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Multiscale spatiotemporal characterisation of embodied environmental performance of building structures in Geneva from 1850 to 2018

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ABSTRACT

Load-bearing systems in buildings, significant in material use and embodied greenhouse gas emissions (EGHGE), have lacked detailed analysis on their environmental and functional relationships over time and space. This study evaluates the environmental impacts of building structures in Geneva, Switzerland, considering factors like material usage, EGHGE, and urban development. A new method using a similarity-weighted function projects environmental impacts onto a GIS-based building stock, analysing 48 archetypal and 84,477 stock buildings built from 1850 to 2018. Results show a 37% reduction in structural volume per floor area and a 10% increase in mass over time. Buildings predating the masonry-to-concrete transition would produce 7% more EGHGE if constructed today. Multi-residential buildings emit 14% less EGHGE than single homes. A new indicator amortizes upfront environmental effects over a building's lifespan, aiding in historical comparisons of building stocks. This approach underscores the need for spatial-temporal environmental impact mapping to understand sustainable urban development dynamics.

Table of Abbreviations

ABOVE	Number of stories, including ground floor
b	Building
b^*	Sample building
B	Stock of buildings
B^*	Set of sample buildings
BELOW	Number of underground stories
C	Construction year
C_{diff}	Difference of construction years
C_{thr}	Threshold distance in construction year dimension
C_{lb}	Lower bound of construction year
CO_2e	Carbon dioxide equivalent
D	Demolition year
dist	Distance
EC	Embodied greenhouse gas emissions coefficient
FPA	Ground floor footprint area
g	Construction group
GFA	Gross floor area
EGHGE	Embodied greenhouse gas emissions
GIS	Geographical information system
H	Building height
H_{ub}	Upper bound of building height
H−	Group of horizontal supports in underground levels
H○	Group of horizontal supports in ground level
H+	Group of horizontal supports in upper levels
H_{diff}	Difference of building height
H_{thr}	Threshold distance in building height dimension
L	Location of building
L_{thr}	Threshold distance in building location dimension
m	Material
M	Set of all construction materials
max	Maximum
MEQ	Material and emissions quantities
min	Minimum
p	Reference period

(continued on next page)

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(*continued*)

ABOVE	Number of stories, including ground floor
ρ	Material density
R	Roof or attic structural system
s	Building component
S	Set of all building components
t	Reference year
U_MEQ	Unutilised material and emissions quantities
U_EGHGE	Unutilised embodied greenhouse gas emissions
V−	Group of vertical supports in underground levels
V∘	Group of vertical supports in ground level
V+	Group of vertical supports in upper levels
VOL	Volume
w	Weight
X_{diff}	Difference of X coordinates
Y_{diff}	Difference of Y coordinates

1. Introduction

1.1. Context

Construction generates the highest amount of waste in volume and mass in Europe (European Commission, 2018). Lower bound values for embodied greenhouse gas emissions (EGHGE) in buildings – i.e., greenhouse gas emissions during material extraction, production, transport, construction, use, and end-of-life treatment of the building – amount to at least 11% (International Energy Agency, 2019) of overall yearly energy- and process-related emissions worldwide (more than 20%. when only CO_2 emissions are considered (Global Alliance for Buildings and Construction, 2022)). Still, the reduction of embodied environmental flows in buildings remains less addressed than reduction of operational flows (Hoxha et al., 2017; Rö et al., 2020) related to the heating, cooling, ventilation, hot water, lighting, and electricity necessary for the operation of the building. Embodied environmental flows must also be reduced to improve the life cycle environmental performance of the built environment (Rö et al., 2020). Because of their large volumes and energy-intensive manufacturing processes, load-bearing systems constitute a significant part of the contributions of buildings to climate change and biosphere deterioration (Hoxha et al., 2017; Anderson et al., 2015; Dixit, 2017). A better understanding of the underlying design-related causes is needed to achieve further material savings and limit global warming (Orr, 2018).

Considering load-bearing systems, achieving greater environmental performance involves using materials with fewer detrimental effects, designing structures with reduced material quantities, and increasing component lifespan through maintenance and reuse (Fivet et al., 2020). Building structures have long service lives (Kohler and Yang, 2011) and significantly influence human activities, necessitating an environmental analysis that extends beyond the building scale to encompass changing construction technologies, architectural needs, human development dynamics, and socio-industrial contexts (Leupen, 2006; Tombesi, 2006; Lin et al., 2017). Exploring patterns of past development supports future planning but is challenging due to extensive and diverse recorded data, requiring new data visualisation methods and indicators to identify, synthesise, and communicate these patterns (Petit-Boix et al., 2017; Creutzig et al., 2019; Kaplan and di Lenardo, 2020).

1.2. Research gaps

Greenhouse gas emissions must be reduced across the entire life cycle of buildings to pursue societal goals of resource use and climate change mitigation (International Energy Agency, 2022). This study contributes to filling two research gaps. The first gap is the lack of knowledge on material use in the building stock and its associated environmental effects underscored by several studies in Switzerland (Frischknecht et al., 2020; SBV et al., 2021) and elsewhere (Lederer et al., 2020; Lausselet et al., 2020). The second relates to the difficulty of modelling large building stocks with reasonable assumptions – as modelling large building stocks by making practical and justifiable abstractions while also ensuring accuracy and reliability in the analysis is methodologically challenging (Stephan et al., 2022; Arbabi et al., 2022).

Prior research has estimated building lifespans in Switzerland (Aksö et al., 2017; Hart et al., 2021) or compared the environmental-economic assessment of building materials (Meglin et al., 2022). However, no study at the territorial scale has addressed the historical development of material use in the Swiss context, nor EGHGE related to load-bearing systems and across building types. The mistaken belief that EGHGE are negligible aspects of a building's environmental performance (Rö et al., 2020) or the fact that advances in minimising operational emissions have only recently generated a shift in attention to EGHGE (Akbarnezhad and Xiao, 2017) could explain why relevant studies are limited in number, variety, and scope. Research on EGHGE and energy demands in the Swiss building stock either fails to assess core structural components (Ostermeyer et al., 2017; Heeren and Hellweg, 2018), or only assesses residential buildings (Drouilles et al., 2017, 2019), or operational demands (Schneider et al., 2017; Streicher et al., 2019). Systemic environmental benchmarks are lacking to support the building sector in significantly reducing emissions (Frischknecht et al., 2019). In parallel, temporal analyses of material flows and EGHGE have emerged elsewhere that advance understanding and visualisation of territorial transformation by reconstructing the past (Bai et al., 2019; Li et al., 2022, 2023), plotting the possible futures (Lausselet et al., 2021; Arehart et al., 2022), or both (Hingorani et al., 2023).

Modelling building stocks and their associated environmental effects have been reviewed (Lotteau et al., 2015; Mastrucci et al., 2017). Geographical information systems (GIS), used as the inventory input data when considering large building stocks, contain many building entries. Except in rare databases (Tirado et al., 2021; Francart et al., 2023), entries are defined by fields limited to descriptions of overall building features – e.g., building location, footprint, height, construction year, and use. Construction classification system databases need to be improved to increase the quantity and the quality of the data used to describe and analyse the built environment while guaranteeing its broader readability and accessibility (Guven et al., 2022). Emerging techniques, such as street view imaging and machine learning for resource cadastre generation and pre-demolition audit assessment, are significant for improvements (Raghu et al., 2023). Since environmental effects cannot be computed from only GIS data, methods have been developed to infer the environmental effects of building stocks from a few archetypal buildings, either *simulated* (often parametric, idealised building models whose construction features are assumed to be representative of a particular category of stock buildings) or *sampled* (defined by surveyed building data, usually selected from within the stock, which might be subject to uncertainty) (Lederer et al., 2021; Slavkovic et al., 2022).

Methods to infer material usage in large building stocks have been reviewed in depth (Lotteau et al., 2015; Mastrucci et al., 2017; Augiseau and Barles, 2017; Li et al., 2021). Such methods require assumptions that often reduce the validity of results or the scope of findings (Augiseau and Barles, 2017). Assumptions may be related to (a) construction technologies used in archetypal buildings (Lanau et al., 2021), (b) the coverage of the stock by archetypal buildings (Li et al., 2022), and (c) the granularity of archetypal building data used to model stock buildings (Tirado et al., 2021; Francart et al., 2023; Mayer and Bechthold, 2019; Lanau and Liu, 2020).

Regarding (a), simulated buildings are often modelled using assumptions from nation-wide mean values (Heeren and Hellweg, 2018; Condeixa et al., 2017) or what is customary at a particular time or for a particular building use (Condeixa et al., 2017; Mastrucci et al., 2016; Stephan and Athanassiadis, 2017, 2018). In contrast, analyses relying on sample buildings are based on as-built bills of quantities or in-situ surveys (De Wolf et al., 2017) but are often guided by data availability or the author's assumption of what a representative set of buildings is.

Regarding (b), the number of building archetypes used in research are often less than 1‰ of the building stock (Mastrucci et al., 2017; Condeixa et al., 2017; Tanikawa et al., 2015; Kleemann et al., 2016a; Miatto et al., 2019; Stephan et al., 2013; Wiedenhofer et al., 2015). Depending on the propagation method, an increase in archetypal buildings does not necessarily lead to increased accuracy of results (Slavkovic et al., 2022). Archetypal classes are based on commonly available GIS features: building location, footprint, height, construction year, and use.

Regarding (c), most studies addressing material and emissions quantities (MEQs) in buildings use homogeneous material intensities per square meter of building floor area to relate material usage from archetypal buildings to stock buildings (Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009; Marcellus-Zamora et al., 2016; Kleemann et al., 2016b). Recent studies have increased the granularity by using building layers (De Wolf et al., 2017) or groups of components (Stephan and Athanassiadis, 2017, 2018) instead, quantities calculated from available geometric features of each stock building. A higher level of granularity is needed to discuss material intensities with the use values of component typologies.

The methods developed in this paper aim to help tackle current challenges of producing more accurate and nuanced stock analyses by respectively reducing the number of initial assumptions, minimising coverage errors between the large building stock and the small number of archetypal or sampled data, and increasing the granularity of data transferred from archetypal buildings to stock buildings.

1.3. Aims and significance

For insights into the environmental performance of the structural materials in large building stocks and their spatiotemporal distribution, this paper provides a detailed analysis of material usage and EGHGEs in both sample buildings and the broader building stock in the Canton of Geneva. Contrary to existing literature, the study includes holistic and cross-scalar analyses of the environmental impact of building structures for better understanding their design-related causes and bridging production and spatio-social challenges (Ceschin and Gaziulusoy, 2016). It investigates the interplay between environmental effects, urban development, construction history, socio-industrial development, and structural performance to show that including diverse building types, spatial considerations, and historical data analysis contributes to a more comprehensive understanding of urban sustainability.

