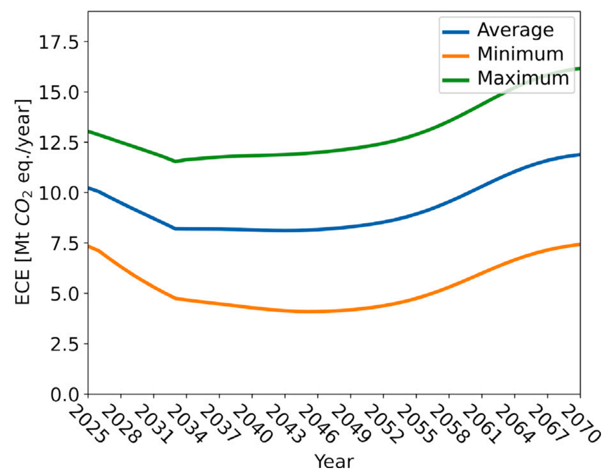

Fig. 13. ECE based on the average-, upper-, and lower-bound population projection (2025–2070; "Current practice" (baseline) scenario).

of the German population, see Fig. 3a. While qualitatively the three graphs follow the same trend, significant quantitative differences can be observed. In terms of the accumulated ECE, from 2023 to 2045, the difference between the average and upper bound scenario amounts to approximately 40%. For the minimum population scenario, this difference is approximately −42%. These numbers denote a strong sensitivity of the results to variations in the population projections. A similar sensitivity is expected for different models of the UFA per capita.

5. Conclusions and future work

This paper reflects the results of an interdisciplinary study between the disciplines of Structural Engineering and Industrial Ecology. The former is in need of powerful tools that support rational decisions on the implementation of standardised strategies for mitigating the environmental impact of constructions. The latter can provide a sound modelling basis for this purpose, while at the same time requiring structural engineering domain knowledge to build and feed such models.

Our study quantifies the stocks and flows of expected structural materials and their associated embodied carbon emissions in German residential buildings over the coming decades. The effect of combining two different measures for achieving an emission reduction has been analysed in the context of different mass-balance consistent scenarios, namely a gradually increasing replacement of the future masonry structure stock by functionally equivalent timber structures, and a general downsizing of structural material quantities, regardless of the material type.

The results show that approximately 194 Mt of mainly production-related $CO_{2,eq}$ emissions are expected to be embodied in structural materials for new German residential buildings between 2023 and 2045 if current practices are extended over this period. Among these, reinforcing steel assumes the largest share, followed by concrete, brick material, timber and mortar (for load-bearing masonry structures). By means of implementing "moderate" mitigation actions, the total emissions in the mentioned period could be reduced by approximately 15%, whereas the deployment of "strong" actions would enhance the mitigation potential to approximately 28%. The "moderate" and "strong" action scenario would contribute with, respectively approximately 4% and 8% to the German annual average target mitigation rate for achieving $CO_{2,eq}$ emission neutrality in 2045.

The technologies for achieving such substantial contributions are readily available. Authorities are advised to promote and facilitate their urgent implementation in practice. Not only should the most conventional structural materials (e.g. concrete, steel, fired bricks) be decarbonised to the extent possible, but also their substitution by alternative, more climate-friendly materials (e.g. timber, unfired bricks) be supported. In addition, structural design codes and the underlying procedures and compulsory decision rules should be thoroughly revised in order to envisage optimised design solutions from the perspective of both the economy and the environment.

The emission savings estimated in this study could be further increased when enhancing its scope to non-residential buildings and other types of structures (e.g. bridges). Future work should also address a refined modelling of the structural prototypes and an enhanced MFA system, which explicitly includes end-of-life processes and circularity potential of structures and their constitutive components and materials.

CRediT authorship contribution statement

Ramon Hingorani: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nils Dittrich:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Jochen Köhler:** Writing – review & editing, Funding acquisition. **Daniel B. Müller:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110830.