In addition, the paper addresses challenges in modelling large building stocks by proposing new methods to improve accuracy and granularity when analysing material usage. It introduces a similarity-weighted function for inferring MEQs of building stocks from sample buildings, along with a novel indicator (U_MEQ) that considers the payback on environmental investment when measuring MEQs in buildings and cities over different periods. Because this new indicator measures how well a city maintains its building stock over time using the concept of environmental investment, it can be a powerful tool for planners and other decision-makers when tackling the long-term implementations of circular economy principles. By using a weighing function to interpolate between building archetypes, the indicator avoids the so-called "threshold effect," which results in sudden jumps in model outputs linked to relatively coarse and discrete representation of the stock.

Results from applying this new method to an urban building stock reveal significant findings – e.g., the evolution of the volume, mass, and environmental efficiency of load-bearing components per gross floor area (GFA) over time – that can indicate whether newer materials and construction techniques involve more carbon-intensive manufacturing processes. Relationships between building types, building heights, and MEQs also indicate whether an optimal building height exists or what urban forms perform better in EGHGE, relevant to guidelines for urban planning.

The significance extends beyond immediate findings. Conclusions link material use and use value in buildings and highlight the need for better use of available resources while minimising adverse environmental effects. The data produced, combined with other energy, mobility, and socio-economy indicators, contributes to a comprehensive characterisation of city-level environmental performance. This holistic understanding is crucial for both academia and city administrations, as it helps synthesise complex industrial and cultural interactions, assess past evolutions, and inform prospects through new forms of visualisations and interactions. This research calls for deeper inquiries into the dynamics between material efficiency, construction technologies, urban planning, and real estate development.

1.4. Scope

The present study measures and maps *environmental performance* – the ratio between adverse environmental effects and use value, e.g., EGHGE per gross floor area times years of use – in building structures in the Canton of Geneva from 1850 to 2018. Dwelling, office, educational, industrial, and retail buildings are considered, but not community and appendix buildings (see Section 2.1).

Adverse environmental effects related to the production and construction of building structures before their use stage, i.e., from cradle to gate, are assessed. Studied objects comprise all structural components, from ground slab to roof structure, excluding foundations, stairs, and balconies. The focus on structural components is justified because they form a distinct building layer (Brand, 1994) with a specific design logic and use value. As demonstrated by multiple studies (Stephan and Athanassiadis, 2017; Hammond and Jones, 2008; Kaethner and Burridge, 2012; Huberman et al., 2015; Helal et al., 2020; De Wolf et al., 2020; De Wolf et al., 2016), they are the single most significant contributor to initial embodied environmental effects when excluding material replacements over time. Moreover, structural elements tend to represent the majority of the building's mass, and they usually have the longest lifespan in the building.

Regarding scope and assumptions, in the absence of adequate data, EGHGE coefficients related to the past production of materials are assumed to be equivalent to contemporary ones. This means that the results may only correspond to EGHGE that buildings would produce if they were built today, irrespectively of their actual construction year. Effects related to the modification of load-bearing systems during the use phase of buildings are out of scope in the absence of useable historical data. End-of-life treatments of building structures are highly time-dependent and expected to evolve, which increases uncertainty; therefore, they are also excluded.

2. Methods

This paper introduces a new interpolation method for MEQs in buildings, addressing common limitations of threshold effects and enhancing data accuracy. This method's originality lies in its similarity-weighted function, which ensures accurate data representation and enhances data granularity by parameterising buildings at the structural component level, allowing for differentiation across construction materials and building levels.

Measures include material use in terms of mass, volume, and associated initial EGHGE. For simplicity, these three measures are referred to as MEQs. To evaluate the environmental performance of building structures in Geneva over time and space, a 'bottom-up interpolation' method is developed in this section and applied in Section 3. In response to the research gaps (Section 1.2), the method includes.

- characterisation of sample buildings with as-built material quantities, which, compared to archetypal simulations, embeds historical variations due to time-changing building norms, structural design codes, and regional industrial habits;

〉 statistical inference from sampling results to the GIS-based stock using a similarity-weighted function, which, compared to discrete archetypal categories, avoids threshold effects and provides more accuracy as the number of samples increases;
〉 comparison of similarity according to building use, height, location, and construction year, i.e., commonly available GIS database fields assumed to influence material use in load-bearing systems;
〉 computation of MEQs for each structural component group and associated construction material in buildings to enable detailed analyses of material distributions within buildings;
〉 interpolation from sample to stock buildings using their gross floor area (GFA) and the number of underground and aboveground levels, considering that underground, ground, and aboveground stories are built using different construction techniques, geometries, or load cases.

The process is divided into three main steps (Fig. 1).

1. GIS data curation to describe the building stock (Section 2.1);
2. selection and environmental assessment of sample buildings (Section 2.2);
3. interpolation of values from sample buildings to stock buildings (Section 2.3).

Material usage characterisations are extracted from both steps 2 and 3. A new indicator links environmental effects and use value (Section 2.4). The various methods are applied to the case study of the Geneva case study (Section 3).

2.1. Building stock: data curation

The first step in evaluating the environmental performance of city building structures entails acquiring and preparing data on demolished and current buildings in the studied stock. Datasets are aggregated from various cadastral GIS, municipal records, or statistical offices. After data preprocessing, every building entry b in a stock B is defined by fields given in Table 1. Data preparation includes merging datasets, extrapolating missing fields, removing duplicates, correcting value types, and standardising values.

In this study, a building use USE(b) is one of seven categories, based on the intended purpose occupying the highest ratio of GFA at the time of building permit. Assuming one single use per building lifespan is reasonable since the structural system is usually unique for the building, and changes of use over time usually only slightly modify the structural system. Each use category is characterised by typical structural demands, i.e. whether building floors in the category are predominantly subject to low or high live loads, and present short of long spans (Appendix A.10).

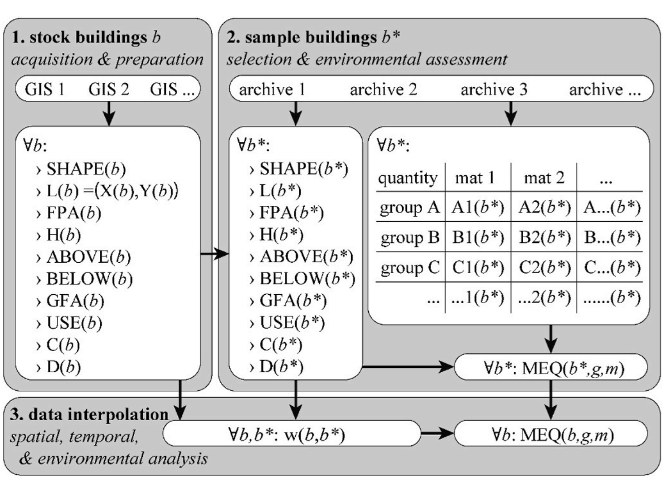

Fig. 1. Research design and methodology. Abbreviations are given in Table 1.

2.2. Sample buildings: selection and environmental assessment

The second step consists of selecting sample buildings, collecting their construction plans, extracting material quantities, and assessing their MEQs.

To ensure accurate interpolations, it is expected that the sampling represents well the breadth of stock buildings across space and time, according to two types of features: their main features provided in the GIS database (type 1); and other features like construction typology, structural geometries, material choices, and assembly processes (type 2). The quality measure of type-1 features is discussed in Section 4.1. Prior expert knowledge of the stock, though often inexistent, is needed to assess the quality of type-2 features. The quality of type-2 features is assumed to increase when large amounts of sample buildings are selected randomly from the stock. Due to the similarity-weighted interpolation function (Section 2.3), the absence of correlated proportionality between sample and stock types does not decrease the interpolation accuracy but may decrease the coverage of its validity.

Consequently, provided that the sampling is large and random, and compared to propagation methods based on simulated archetypes, the method is less dependent on the operator's subjective choices. For instance, there is no need to define any number of archetypal categories, architectural design options, structural design methods, or manufacturing processes beforehand. Although little literature exists on the subject, sampling methods seem, therefore, more appropriate when considering material usage in historical stocks – i.e., when outputs are known, but design and manufacturing processes are mostly unknown – as is the case in this study.

Construction plans and textual descriptions for each sample building are typically obtained from original or published floor plans, sections, material bills, and construction notes. Values for the fields (Table 1) initiate each record. Material quantities per GFA are extracted according to load-bearing components (slabs, beams, walls, posts, and roof framework/cover), construction materials (reinforced concrete, metals, timber, masonry), and construction groups (components that assume a similar load-bearing function; Table 2).

Construction groups are key to assessing MEQs of buildings according to the number of underground and aboveground levels. When stories and structural components are built differently – e.g., with different floor plans or structural member cross sections – material quantities are averaged over all stories in the construction group, weighted by GFA.

Concretely, MEQs are evaluated through three indicators: load-bearing material usage in volume, mass, and EGHGE. They are first computed for each structural component s of construction material m in construction group g of sample building b^*:

$$\mathrm{VOL}(b^*, g, m) = \sum_{s \in S(b^*, g, m)} \mathrm{VOL}(s)\left[m^3\right] \tag{1}$$

Table 1
Features of a building b in stock B.

SHAPE(b)	shape of building ground floor footprint
L(b) = ⟨X(b), Y(b)⟩	location in the reference coordinate system
FPA(b)	ground floor footprint area $[m^2]$
H(b)	height [m], distance between highest point of the building and the ground
ABOVE(b)	number of stories, including ground floor
BELOW(b)	number of underground stories
GFA(b)	total gross floor area $[m^2]$
USE(b)	use category
C(b)	construction year
D(b)	demolition year (optional)

$$\mathrm{MASS}(b^*, g, m) = \sum_{s \in S(b^*, g, m)} \mathrm{VOL}(s)\rho(m)[kg] \quad (2)$$

$$\mathrm{EGHGE}(b^*, g, m) = \sum_{s \in S(b^*, g, m)} \mathrm{VOL}(s)\rho(m)\mathrm{EC}(m)[kgCO_2e] \quad (3)$$

where $S(b^*, g, m)$ is the set of all structural components s with the same m, g, and b^* values; $\mathrm{VOL}(s)$ is the volume of component s $[\mathrm{m}^3]$; $\rho(m)$ is the density of material m $[\mathrm{kg}/\mathrm{m}^3]$; $\mathrm{EC}(m)$ refers to the *EGHGE coefficient* of material m, measured as a mass of carbon dioxide equivalent per mass of material $[\mathrm{kgCO_2e}/\mathrm{kg}]$. In the remainder of this paper, MEQ refers to any of the three VOL, MASS, or EGHGE quantities.

Coefficients for $\mathrm{EC}(m)$ come from life cycle assessment databases for construction materials (Martí et al., 2016). For reasons explained in Section 1.4, environmental effects are quantified before the use phase – i.e., for phases A1 to A3 according to EN15978 (European Committee for Standardization, 2011). As historical EC are unknown, EGHGE are computed as if the stock was to be built using current technologies and associated impacts, as in (Stephan and Athanassiadis, 2017).

MEQs related to all components of material m in sample building b^* are obtained by summing over all construction groups g_i, considering the number of underground and aboveground floors (Equation (4)). MEQs related to all components in a sample building b^* are obtained by summing over all construction materials $m \in M$ (equation (5)):

$$\mathrm{MEQ}(b^*, m) = [\mathrm{MEQ}(b^*, H-, m) + \mathrm{MEQ}(b^*, V-, m)]BELOW(b^*) + \mathrm{MEQ}(b^*, H\circ, m) + \mathrm{MEQ}(b^*, V\circ, m) + [\mathrm{MEQ}(b^*, H+, m) + \mathrm{MEQ}(b^*, V+, m)][ABOVE(b^*) - 1] + \mathrm{MEQ}(b^*, R, m)\,[m^3] \; or \; [kg] \; or \; [kgCO_2e] \quad (4)$$

$$MEQ(b^*) = \sum_{m \in M} MEQ(b^*, m)\,[m^3] \; or \; [kg] \; or \; [kgCO_2e] \quad (5)$$

Table 2
Description of construction groups.

group	component type	typical floor
H−	horizontal supports (slabs and beams)	underground level
V−	vertical supports (walls and columns)	
H○	horizontal supports (slabs and beams)	ground level
V○	vertical supports (walls and columns)	
H+	horizontal supports (slabs and beams)	upper level
V+	vertical supports (walls and columns)	
R	roof or attic structural system	

2.3. Data interpolation

In the third step, data on sample buildings b^* are interpolated to estimate MEQ s of each building b in the comparatively vast stock B using only global building features on b, as defined in Table 1. The rationale is that a reasonable estimate of $\mathrm{MEQ}(b, g, m)$ for a stock building b is close to $\mathrm{MEQ}(b^*, g, m)$ of any sample building b^* that shares similar building features with b. Existing methods for defining similarity between sample buildings b^* and stock buildings b either segment the stock into hermetic archetypal categories defined by ranges of feature values (Fig. 2a) or assign stock buildings to their nearest-neighbor archetype based on feature values (Fig. 2b). The present work uses a similarity-weighted function (Fig. 2c) to limit threshold effects. Similarity-weighted functions are commonly used in pattern recognition, e.g., in weighted k-nearest-neighbor classifiers (Hechenbichler and Schliep, 2004).

Accordingly, each building MEQ depends on a series of similar sample buildings, each influencing the building with a stronger or weaker weight depending on the level of similarity. $\mathrm{MEQ}(b, g, m)$ values are weighted averages of $\mathrm{MEQ}(b^*, g, m)$ values of all buildings b^* in sample B^* that belong to the same building use category as b (Fig. 2c):

$$\mathrm{MEQ}(b, g, m) = \frac{\mathrm{GFA}(b) \sum_{\substack{b^* \in B^* \\ \mathrm{USE}(b^*) = \mathrm{USE}(b)}} \left(w(b, b^*) \frac{\mathrm{MEQ}(b^*, g, m)}{\mathrm{GFA}(b^*)} \right)}{\sum_{\substack{b^* \in B^* \\ \mathrm{USE}(b^*) = \mathrm{USE}(b)}} w(b, b^*)} \; [m^3], [kg], or \; [kgCO_2e] \quad (6)$$

Global values of $\mathrm{MEQ}(b)$ are obtained using equations (4) and (5). Each weight $w(b, b^*)$ is computed from a distribution function applied to selected building features. Three building features are used in this study: construction year C; building height H; and building location L. They are chosen because they are commonly provided in national GIS databases. Sample buildings b^* that are too dissimilar from b – i.e., that lie beyond a predefined threshold ellipsoid around b (Fig. 3a) – are discarded when computing that b.

The chosen distribution function is a linear decrease within this threshold (Fig. 3b). Other available distribution functions are, for instance, a constant value, a sine decrease, or a normal decrease (right half of a normal distribution). In all functions, the weight is equal to 1 when the distance $\mathrm{dist}(b, b^*)$ is 0, decreases to 0 when the distance $\mathrm{dist}(b, b^*)$ reaches 1, and is equal to 0 when it is greater than 1. Assuming a linear decrease, this distribution translates to equation (7). The 4-dimensional Euclidean distance $\mathrm{dist}(b, b^*)$ is computed over all chosen building features (equation (8)). The Euclidean distance is chosen from available types of distances (Wilson and Martinez, 2000).

$$\mathrm{w}(b, b^*) = 1 - min(1, \mathrm{dist}(b, b^*))[-] \quad (7)$$

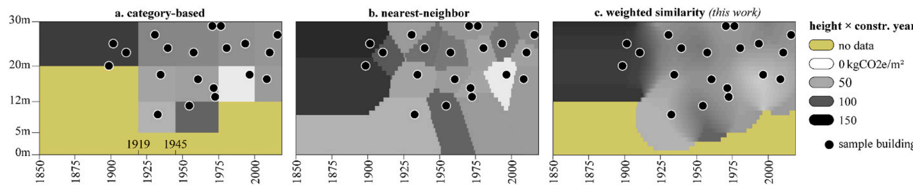

Fig. 2. Interpolation methods: example of EGHGE per GFA values for construction group g_D in multi-residential buildings assuming a 2-dimensional similarity based on building height and construction year only.

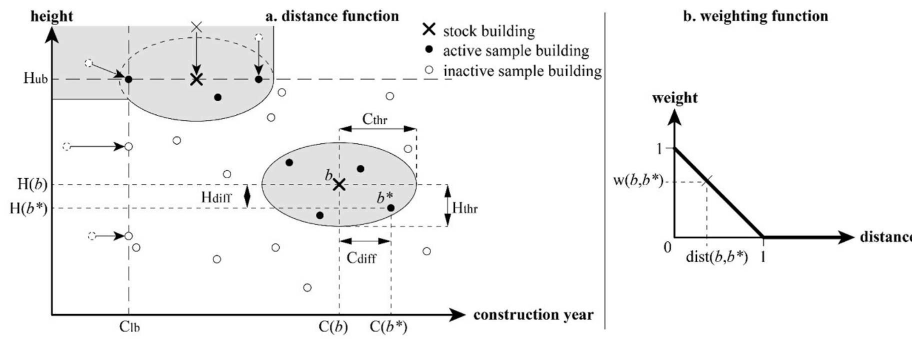

Fig. 3. *Similarity-weighted function: (a) example of ellipsoidal distance threshold; (b) linear weighting on two dimensions (construction year and building height).*

$$\text{dist}(b,b^*) = \sqrt{\left(\frac{C_{\text{diff}}(b,b^*)}{C_{\text{thr}}}\right)^2 + \left(\frac{H_{\text{diff}}(b,b^*)}{H_{\text{thr}}}\right)^2 + \left(\frac{X_{\text{diff}}(b,b^*)}{L_{\text{thr}}}\right)^2 + \left(\frac{Y_{\text{diff}}(b,b^*)}{L_{\text{thr}}}\right)^2} \, [-] \tag{8}$$

where C_{thr} , H_{thr}, and L_{thr} define the threshold distances in the construction year, building height, and building location dimensions, respectively (Fig. 3a). Functions $C_{diff}(b,b^*)$, $H_{diff}(b,b^*)$, $X_{diff}(b,b^*)$ and $Y_{diff}(b,b^*)$ return the unidimensional differences between stock and sample building features:

$$C_{\text{diff}}(b,b^*) = max(C_{lb}, C(b)) - max(C_{lb}, C(b^*))[yr] \tag{9}$$

$$H_{\text{diff}}(b,b^*) = min(H_{ub}, H(b)) - min(H_{ub}, H(b^*))[m] \tag{10}$$

$$X_{\text{diff}}(b,b^*) = X(b) - X(b^*)[m] \tag{11}$$

$$Y_{\text{diff}}(b,b^*) = Y(b) - Y(b^*)[m] \tag{12}$$

Depending on the considered dimension, unidimensional differences below lower or above upper bounds are neglected to ensure a high density of active sample buildings, even for buildings with extreme features. For instance, in the construction year dimension, buildings constructed before a specific date C_{lb} are assumed to be the result of similar construction techniques with similar environmental effects, especially if C_{lb} precedes the industrial revolution. Values of construction years $C(b)$ and $C(b^*)$ older than a lower bound C_{lb} are therefore assumed to be equivalent to that lower bound (equation (9)). Similarly, values of building height $H(b)$ and $H(b^*)$ higher than an upper bound H_{ub} are moved down to that upper bound (equation (10)).

The fields VOL(b), MASS(b), and EGHGE(b) are finally added to each building entry b in the GIS database.

2.4. Definition of indicator to associate environmental effects and aspects of use value

In addition to the method given in Section 2.3, an indicator is introduced to relate MEQs with some aspects of building use value synthetically. Conceptually, a building's MEQ is considered a one-time investment to create a new commodity, and the building use value measures the expected return on investment. In this paper, the meaning of building use value is confined to the availability of space over a reference period p. The indicator quantifies the amount of invested MEQ s yet to be returned at a time t. In other words, the indicator quantifies the ratio of MEQ s that is inversely proportional to the utilisation of the building(s), where utilisation is understood as the ratio between effective service life at time t – i.e., $\min(D(b),t) - C(b)$ – and the reference period p. Consequently, the indicator allows a comparison of MEQ s between buildings or building stocks while accounting for the different historical developments – i.e., accounting for the fact that they have been utilised differently at a time t of the measure.

Concretely, the indicator $U\_MEQ_{t,p}(b)$ quantifies the unutilised MEQ (MASS, VOL, or EGHGE) of a building b at a reference time t, assuming

Table 3
Summary of GIS data aggregation.

	# building entries	footprint area	gross floor area
total after integration	84,477 (100%)	1447 ha (100%)	6056 ha (100%)
useable entries in main source, before integration	9624 (11.4%)	175 ha (12.1%)	2163 ha (35.7%)
useable entries after integration	64,368 (76.2%)	1278 ha (88.3%)	5557 ha (93.3%)

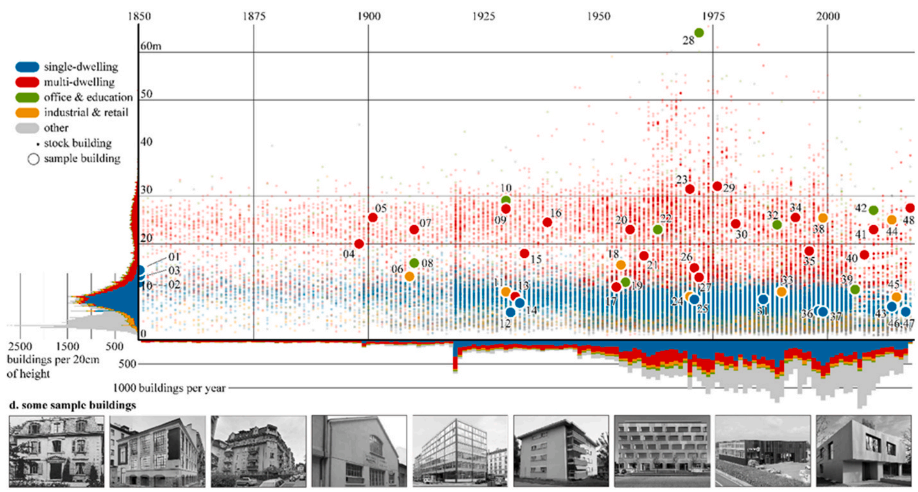

Fig. 4. Characterisation of the 84,477 building entries and 48 sample buildings. See Figures A1, A3, and B.1 in the appendices for the location of buildings.