References

[1] CIB, Agenda 21 on Sustainable Construction, Report, International Council for Research and Innovation in Building and Construction (CIB), Comission W81, 1999.

[2] Daniel B. Müller, et al., Carbon emissions of infrastructure development, Environ. Sci. Technol. 47 (20) (2013) 11739–11746, http://dx.doi.org/10.1021/es402618m.

[3] L. Huang, et al., Carbon emission of global construction sector, Renew. Sustain. Energy Rev. 81 (2018) 1906–1916.

[4] EC, Emissions Database for Global Atmospheric Research (EDGAR), Release EDGAR V6.0 (1970–2018), European Comission, 2021, URL https://edgar.jrc.ec.europa.eu.

[5] GABC, 2021 Global Status Report for Buildings and Construction, Report, Global Alliance for Buildings and Construction. United Nations Environment Programme, 2021.

[6] A.H. Buchanan, et al., Energy and carbon dioxide implications of building construction, Energy Build. 20 (3) (1994) 205–217, http://dx.doi.org/10.1016/0378-7788(94)90024-8, URL https://www.sciencedirect.com/science/article/pii/0378778894900248.

[7] K.J. Eaton, A. Amato, A comparative life cycle assessment of steel and concrete framed office buildings, J. Construct. Steel Res. 46 (1–3) (1998).

[8] A. Dimoudi, C. Tompa, Energy and environmental indicators related to construction of office buildings, Resour. Conserv. Recy. 53 (1) (2008) 86–95, http://dx.doi.org/10.1016/j.resconrec.2008.09.008, URL https://www.sciencedirect.com/science/article/pii/S0921344908001481.

[9] S.C. Kaethner, J.A. Burridge, Embodied CO2 of structural frames, Struct. Eng. 90 (5) (2012) 33–40.

[10] H. Gervásio, L.S. da Silva, Comparative life-cycle analysis of steel-concrete composite bridges, Struct. Infrastruct. Eng. 4 (4) (2008) 251–269, http://dx.doi.org/10.1080/15732470600627325.

[11] L. Huang, et al., Life cycle assessment of norwegian road tunnel, Int. J. Life Cycle Assess 20 (2) (2015) 174–184, http://dx.doi.org/10.1007/s11367-014-0823-1.

[12] Mohammad Nahangi, et al., Embodied greenhouse gas assessment of a bridge: A comparison of preconstruction building information model and construction records, J. Clean. Prod. 295 (2021) 126388.

[13] David Collings, The carbon footprint of bridges, Struct. Eng. Int. 32 (4) (2022) 501–506, http://dx.doi.org/10.1080/10168664.2021.1917326.

[14] P. Hájek, C. Fiala, M. Kynčlová, Life cycle assessments of concrete structures – a step towards environmental savings, Struct. Concr. 12 (1) (2011) 13–22, http://dx.doi.org/10.1002/suco.201000026, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/suco.201000026.

[15] L. Aye, T. Ngo, R.H. Crawford, R. Gammampila, P. Mendis, Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy Build. 47 (2012) 159–168, http://dx.doi.org/10.1016/j.enbuild.2011.11.049, URL https://www.sciencedirect.com/science/article/pii/S0378778811005950.

[16] H.R. Lu, A. El Hanandeh, B.P. Gilbert, A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: Environmental and economic perspective, J. Clean. Prod. 166 (2017) 458–473, http://dx.doi.org/10.1016/j.jclepro.2017.08.065, URL https://www.sciencedirect.com/science/article/pii/S095965261731781X.

[17] A. Oladazimi, S. Mansour, S.A. Hosseinijou, Comparative life cycle assessment of steel and concrete construction frames: A case study of two residential buildings in Iran, Buildings 10 (3) (2020) http://dx.doi.org/10.3390/buildings10030054.

[18] BIM-based life cycle assessment for different structural system scenarios of a residential building, Ain Shams Eng. J. 13 (6) (2022) 101802, http://dx.doi.org/10.1016/j.asej.2022.101802, URL https://www.sciencedirect.com/science/article/pii/S2090447922001137.