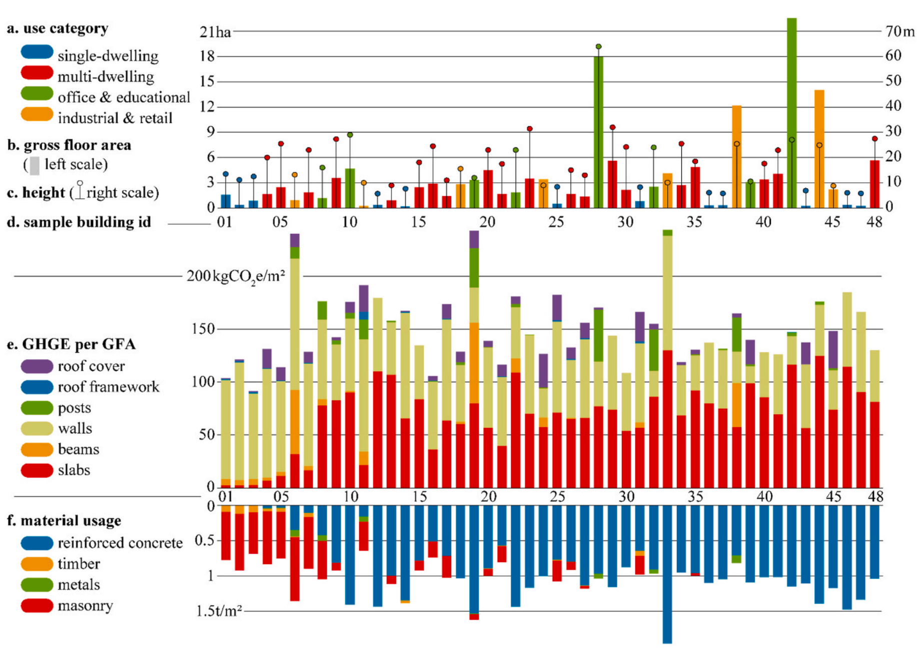

Fig. 5. Main features and environmental assessment results of 48 sample buildings, ordered from oldest to newest construction date.

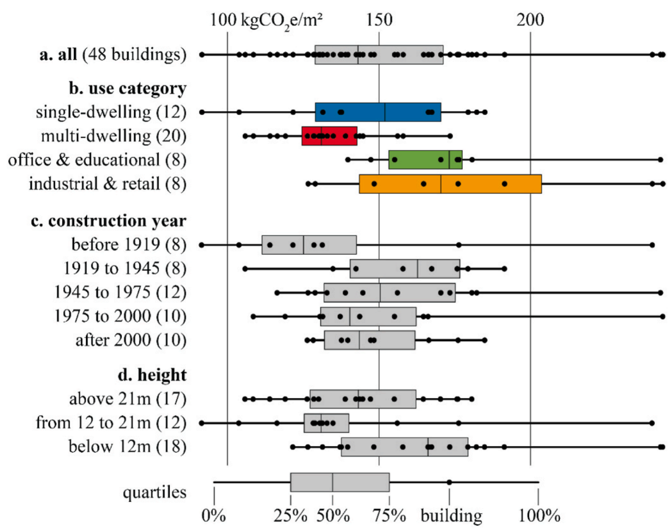

Fig. 6. Distributions of EGHGE per GFA for all sample buildings, by main use, construction year, and height. Colours are similar to those of Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

full utilisation after period p after construction (equation (13)). For instance, buildings with an effective service life greater than p in year t have a zero value. The value will increase up to MEQ(b) as the building service life measured in year t decreases up to 0. A greater period p diminishes the impact of time: $\text{U\_MEQ}_{t,\infty}(b) = \text{MEQ}(b)$. Two implementations of this indicator are showcased in Figs. 9c and 12.

$$\text{U\_MEQ}_{t,p}(b) = \min\left(1, \max\left(0, 1 - \frac{\min(\text{D}(b), t) - \text{C}(b)}{p}\right)\right)\text{MEQ}(b) \quad [m^3], [kg], or\ [kgCO_2e] \tag{13}$$

When applied to a building stock B, the indicator describes the density of unutilised MEQs per available GFA at a time t (equation (14)), which is particularly relevant when the stock includes buildings that have been demolished before reaching full utilisation. Low values correspond to stocks presenting low renewal rates, large quantities of old buildings, or large quantities of buildings with low MEQs per GFA. An implementation of this ratio is showcased in Fig. 11d.

$$\text{U\_MEQ}_{t,p}(B)/\text{GFA}_t(B) = \sum_{\substack{b\in B \\ \text{C}(b)\le t \\ \text{D}(b)\ge t-p}} \text{U\_MEQ}_{t,p}(b) \Big/ \sum_{\substack{b\in B \\ \text{C}(b)\le t \\ \text{D}(b)\ge t}} \text{GFA}(b) \quad [m^3/m^2], [kg/m^2], or\ [kgCO_2\,e/m^2] \tag{14}$$

3. Application to the Canton of Geneva, Switzerland

The application of the methods (Section 2) to the case study defined in Section 3.1 leads to various types of results: an environmental assessment of sample buildings (Section 3.2); global material uses in the building stock (Section 3.3); and spatiotemporal analyses of MEQs in the interpolated building stock (Sections 3.4, 3.5, 3.6).

3.1. Building stock

The Canton of Geneva is chosen as a case study and offers extensive building records and easily accessible stock and sample data. It has an area of 282 km^2 and a population of 507,000 (R é et al., 2018; R é et al., 2020). Integrating various GIS datasets is necessary to ensure a sufficiently large number of buildings with properly defined fields, as listed in Table 1. All details of the integration are provided in Appendix A. A summary of this operation is given in Table 3.

Fig. 4 plots all buildings by height, use, and approximated construction year. The oldest building in the set was constructed in 1724. Most building construction happened after World War II, with an average construction date in 1970. Sudden increases in construction activity – e.g., in 1899, 1919, or 1970 – are most probably artefacts of the way local administrations have recorded construction years. The uniform distribution of construction years prior to 1919 is an artefact of the randomisation method used when different construction years are found for the same building entry (see Appendices A.7 and A.8).

Fig. 4 highlights a correlation between building uses and building heights. *Industrial & Retail* buildings concentrate below 13 m. *Single-dwelling* building heights follow a normal distribution with a mean value of around 9 m. *Multi-dwelling* buildings are generally higher than 10 m. Until the 1950s, a noticeable gap exists between building heights of 15 and 20 m. The reasons behind this gap are unknown to the authors and may be due to local legislation on building heights or economic performance logic.

3.2. Sample buildings

The selected sample buildings span the full spectrum of building uses, construction years, and heights in the Canton of Geneva (Fig. 4). Their main features are provided in Appendix B, together with a description of the sources used to extract their construction drawings and material quantities. The chosen quantity of 48 sample buildings met time restrictions for the study while ensuring a good representativity of the building stock, as discussed in Section 4.1.

The Swiss official reference for environmental effects of building materials, KBOB (Koordinationskonferenz der Bau-und Liegenschaftsorgane der ö and ffentlichen Bauherren, 2016), was used to obtain EC coefficients (equation (3), Appendix C), which relies on

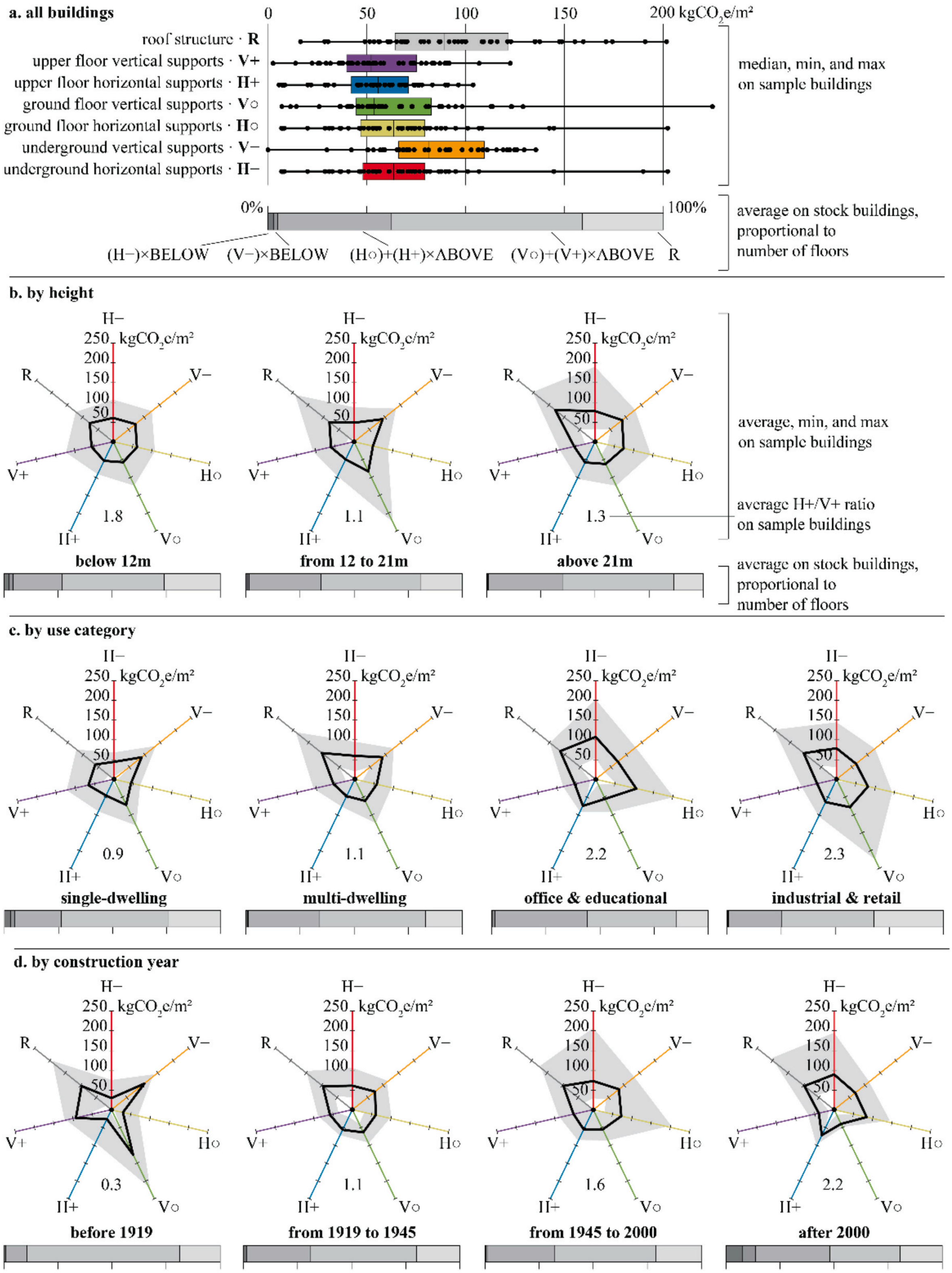

Fig. 7. Magnitude of construction groups' EGHGE per GFA on sample and stock buildings.

process analysis as a life cycle inventory technique. MEQs from the analysis of sample buildings are depicted in Figs. 5 and 6. On average, most EGHGE impacts are due to slabs (44.5%) and walls (44.4%). Multi-dwelling buildings contribute less than single-dwelling buildings (Fig. 6b) regarding EGHGE per GFA. Office, educational, industrial, and retail buildings present larger values than housing buildings. Buildings built before World War I showcase significantly little EGHGE, but no trend can be extracted for buildings built after that (Fig. 6c).

Regarding material usage (Fig. 5f), reinforced concrete is the primary load-bearing material for buildings built after the 1930s. Intensities are generally twice as large as the minimum structural requirements simulated in (D'Amico et al. 2020), as the latter study only considers vertical

Table 4
Volume, mass, and EGHGE of structural elements in the building stock. (*) the projection made from interpolated data assumes the same ratio between studied GFA and total GFA

	studied	total	total per capita	average by building GFA
Population (residents only | residents + commuters)		507,000 | 650,000 capita		
gross floor area	47,265,687 m^2	59,574,149 m^2	118 | 92 m^2/capita	
volume of structural material	21,396,024 m^3	26,967,765 m^3 (*)	53 | 41 m^3/capita (*)	**0.52 m^3/m^2**
mass of structural material	44,675,621 t	56,309,604 t (*)	111 | 86 t/capita (*)	**0.989 t/m^2**
upfront EGHGE in structural elements	6,448,114 tCO_2e	8,127,268 t CO_2e (*)	16 | 13 t CO_2e/capita (*)	**0.147 t CO_2 e/m^2**

load bearing systems. Masonry comes second and is the most common load-bearing material prior to the introduction of concrete. Nearly all sample buildings use timber and metal in negligible quantities.

3.3. *Data interpolation parameters and global results*

The interpolation method described in Section 2.3 relies on a series of constants. In this study, thresholds C_{thr} and H_{thr} are respectively set equal to 25 years and 8 m – i.e., assuming that design and construction techniques are similar within those ranges. Threshold L_{thr} is set to infinity because all sample and stock buildings in this study are located in the same industrial region and built according to the same regulations and building techniques (Schwab and Rinquet, 2018a). Bounds C_{lb} = 1900 and H_{ub} = 30m are chosen in light of the building stock distribution and the availability of sample buildings. The low value for H_{ub} means that no 'premium for height' effect (Helal et al., 2020; Khan and Rankine, 1981; Ali and Moon, 2007) is considered for buildings higher than 30 m. This omitted effect has little consequence in this case study since the number of high-rise buildings is tiny.

Fig. 7 presents results for EGHGE per GFA. Other MEQ metrics are available in the linked dataset (Fivet et al., 2023). Contributions of each construction group have similar magnitude and tendency when normalized by GFA (Fig. 7a), suggesting that the number of stories has little influence on the interpolated EGHGE per GFA globally. However, this global trend does not apply to buildings that are 12–21 m high (Fig. 7b), office, educational, industrial, and retail buildings (Fig. 7c), and buildings that are not built between the two World Wars (Fig. 7d). This observation calls for a closer inspection of the underlying reasons, especially with regards to historical construction methods and design guidelines.

When comparing building use categories (Fig. 7c): dwelling buildings are characterised by low-impact horizontal supports, which can be explained by typical small spans; horizontal supports in office and educational buildings are expected to have proportionally larger cross-

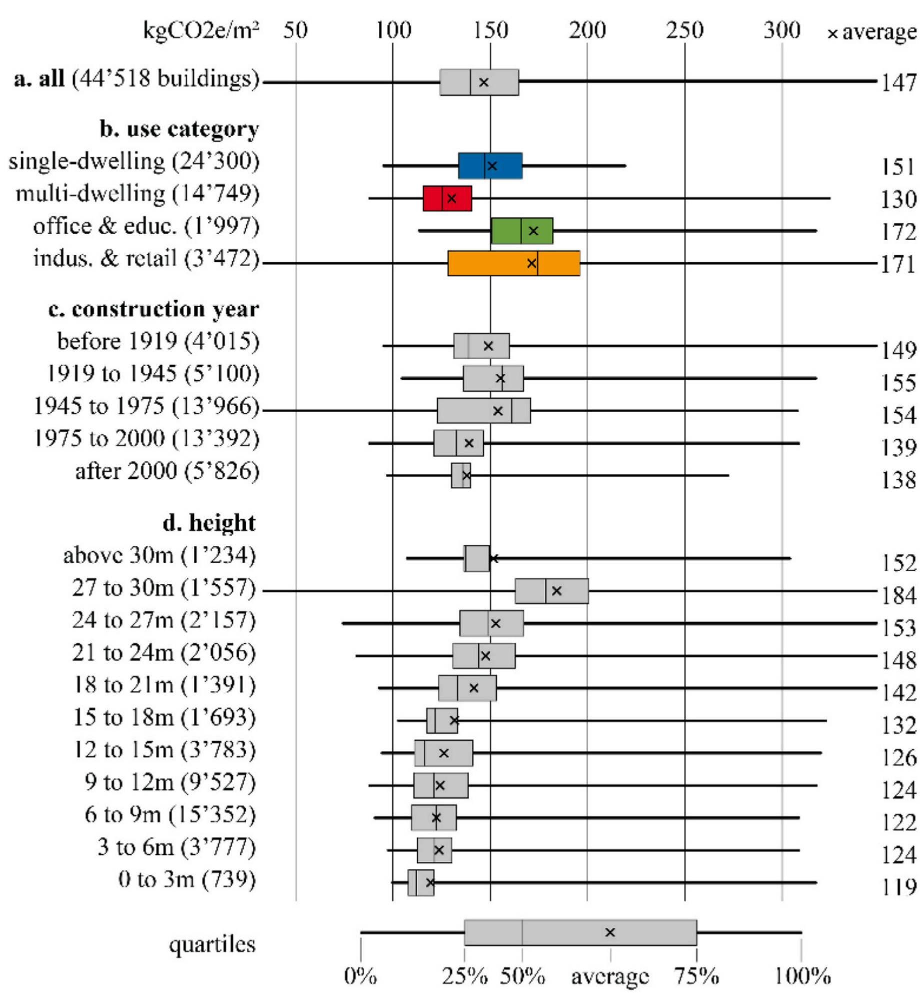

Fig. 8. Distributions of EGHGE per GFA for all stock buildings by use category, construction year, and height.

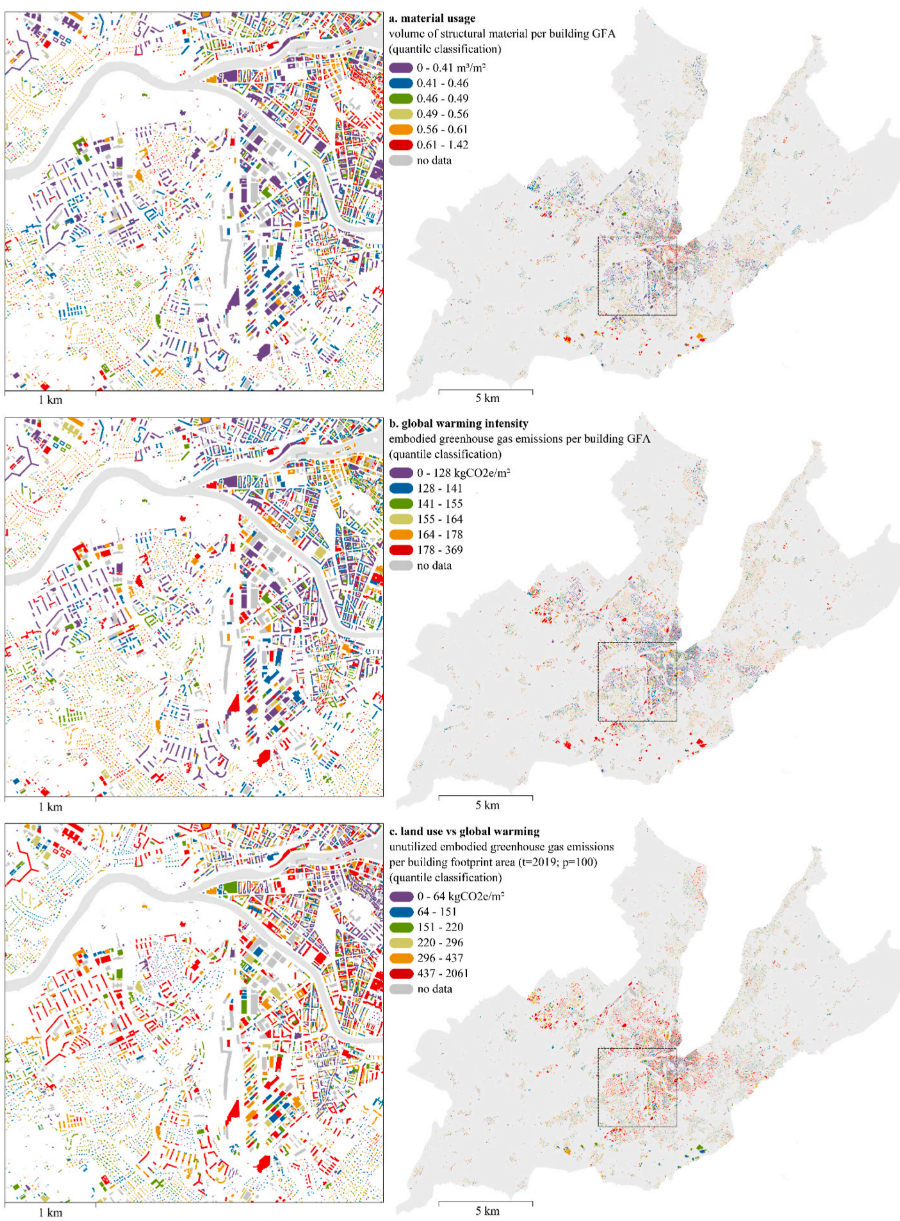

Fig. 9. Geographical distributions of material usage, EGHGE, and unutilised EGHGE.

Fig. 10. Spatial distribution of material usage in terms of mass. One dot per building.

section dimensions, which can be explained by larger spans and higher applied loads; ground floor vertical supports in industrial and retail buildings have a high impact, probably because most of those buildings are one-story high with large spans and long vertical supports that must be designed against buckling. EGHGE ratios between horizontal and vertical elements are more than twice as great in office buildings (2.2) than in single-dwelling housing (0.9). The same ratio increased eight times since 1919 (0.3–2.2, Fig. 7d).

The relative impact of aboveground horizontal supports in terms of EGHGE per GFA continuously increased over time, from 10% prior to 1919 to 34% after 2000 (Fig. 7d). Distribution trends across construction groups are globally equivalent when considering buildings built after 1919. Construction groups H−, H○, and R (Table 2) in buildings built since 1945 present significant variations, but this might be related to the higher rate of office, educational, industrial, and retail buildings in this period.