[19] Carine Lausselet, et al., Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock, J. Ind. Ecol. 25 (2) (2021) 419–434, http://dx.doi.org/10.1111/jiec.13049, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.13049.

[20] Daniel B. Müller, Stock dynamics for forecasting material flows—case study for housing in the Netherlands, Ecol. Econ. 59 (1) (2006) 142–156, https://www.sciencedirect.com/science/article/pii/S092180090500460X.

[21] Håvard Bergsdal, et al., Dynamic material flow analysis for Norway's dwelling stock, Build. Res. Inf. 35 (5) (2007) 557–570, http://dx.doi.org/10.1080/09613210701287588.

[22] Ninaa Holck Sandberg, Helge Brattebø, Analysis of energy and carbon flows in the future Norwegian dwelling stock, Build. Res. Inf. 40 (2) (2012) 123–139.

[23] Hiroki Tanikawa, Seiji Hashimoto, Urban stock over time: spatial material stock analysis using 4d-GIS, Build. Res. Inf. 37 (5–6) (2009) 483–502, http://dx.doi.org/10.1080/09613210903169394.

[24] Jakob Lederer, et al., Material flows and stocks in the urban building sector: A case study from vienna for the years 1990–2015, Sustainability 12 (1) (2020) http://dx.doi.org/10.3390/su12010300, URL https://www.mdpi.com/2071-1050/12/1/300.

[25] Georg Schiller, Felix Müller, Regine Ortlepp, Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy, Resour. Conserv. Recy. 123 (2017) 93–107, http://dx.doi.org/10.1016/j.resconrec.2016.08.007, URL https://www.sciencedirect.com/science/article/pii/S0921344916301999.

[26] Georg Schiller, Karin Gruhler, Regine Ortlepp, Continuous material flow analysis approach for bulk nonmetallic mineral building materials applied to the german building sector, J. Ind. Ecol. 21 (3) (2017) 673–688, http://dx.doi.org/10.1111/jiec.12595, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12595.

[27] Bahareh Nasiri, Chiara Piccardo, Mark Hughes, Estimating the material stock in wooden residential houses in Finland, Waste Manag. 135 (2021) 318–326, http://dx.doi.org/10.1016/j.wasman.2021.09.007, URL https://www.sciencedirect.com/science/article/pii/S0956053X21004967.

[28] P. Berril, E.G. Hertwich, Material flows and GHG emissions from housing stock evolution in US counties, 2020–60, Build. Cities 2 (1) (2021) 599–617, http://dx.doi.org/10.5334/bc.126.

[29] Jay H. Arehart, Francesco Pomponi, Bernardino D'Amico, Wil V. Srubar, Structural material demand and associated embodied carbon emissions of the United States building stock: 2020–2100, Resour. Conserv. Recy. 186 (2022) 106583, http://dx.doi.org/10.1016/j.resconrec.2022.106583, URL https://www.sciencedirect.com/science/article/pii/S0921344922004189.

[30] Bernardino D'Amico, Francesco Pomponi, Jim Hart, Global potential for material substitution in building construction: The case of cross laminated timber, J. Clean. Prod. 279 (2021) 123487, http://dx.doi.org/10.1016/j.jclepro.2020.123487, URL https://www.sciencedirect.com/science/article/pii/S0959652620335320.

[31] EC, CO2 emissions from EU territorial energy use, European Comission, 2023, URL https://ec.europa.eu.

[32] GLOBE, Joint Committee on the Global Consensus on Sustainability in the Built Environment, Decarbonizing global construction - draft, september 2022, 2022, URL https://www.rilem.net/globe.

[33] Material efficiency in clean energy transitions, Report, International Energy Agency, 2019, URL https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions.

[34] O.P. Gibbons, J.J. Orr, How to calculate embodied carbon, Report, The Institution of Structural Engineers, 2020, URL https://www.istructe.org.

[35] Ramon Hingorani, Jochen Köhler, Towards optimised decisions for resource and carbon-efficient structural design, Civ. Eng. Environ. Syst. 40 (1–2) (2023) 1–31, http://dx.doi.org/10.1080/10286608.2023.2198767.

[36] Bundesregierung, Klimaschutzbericht 2022, Report, Bundesministerium für Wirtschaft und Klimaschutz, 2022.

[37] Bernardino D'Amico, Francesco Pomponi, On mass quantities of gravity frames in building structures, J. Build. Eng. 31 (2020) 101426, http://dx.doi.org/10.1016/j.jobe.2020.101426, URL https://www.sciencedirect.com/science/article/pii/S2352710219315050.

[38] F. Nemry, A. Uihlein, Environmental Improvement Potentials of Residential Buildings (IMPRO-Building), Report, European Commission, Joint Research Centre, Institute for Prospective Technological Studies, 2008, http://dx.doi.org/10.2791/38942.

[39] DESTATIS Statistisches Bundesamt, Bautätigkeit und wohnungen. Fachserie 5 / Reihe 1. bautätigkeit, 1993-2020, URL https://www.destatis.de.

[40] DESTATIS Statistisches Bundesamt, Bautätigkeit und wohnungen. Mikrozensus - zusatzerhebung 1998 - wohnsituation der haushalte. Fachserie 5 / heft 1. Bestand und struktur der wohneinheiten, 1998, URL https://www.destatis.de.

[41] DESTATIS Statistisches Bundesamt, Gebäude und wohnungen. Bestand an wohnungen und wohngebäuden. bauabgang von wohnungen und wohngebäuden. Lange reihen ab 1969 - 2020. 2020, 2021, URL https://www.destatis.de.

[42] DESTATIS Statistisches Bundesamt, Bevölkerungsentwicklung bis 2070 in deutschland. bevölkerungszahl nach jahren (alle varianten und modellrechnungen), 2021, URL https://www.destatis.de.

[43] Felipe Vásquez, et al., Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock, Energy Build. 111 (2016) 37–55, http://dx.doi.org/10.1016/j.enbuild.2015.11.018, URL https://www.sciencedirect.com/science/article/pii/S0378778815303832.

[44] Ninaa Holck Sandberg, Igor Sartori, Helge Brattebø, Sensitivity analysis in long-term dynamic building stock modeling—exploring the importance of uncertainty of input parameters in Norwegian segmented dwelling stock model, Energy Build. 85 (2014) 136–144.

[45] Lebensdauer von Bauteilen und Bauteilschichten. Infoblatt Nr.4.2, Report, Kompetenzzentrum "Kostengünstig qualitätsbewusst Bauen" im Institut für Erhaltung und Modernisierung von Bauwerken (IEMB, TU Berlin), 2006, URL https://www.kompetenzzentrum-iemb.de.

[46] F. Ritter, Lebensdauer von Bauteilen und Bauelementen (Ph.D. thesis).

[47] D. Diamantidis, M. Sykora, E. Bertacca, Obsolescence rate: Framework, analysis and influence on risk acceptance criteria, in: Caspeele, Taerwe, Frangopol (Eds.), Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision, 2019, pp. 379–386.

[48] K. Sakai, et al., Sustainability design of concrete structures, Struct. Concr. 17 (6) (2016) 1114–1124, http://dx.doi.org/10.1002/suco.201600069, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/suco.201600069.

[49] R.A. Bohne, et al., Estimation of the service life of buildings and building components, in: Conference: Towards the City Surface of Tomorrow, 2006, pp. 29–33.

[50] Uta Hassler, Niklaus Kohler, Wilfried Wang, Umbau - Über die Zukunft des Baubestandes, in: Umbau. Hrsg.: U. Hassler, Wasmuth, 1999, p. 9 S..

[51] Niklaus Kohler, Wei Yang, Long-term management of building stocks, Build. Res. Inf. 35 (4) (2007) 351–362, http://dx.doi.org/10.1080/09613210701308962.