After interpolation over the entire building stock, and given the scope described in Section 1.1, EGHGE per GFA in buildings amount to

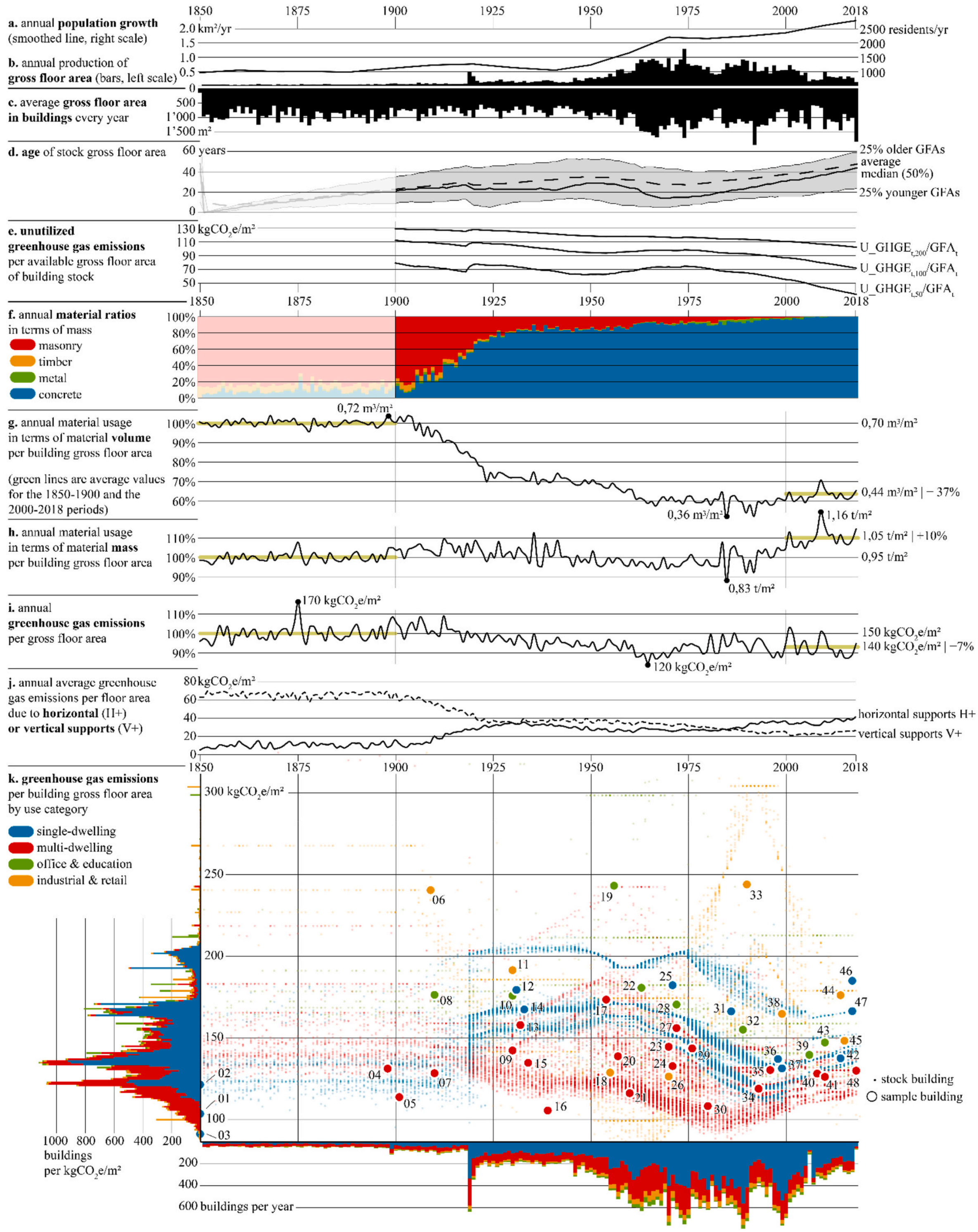

Fig. 11. Temporal analysis of the building stock in Geneva in terms of mass, volume and greenhouse gas emissions.

147 kg CO_2 e/m^2 on average. Also, on average, 989 kg and 0.52 m^3 of load-bearing materials are needed for each square meter of gross floor area (Table 4). Variations of EGHGE per GFA in the interpolated building stock are shown in Fig. 8 for the selected use categories, construction periods, and building heights. Globally speaking, higher buildings have higher EGHGE per GFA (Fig. 8d), which is explained by longer load paths in the building. Average values have reached an all-time low since 2000 (Fig. 8c). On average, multi-dwelling buildings present values that are 14% smaller than single-dwelling buildings (Fig. 8b). This conclusion, which only applies in this context of Geneva and for the assumptions made at the beginning of this section, may simultaneously call for limiting the production of single-family houses in favour of multi-residential buildings and for maintaining (and transforming) existing single-family houses in the long term.

3.4. *Spatial distributions*

A geographical layout of interpolated values is provided in Fig. 9.

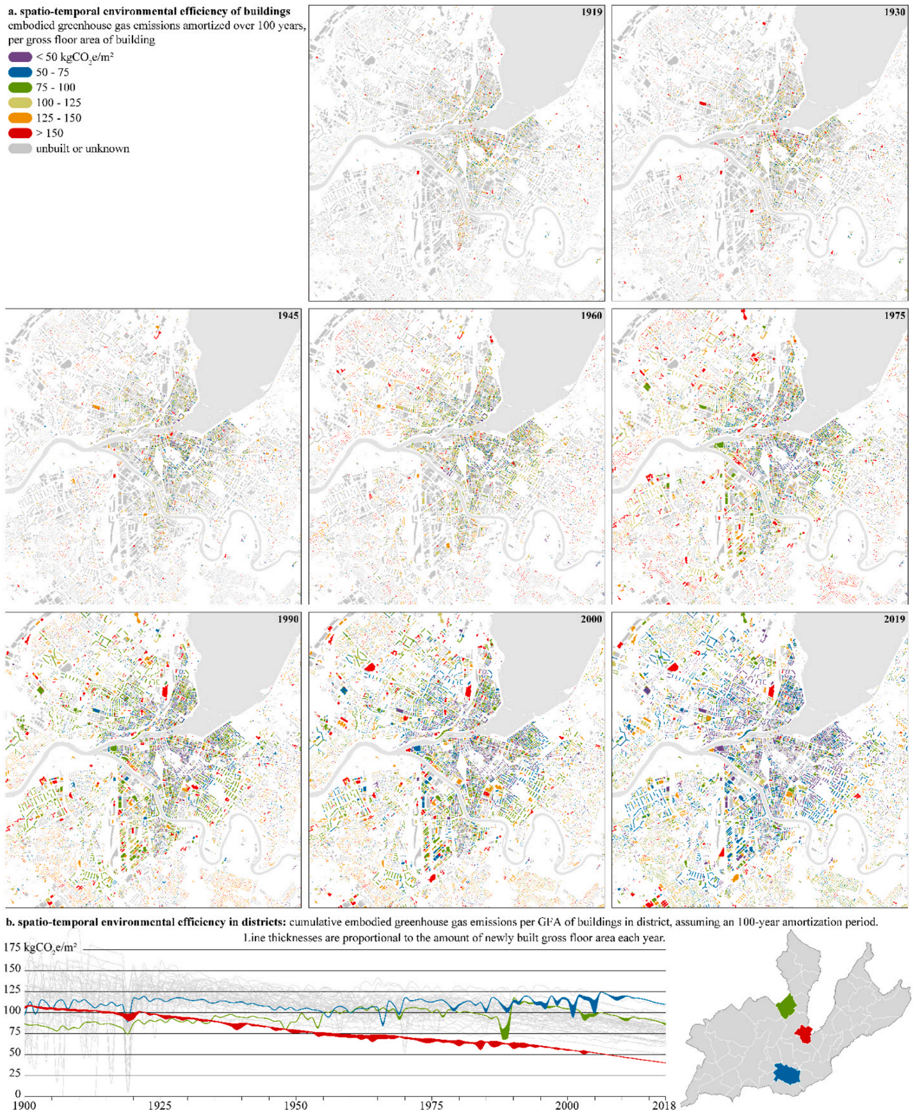

Fig. 12. Evolution of U_EGHGE$_{t,100}$ per GFA (a) by buildings and (b) by districts, see Section 2.4. Colours in figure (b) are unrelated to the legend of figure (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The colouring method spreads buildings into even-sized categories (quantile classification). Assuming a Gaussian distribution of values, this colouring method reduces differentiation near extreme values but increases differentiation in the vicinity of the median value, which is why it is chosen.

Regarding material usage, high densities of materials, above 0.61 m^3/m^2, mainly concentrate in the city centre area and in large industrial buildings outside the city (Fig. 9a). Dense housing and office settings, mostly located directly outside the city centre, are characterised by low values, below 0.46 m^3/m^2, whereas detached houses, mostly located in suburban areas, are characterised by slightly larger values, between 0.46 and 0.61 m^3/m^2.

The geographical distribution of EGHGE per building GFA (Fig. 9b) differs from the previous figure in two instances: in the city centre, where old buildings, mainly made of stone masonry, have a high volume of material with small EC; and in large industrial and retail buildings, mainly made of steel, for opposite reasons.

Interpolated values of U_MEQ$_{2019,100}$ (equation (13)) per building footprint area are mapped in Fig. 9c for an arbitrary period p of 100 years. This indicator reflects the environmental investment lost if a parcel was to be recovered for another land use in 2019, assuming an expected building service life of 100 years. In Fig. 9c, buildings with low values are old buildings in the city centre (below 64 kg CO_2 e/m^2) or low-rise buildings in suburban developments (between 64 and 296 kg CO_2 e/m^2). In the former case, long-standing buildings have proven to withstand changes in functional requirements over time. In the latter case, building demolition would lead to a relatively small loss of environmental investment. Conversely, buildings with high values (above 296 kg CO_2 e/m^2) are younger, more material-intensive, or a combination of both. In any case, high values mean that a change of land use is premature for environmental reasons and that in-situ building transformation should be encouraged over the demolition of the building structure. However, the same buildings might prove unable to adapt to new functional requirements without significant adverse environmental effects.

Fig. 10 displays the intensities of use, in terms of mass, for each of the four main construction materials: (reinforced) concrete, metal, timber, and masonry. In short, metal is mainly used in the city centre; concrete is used everywhere, with high ratios in dense settlements; and timber and masonry use are spread over the canton with higher intensities in the city centre.

3.5. Temporal distributions

Fig. 11 characterises the evolution of material efficiency from 1850 to 2018, considering all 44,701 studied buildings at once. As a reminder, the collected data is limited to buildings that are still standing today, and assessments do not account for environmental effects related to building renovation and transformation.