[52] Mehmet Aksözen, Uta Hassler, Niklaus Kohler, Reconstitution of the dynamics of an urban building stock, Build. Res. Inf. 45 (3) (2017) 239–258, http://dx.doi.org/10.1080/09613218.2016.1152040.

[53] F. Fingerloos, H.U. Litzner, Von 1904 bis 2004: 100 jahre betonbaunormung in deutschland, Beton- und Stahlbetonbau 99 (4) (2004) 608–616, http://dx.doi.org/10.1002/best.200490150.

[54] Regine Ortlepp, Karin Gruhler, Georg Schiller, Materials in Germany's domestic building stock: calculation model and uncertainties, Build. Res. Inf. 46 (2) (2018) 164–178, http://dx.doi.org/10.1080/09613218.2016.1264121.

[55] N. Heeren, T. Fishman, A database seed for a community-driven material intensity research platform, Sci. Data 6 (23) (2019) http://dx.doi.org/10.1038/s41597-019-0021-x.

[56] Sylvia Marinova, et al., Global construction materials database and stock analysis of residential buildings between 1970–2050, J. Clean. Prod. 247 (2020) 119146, http://dx.doi.org/10.1016/j.jclepro.2019.119146, URL https://www.sciencedirect.com/science/article/pii/S0959652619340168.

[57] S. Pauliuk, et al., Global scenarios of resource and emission savings from material efficiency in residential buildings and cars, Nature Commun. 12 (5097) (2021) http://dx.doi.org/10.1038/s41467-021-25300-4.

[58] Sebastiaan Deetman, Sylvia Marinova, Ester van der Voet, Detlef P. van Vuuren, Oreane Edelenbosch, Reinout Heijungs, Modelling global material stocks and flows for residential and service sector buildings towards 2050, J. Clean. Prod. 245 (2020) 118658, http://dx.doi.org/10.1016/j.jclepro.2019.118658, URL https://www.sciencedirect.com/science/article/pii/S0959652619335280.

[59] D. Wiedenhofer, et al., Maintenance and expansion: Modeling material stocks and flows for residential buildings and transportation networks in the EU25, J. Ind. Ecol. 19 (4) (2015) 538–551, http://dx.doi.org/10.1111/jiec.12216, URL https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12216.

[60] Paul Gontia, et al., Material-intensity database of residential buildings: A case-study of Sweden in the international context, Resour. Conserv. Recy. 130 (2018) 228–239, http://dx.doi.org/10.1016/j.resconrec.2017.11.022, URL https://www.sciencedirect.com/science/article/pii/S0921344917304135.

[61] Jim Hart, Bernardino D'Amico, Francesco Pomponi, Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures, J. Ind. Ecol. 25 (2) (2021) 403–418, http://dx.doi.org/10.1111/jiec.13139.

[62] W. Kalusche, S. Herke, BKI Baukosten 2020 Neubau. Statistische Kostenkennwerte für GebäUde, BKI, Baukosteninformationszentrum, Stuttgart, 2020.

[63] CEN, EN15978:2011. Sustainability of construction works - assessment of environmental performance of buildings - calculation method, 2011.

[64] IBU, Institut Bauen und Umwelt e.V., Umwelt-produktdeklaration nach iSO 14025 und EN 15804+A1. Beton der druckfestigkeitsklasse c 35/45. Deklarationsnummer: EPD-IZB-20180098-IBG1-DE, 2018, URL http://www.ibu-epd.com.

[65] IBU, Institut Bauen und Umwelt e.V., Environmental product declaration as per /ISO 14025/ and /EN 15804. reinforcing steel in bars. Declaration number: EPD-arm-20160051-IBD3-EN, 2016, URL http://www.ibu-epd.com.

[66] IBU, Institut Bauen und Umwelt e.V., Environmental product declaration as per /ISO 14025/ and /EN 15804. cross-laminated timber (X-LAM). Declaration number: EPD-SHL-20180035-IBG1-EN, 2018, URL http://www.ibu-epd.com.

[67] IBU, Institut Bauen und Umwelt e.V., Umwelt-produktdeklaration nach ISO 14025 und EN 15804+a1. Mauerziegel (ungefüllt). Deklarationsnummer: EPD-BDZ-20210062-ICG1-DE, 2021, URL http://www.ibu-epd.com.

[68] IBU, Institut Bauen und Umwelt e.V., Umwelt-produktdeklaration nach ISO 14025 und EN 15804+A2. kalksandstein. Deklarationsnummer: EPD-BKS-20210205-IBE2-DE, 2021, URL http://www.ibu-epd.com.

[69] IBU, Institut Bauen und Umwelt e.V., Umwelt-produktdeklaration nach ISO 14025 und EN 15804. ytong-porenbeton. Deklarationsnummer: EPD-XEL-20170147-IAD1-DE, 2017, URL http://www.ibu-epd.com.

[70] IBU, Institut Bauen und Umwelt e.V., Umwelt-produktdeklaration nach ISO 14025 und EN 15804. Mauersteine aus leichtbeton aus natürlichen zuschlägen. Deklarationsnummer: EPD-BVL-20180108-IAG1-DE; EPD-BVL-20180109-IAG1-DE, 2019, URL http://www.ibu-epd.com.

[71] IBU, Institut Bauen und Umwelt e.V., Umwelt-Produktdeklaration nach ISO 14025 und EN 15804. Mineralische Werkmörtel: Mauermörtel. Normalmauermörtel. Deklarationsnummer: EPD-IWM-20190080-IBG1-DE, Verband für Dämmsysteme, Putz und Mörtel e.V. (VDPM), 2019, URL http://www.ibu-epd.com.

[72] VDZ, Verein Deutscher Zementwerke e.V., Decarbonising cement and concrete. A CO2 roadmap for the german cement industry, 2020, URL https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/Executive_Summary_VDZ_Study_Decarbonising_Cement_and_Concrete_2020.pdf.

[73] L. Gustavsson, K. Pingoud, R. Sathre, Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings, Mitig. Adapt. Strateg. Glob. Chang. 11 (3) (2006) 667–691, http://dx.doi.org/10.1007/s11027-006-7207-1.

[74] L. Vukotic, R.A. Fenner, K. Symons, Assessing embodied energy of building structural elements, Proceedings of the Institution of Civil Engineers - Engineering Sustainability 163 (3) (2010) 147–158, http://dx.doi.org/10.1680/ensu.2010.163.3.147, URL https://www.icevirtuallibrary.com/doi/abs/10.1680/ensu.2010.163.3.147.

[75] Julie Lyslo Skullestad, Rolf André Bohne, Jardar Lohne, High-rise timber buildings as a climate change mitigation measure – A comparative LCA of structural system alternatives, Energy Procedia 96 (2016) 112–123, http://dx.doi.org/10.1016/j.egypro.2016.09.112, Sustainable Built Environment Tallinn and Helsinki Conference SBE16, URL https://www.sciencedirect.com/science/article/pii/S1876610216307512.

[76] Y. Niu, et al., Design concept for the sustainable use of timber in structures, in: ICOSSAR 2021-22, 13th International Conference on Structural Safety & Reliability.

[77] J.M. Allwood, Cullen J.M., Chapter 12: Using less metal by design, in: Sustainable Materials - with Both Eyes Open, UIT Cambridge Ltd., 2012, pp. 169–190.

[78] Catherine De Wolf, Endrit Hoxha, Corentin Fivet, Comparison of environmental assessment methods when reusing building components: A case study, Sustainable Cities Soc. 61 (2020) 102322, http://dx.doi.org/10.1016/j.scs.2020.102322, URL https://www.sciencedirect.com/science/article/pii/S2210670720305436.

[79] C.E. Andersen, et al., Comparison of GHG emissions from circular and conventional building components, Build. Cities 1 (1) (2020) 379–392, http://dx.doi.org/10.5334/bc.55, URL https://journal-buildingscities.org/articles/10.5334/bc.55/#.