While the average GFA in buildings has been relatively constant (±970 m^2 per year, Fig. 11c), the annual production of GFA follows a bell curve with a peak in 1974 (1282 km^2, Fig. 11b). The same period corresponds to a loss of correlation between population (Fig. 11a) and GFA growths (Fig. 11b). This is concurrent with when the first law on territorial and urban planning (L'Assemblée fédérale de la Confédération Suisse, 1979) enters into force, which restricts construction on virgin ground. In 2018, the median and average ages of buildings in the Genevan building stock were 45 and 49 years, respectively (Fig. 11d).

The evolution of $U\_EGHGE_{t,p}(\text{Geneva})/GFA_t(\text{Geneva})$ where t varies from 1900 to 2018 is shown for three amortisation periods (Fig. 11e, see Section 2.4). Curves peaked in 1919, decreased until 1945, increased again until the 1970s, and decreased until 2018. Increases correspond to periods of large amounts of construction – i.e., after each World War. The metric has been the lowest since 1850 and keeps declining, which could be interpreted as the fact that the Canton of Geneva's offer in terms of useable space mainly relies on old constructions, with limited new investment for future growth. A study of this metric at the district level is provided in the next section and confirms the interpretation (Fig. 12b).

After 1900, Fig. 11f highlights the transition from masonry (stones and bricks) structural solutions to reinforced concrete. It also emphasises the dominance of reinforced concrete in contemporary constructions in Geneva. On a side note, the presence of concrete in the 19th century is a computational artefact due to the interpolation constant $C_{lb} = 1900$. A lower C_{lb} and the addition of sample buildings built before 1925 would get distributions closer to reality.

Fig. 11g, h, and i give the evolution of material and EGHGE densities in buildings over time. Whereas each point in Fig. 11g, h corresponds to the normalized sum of ratios between a building intensity and its GFA, points in Fig. 11i correspond to the division between the sum of all building intensities and the sum of all building GFAs. The 100% benchmark (green segments on the left) averages over the first 50 years; the final ratio averages values between 2000 and 2018. Over time, volumes of load-bearing material per GFA in buildings have decreased by 37%, with minimum and maximum year averages of 0.36 m^3/m^2 and 0.72 m^3/m^2 (Fig. 11g).

However, the mass of load-bearing material per GFA has slightly increased by 10% (Fig. 11h). This can be partly explained by reinforced concrete allowing smaller cross sections than masonry for the same compressive stresses. Values have reached an all-time low in the 70s (0.83 t/m^2) and significantly increased since then, with unprecedented high values in the recent decades (1.16 t/m^2). A recent increase in structural volume accompanies this recent increase in structural mass. Further research needs to be conducted in order to confirm these trends and to identify whether recent increases are related to higher safety ratios demanded by recent norms, to a homogenisation of poorly-optimised construction methods, or to designers leaning towards more conservative cross-section sizing, as suggested in (Orr, 2018).

Data shows that EGHGE of load-bearing materials per GFA slightly decreased over the past century (Fig. 11i) with an average drop from 150 to 140 kg CO_2e/m^2, and a minimum achieved in the 60s (120 kg CO_2e/m^2). These variations are smaller than the interpolation error (Section 4.2), and a sensitivity analysis is needed to validate them. Also, it must be recalled that, due to the lack of proper data on historical ECs, ECs are assumed to be equivalent to those produced today, which is potentially far from accurate. Under these assumptions, the chart suggests that the transition from masonry to reinforced concrete did not significantly influence the environmental impact of new construction.

A clear shift of preponderance between vertical – e.g., columns & walls – and horizontal supports – e.g., beams and slabs, happened in the last 100 years (Fig. 11j). Before 1900, EGHGE related to horizontal supports were about 20% of those related to vertical supports (about 70 kg CO_2e/m^2). The gap vanished from 1900 to 1925, which correlates to the shift of primary material from masonry (stone and bricks) to concrete and reinforced concrete (Fig. 11f), and the decrease of overall material volume over the same period (Fig. 11g). The transition led to common values ranging between 30 and 40 kg CO_2e/m^2 until 1985. Then, EGHGE related to vertical supports dropped to 67% of those related to horizontal supports (40 kg CO_2e/m^2) in recent years, which is relatively high compared to minimum structural requirements for reinforced concrete frame systems and might be explained by a regional tendency to favour load-bearing partitioning walls over layouts of load-bearing columns and lightweight partitions. It might also be explained by recent demands for office, industrial, or commercial building typologies with larger spans.

After 1919, distinct clusters by building use category exist when plotting buildings' EGHGE per GFA against their construction year (Fig. 11k). The wave-like aspect of these clusters is due to the weighing function used for interpolation. The sharpness of the edges of these groups is due to the low number of sample buildings. More sample buildings would make group boundaries blurrier.

3.6. Spatiotemporal distributions

Fig. 12a spatializes $U\_EGHGE_{t,100}(b)/GFA(b)$ values for all buildings b built from 1919 to 2019. The indicator (see Section 2.4) can be interpreted as the investment loss that the demolition of a building would cause when considering its contribution to the global GFA of the stock during the past 100 years. At the time of construction year, buildings already showcase a variety of magnitudes. These values then all decrease over time. Not only does the sequence inform about the continuous spread of buildings away from the city centre in the past century, it also allows the comparison of EGHGE of newly constructed buildings with older ones. For example, buildings with efficient construction in terms of EGHGE start with lower values – e.g., smaller than 75 kg CO_2e/m^2 – that other less efficient buildings might only achieve after a long period – e.g., 30 years. In addition, Fig. 12 highlights that the frequency and footprint of buildings with high EGHGE per GFA – i.e., over 150 kg CO_2e/m^2 – increased in the past three decades.

The evolution of the $U\_EGHGE_{t,100}$ per GFA indicator is also useful to compare how different building stocks capitalise on past or recent EGHGE to make floor areas available, or in other words, how old their EGHGE contributions are, and how much is yet to be paid back in terms of useable space over time. For instance, Fig. 12b compares three different districts in the canton. The red one was built at a regular pace, in small amounts, for a very long time: the indicator has been decreasing linearly since 1900. The other two have been home to large realty developments only in recent decades: their indicator is twice as high today, suggesting that eventual upcoming systemic demolitions in those districts would present a greater loss on EGHGE investment than in the red district. Simultaneously, the older red district has also demonstrated its ability to adapt to new functional demands over time.

To conclude, Fig. 12 stresses the need for further multiscale and multidisciplinary studies linking variations of EGHGE over space and time with the evolution of urban fabrics, renewal rates, realty assessments, urban regulations, development strategies, societal needs, building typologies, design norms, construction techniques, and industrial economy.

3.7. Validation

The quality of results presented in this section is discussed across two aspects in Appendix D: quality of data coverage after interpolation (Appendix D.1), which shows a high coverage ratio (79% of total GFA) despite a very small ratio of sample buildings (0.06%); and estimation of interpolation errors (Appendix D.2), which presents value similar to previous publications.

4. Discussion and conclusion

4.1. Summary of contributions

For insights into structural material efficiency over large building stocks, this paper presented: a new method to interpolate material and emissions quantities (MEQs) from sample buildings; a new indicator $U\_MEQ_{t,p}$ to consider payback on environmental investment when measuring MEQ s in buildings and cities over different periods; the detailed analysis of material usage (mass and volume) and embodied greenhouse gas emissions (EGHGE) in 48 building samples; and the analysis of structural material efficiency in 84,477 buildings in the Canton of Geneva, from 1850 to 2018. A threefold error analysis validated the results.

The originality of the interpolation method presented lies in using a similarity-weighted function, which avoids threshold effects between building typologies and increases data accuracy as the number of studied sample buildings grows. The method ensures both a similar probabilistic distribution between stock and sample features, and a uniform correlation between building features and resulting values. It also improves data granularity by parameterising buildings down to the structural component level, differentiating between slabs, beams, columns, and walls across construction materials and underground, ground, aboveground, and roof levels.

The application of the method to Geneva's building stock leads to the following results.

- The volume of load-bearing components per GFA has decreased by 37% since 1900, due to the transition from masonry and timber materials to reinforced concrete in the first quarter of the 20th century, and is linked to an increase of EGHGE share by horizontal supports over the same period;
- Masses and EGHGE of load-bearing components per GFA remained steady since 1850, fluctuating around 1 t/m^2 and 150 kg CO_2e/m^2 (using a process-based life cycle inventory analysis);
- The two points above suggest that materials and construction techniques introduced in the past century occupy less volume in buildings for a same mass.
- Multi-residential buildings generally present lower MEQs per GFA than single-dwelling housing;
- Sources of MEQs concentrate in columns and walls in housing buildings, and in beams and slabs in office buildings;
- Data suggest that an optimal building height minimising MEQs per GFA may exist;
- The largest increase of MEQs in newly built GFA occurred after each World War and is well captured by the new indicator of unutilised MEQ ($U\_MEQ_{t,p}$), which is based on the concept of environmental investment;
- Since the end of the 20th century, the $U\_MEQ_{t,100}$ values have been the lowest and continue to decrease across the entire canton – however, these values show significant variation at the district level due to different historical urban development patterns;
- The demolition of buildings in the historic centre would be less detrimental in terms of loss of invested EGHGE, but the same buildings also demonstrate their resilience to adapt to new functional demands over time.

4.2. Limitations and future developments

Future developments of the method must overcome current limitations on inventory characterisation, life cycle assessments of sample buildings, and interpretations of results.

The inventory characterisation will improve with more sample buildings, which will decrease mean errors of interpolation but increase the reliance on local raw data on sample buildings. It will also improve by adding data on changes in building uses, building transformations, e.g. in (Rauf and Crawford, 2015), and demolished buildings. As interpolation accuracy will vary with the choice of threshold values, similarity-weighted functions and distance functions, dedicated sensitivity analyses should increase accuracy of the results, which should be the focus of future research developments. It will then be appropriate to compare the performance of our similarity-weighted function with other state-of-the-art methods, especially with regards to the impact of the sample size onto the interpolation error.

Life-cycle assessments will improve with: the use of more context-specific functional units, other than building units and GFA; the computation of historical EGHGE coefficients of construction materials if available or other indicators that remain relevant over long periods; the extension of the scope to include foundation works and other construction components in buildings as well as non-building city infrastructure; the inclusion of the end-of-life stage; the replacement of a process-based life cycle inventory technique with a hybrid analysis (Crawford et al., 2018a).

The interpretations of results will benefit from: a more nuanced description of the expected functional requirements of the studied components (e.g., some bearing components also fulfil non-structural requirements, and their volume is not only related to pure structural considerations); a correlation analysis between building stocks and residential/working population growths, at the district level and for various urban density gradients; a comparison with other cities in Europe and worldwide; and an in-depth search for correlations between architectural typologies, construction techniques, historical urban developments, and developments of functional demands by societies.

The parameters used to compute $U\_MEQ_{t,p}$ values are chosen at 50, 100 and 200 years based on common values and to demonstrate the concept. However, the choice of an appropriate amortisation period p should be supported by other studies on long-term urban developments. Because of arbitrariness related to the choice of p and because the computed EGHGE values assume constant EGHGE factors irrespectively of the actual year of building construction, it is expected that the $U\_MEQ_{t,p}$ values may only be relevant when comparing different cities or districts. Nevertheless, more reflections are needed to better frame the limit of interpretation of $U\_MEQ_{t,p}$ values, especially for policy making.