[80] D. Miller, J.-H. Doh, Incorporating sustainable development principles into building design: a review from a structural perspective including case study, Struct. Design Tall Special Build. 24 (6) (2015) 421–439, http://dx.doi.org/10.1002/tal.1172, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/tal.1172.

[81] A. Hollberg, et al., A data-driven parametric tool for under-specified LCA in the design phase, in: IOP Conf. Series: Earth Environ. Sci., 588, (5) IOP Publishing, 2020, 052018.

[82] M. Sarkisian, D. Shook, Embodied carbon in structures and cities, in: IABSE Symposium Madrid: Engineering for Progress, Nature and People, 2014, pp. 3166–3173.

[83] Grundlagen des Mauerwerksbaus, Deutsche Gesellschaft für Mauerwerks- und Wohnungsbau e. V., 2022, URL https://www.mauerwerksbau-lehre.de/vorlesungen/1-grundlagen-und-baustoffe-des-mauerwerksbaus.

[84] Regine Ortlepp, Karin Gruhler, Georg Schiller, Material stocks in Germany's non-domestic buildings: a new quantification method, Build. Res. Inf. 44 (8) (2016) 840–862, http://dx.doi.org/10.1080/09613218.2016.1112096.

[85] VDZ, Verein Deutscher Zementwerke e.V., Bautätigkeit und zementverbrauch, 2020, URL https://www.vdz-online.de/zementindustrie/baunachfrage.

[86] Francesco Pomponi, et al., Buildings as a global carbon sink? A reality check on feasibility limits, One Earth 3 (2) (2020) 157–161, http://dx.doi.org/10.1016/j.oneear.2020.07.018, URL https://www.sciencedirect.com/science/article/pii/S2590332220303626.

[87] W. Hawkins, et al., Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure, Structures 33 (2021) 90–98, http://dx.doi.org/10.1016/j.istruc.2020.12.013, URL https://www.sciencedirect.com/science/article/pii/S2352012420307323.

[88] DIN, DIN 18940, tragendes Lehmsteinmauerwerk – Konstruktion, bemessung und ausführung, 2023.

[89] Leonora Charlotte Malabi Eberhardt, Harpa Birgisdóttir, Morten Birkved, Life cycle assessment of a danish office building designed for disassembly, Build. Res. Inf. 47 (6) (2019) 666–680, http://dx.doi.org/10.1080/09613218.2018.1517458.

[90] Jan Brütting, et al., Environmental impact minimization of reticular structures made of reused and new elements through life cycle assessment and mixed-integer linear programming, Energy Build. 215 (2020) 109827, http://dx.doi.org/10.1016/j.enbuild.2020.109827, URL https://www.sciencedirect.com/science/article/pii/S0378778819330439.

[91] Ingrid Bertin, et al., Environmental impacts of design for reuse practices in the building sector, J. Clean. Prod. 349 (2022) 131228, http://dx.doi.org/10.1016/j.jclepro.2022.131228, URL https://www.sciencedirect.com/science/article/pii/S0959652622008599.

[92] Fengming Xi, et al., Substantial global carbon uptake by cement carbonation, Nat. Geosci. 9 (12) (2016) 880–883, http://dx.doi.org/10.1038/ngeo2840.

[93] Behzad Sodagar, et al., The carbon-reduction potential of straw-bale housing, Build. Res. Inf. 39 (1) (2011) 51–65, http://dx.doi.org/10.1080/09613218.2010.528187.

[94] Verena Göswein, et al., Land availability in europe for a radical shift toward bio-based construction, Sustainable Cities Soc. 70 (2021) 102929, http://dx.doi.org/10.1016/j.scs.2021.102929, URL https://www.sciencedirect.com/science/article/pii/S2210670721002158.

[95] Walter Roedel, Die demographische entwicklung in deutschland 1770-1820, 2023, URL https://www.regionalgeschichte.net.