4.3. Relevance and outlook

Results developed in this paper raise new questions, recommending future studies to seek a finer understanding of the underlying transscalar dynamics between material efficiency in building structures, historical development of construction technologies, urban planning, and real estate development.

The value of buildings varies according to whether they are considered material sinks, catalysts of activities, cultural heritage, or future material banks (Romero Perez de Tudela et al., 2020; Tazi et al., 2020). By quantifying MEQs of load-bearing systems over an entire city and over time, this work emphasises the link between material use and use value – i.e., a relationship that must be further studied to better use and reuse available resources while ensuring minimum adverse environmental effects following the circular economy principles.

Combined with other indicators related to operational energy in buildings, mobility, and socio-economy, the data contributes to a more comprehensive characterisation of environmental performance at the city level, a topic gaining momentum in academia and city administrations (Huang et al., 2015; Verma and Raghubanshi, 2018). The complexity of such a topic can only be harnessed with new forms of visualisations and interactions (Kaplan and di Lenardo, 2020). Mapping environmental effects onto a uniform spatial and temporal referential constitutes a new essential tool for governing bodies and normative agencies to synthesise the complex industrial and cultural interactions at play, their past evolution, and their prospects.

Authors' contributions

Funding acquisition (CF, CDW); literature review (CF, TM, AS, CDW); methodology (CF); GIS curation (SV, CF); identification and characterisation of sample buildings (TM, CDW); environmental assessment of sample buildings (CDW, TM); propagation methods, indicators, and computations (CF); result analysis and interpretation (CF), validation of results (CF, CDW); GIS maps production (CF, SV); writing of paper and artwork production (CF); internal in-depth review of the paper (AS, CDW, CF); revision of the paper (CDW, TM, AS, CF).

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CRediT authorship contribution statement

Corentin Fivet: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Catherine De Wolf:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Thibaut Menny:** Data curation, Formal analysis, Investigation, Validation, Writing – review & editing. **Serena Vanbutsele:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **André Stephan:** Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

Data availability

Process data and Figure data are available as spreadsheet in the supplementary material.

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Appendix A. GIS Data Preparation

A.1 GIS datasets

GIS Data on Switzerland and especially on Geneva are generally highly coherent and up-to-date. However, there is still a need to merge datasets from various sources in order to work with as many well-defined entries as possible.

The following datasets have been identified.

- Dataset 'I': 'mensuration/cadastre' CAD_BATIMENT_HORSOL (ID: 9810) provided by the 'direction de l'Information du Territoire' (DIT), Canton of Geneva;
- Dataset 'II': the 'registre fédéral des bâtiments et des logements (RegBL)' dataset provided by the Département fédéral de l'intérieur DFI - Office fédéral de la statistique OFS - Bâtiments et logements
- Dataset 'III': 'plans cadastraux historiques des bâtiments' provided by the DIT Archives (internship of Alexandre Bellward from the UNIGE, directed by Vincent Gallez);
- Dataset 'IV': Georeferenced historical maps 'Voyage dans le temps', provided by the 'Office fédéral de topographie' (Swisstopo.ch);
- Dataset 'V': 'Atlas du Territoire Genevois'.
- Dataset 'VI': Historical maps

Dataset 'I', 'mensuration/cadastre', is used as a primary source. It is extracted from the Système d'Information du Territoire Genevois (http://ge.ch/sitg/, downloaded on 07-07-2018), which provides 886 layers of geographical information related to the Canton of Geneva. Generally speaking, it informs about ownership of land plots and locates them on the map. Cadastral offices create new entries, which are then transferred to the Cantonal office and eventually to the Federal Office of Statistics before being used in dataset 'II'.

Dataset 'I' provides an entry for all buildings in the Canton of Geneva (89′645 buildings representing 14′446′616 m^2 of total footprint area), their location, the geometry of their footprint, their area, the number of floors, their height, their function, and partially the period of construction of buildings. In this dataset, only 9′624 buildings (out of 89′645 buildings) possess an exact year of construction and 42′523 buildings (50%) possess a period of construction. The rest are mainly small and secondary buildings such as porches, garages, and adjacent appendices. Moreover, there is no information about buildings built before 1919 as the cadastral information started to be collected in 1919. The dataset also requires additional cleaning. For instance, it contains polygons of zero or nearly zero footprint area and entries (i.e. polygons) sharing a same EGID are used to model a unique building.

Dataset 'II', 'registre fédéral des bâtiments et des logements (RegBL)', covers all Switzerland and could potentially be used to extend the geographical scope of this study. The dataset only records construction periods for housing (GKAT = 1020,1030,1040, 1060, 1080) larger than 20 m^2.

This means that only 50′000 buildings are recorded by dataset 'II' for the Canton of Geneva. In addition, the construction period recorded in this dataset is not entirely reliable because it comes from the 2000 survey (RFP, 2000). See ' Catalogue des caractères Registre fédéral des bâtiments et des logements Version 4.1′ p.70). The dataset was provided in June 2019.

Dataset 'III', 'plans cadastraux historiques des bâtiments', contains 24′000 entries on buildings built from 1863 to 1935 in the canton of Geneva. Only 5′304 of them share an EGID (see section A.2) with dataset 'I'. The dataset originates from paper maps that have been digitalized and geo-referenced.

Dataset 'IV' contains additional years of construction of buildings, especially those built before 1919. The dataset was browsed using the "voyage dans le temps" tool that offers a time series of maps from 1864 (1845 for Geneva) until today. This series of maps ('cartes Dufour', 'cartes Siegfried' and 'cartes nationales') provides a precise overview of the evolution of the territory during the 19th and 20th century. The maps are available at https://www.swisstopo.admin.ch/fr/cartes-donnees-en-ligne/cartes-geodonnees-en-ligne/voyage-dans-le-temps.html).

Dataset 'V', 'Atlas du Territoire Genevois' (1993), are maps representing the transformation of built environment in Geneva over time. Maps display transformations from 1808 (Cadastre Napoléonien) to 1935–1959 (first edition of the 'plan d'ensemble') and from this one to 1990 ('plan d'ensemble'). This dataset was used to collect locations of past building demolitions. However, source maps from dataset 'IX' have been preferred to collect construction periods more effectively.

Dataset 'VI' consists in a series of historical paper maps already geo-referenced by the SITG.

- Plan Billon (1726–1728) focusing on the city centre within defensive walls;
- Plan Céard (1837–1840) focusing on the city centre within defensive walls;
- Carte Dufour (1842) showing the city centre and its outskirt with the defensive walls;
- Plan Magnin (1850) is based on a physical model;
- Plan Grange (1896–1911).

Maps 'Plan Billon', 'Plan Céard', and 'Plan Grange' have been used in this study to obtain the location of past demolished buildings.

A.2 Identifier

Building identifiers are built upon the 'EGID' attribute, which is present in most datasets. EGID is a unique number for identifying buildings at the federal level. This number is used to combine data between various datasets. Multiple polygons may have the same EGID. Some buildings, like car parks and carports, do not have any EGID.

A.3 Footprint Area

The building footprint polygons are directly collected from dataset I. Each building footprint area is computed from those polygons.

A.4 Height

Building heights are directly taken from the 'HAUTEUR' attribute in dataset I. The height of a building corresponds to the 'total height' of a building. It corresponds to the distance from the highest point of the roof of a building to the lowest altitude of the building. This information comes from a LIDAR survey that has been used for the 3D model of Geneva.

A.5 Aboveground and Underground Levels

The number of underground and aboveground levels is directly collected from corresponding attributes in dataset I, under the attributes NIVEAUX_SS and NIVEAUX_HO, respectively.

When the number of aboveground levels is smaller or equal to 0 and the 'Building Height' is greater than 0, the number of aboveground levels is corrected to the rounded-down ratio between the 'Building Height' attribute and the average level height over all buildings in the dataset.

The average level height of a building is defined as 0 when NIVEAUX_HO is equal to 0, or as the ratio between 'Building Height' and NIVEAUX_HO otherwise.

A.6 Gross Floor Area

The gross floor area of each building is computed as the product between the footprint area of the building and the sum of underground and aboveground levels. In other words, the ratio between the gross floor area and the footprint area of a building provides the total number of building levels, assuming the same floor plan at every level.

A.7 Construction Period

Four datasets have been used to complete the 'Construction Period' attribute: datasets 'I', 'II', 'III', and 'IV'. About only half of those entries could have been used prior to merging the construction dates from the four selected datasets.

Dataset 'I' comprises the following useful attributes.

- 'ANNEE_CONS' corresponds to the year in which the construction of a new building has been completed (cf: DIT, Glossaire des attributs de la Mensuration Officielle, nov 2016). This attribute is highly flawed. Only 9′624 out of 89′645 polygons have a value for that attribute.
- 'EPOQUE_CON' corresponds to the period of completion of the construction (e.g. "1985–2000") (cf: DIT, Glossaire des attributs de la Mensuration Officielle, nov 2016). 42′523 out of 89′645 polygons have a value for that attribute. This attribute is more complete than 'ANNEE_CONS' but only provides a period.
- 'MUTORI' corresponds to the number in the mutation table that allowed the creation of a new object (cf: DIT, Glossaire des attributs de la Mensuration Officielle, nov 2016). This attribute is more complete than 'ANNEE_CONS' and 'EPOQUE_CON' but is not 100% reliable. 60′831 out of 89′645 polygons have a value for that attribute.

In theory, the mutation date extracted from the 'MUTORI' value is chronologically close to the building construction. Practically, the date corresponds to the very first registration of the building in the Official Measurement ('Mensuration Officielle, MO') records. Before data digitalization, paper documents (named 'Etats des contenances') collected information on parcels and objects on parcels. Each comprised a parcel number, the owners, a description of objects on the parcel, and a MUTORI value. The MUTORI value is composed of a file number (1–3 digits) and a year (2 or 4 digits)

Today, the MUTORI value is recorded when cadastral points are set up and is (in theory) never updated. However, a MUTORI value might be recorded several years after the building construction, and there is no means to understand how many years have gone by, and what buildings are affected.

Also, several buildings might share the same MUTORI value (file number and date). Although the duration between the construction of a building and the creation of a MUTORI value is highly variable, the MUTORI value can safely be taken as an upper-bound value for the construction year.

Dataset 'II' comprises the following useful attributes.

- 'GBAUJ' defines the construction year of a building. The year and month (GBAUM) of construction define the time when the construction of the building is physically completed, independently of the state of the construction project. For residential buildings, the value is the date when the building is ready to be inhabited. The transformation of non-residential buildings (e.g. agricultural facilities, factories) into residential buildings is understood as a renovation and does not affect the construction year. See OFS, catalogue des caractères, registre fédéral des bâtiments et des logements, version 4.1, p. 69. 11′478 polygons have a GBAUJ value. They are generally the same as those with a value in Dataset I, but not only.
- 'GBAUP' defines the construction period of a building. The division into construction periods follows, until construction year 1980 included, prescriptions on the census of buildings and housings from RFP 2000. Since 1981, construction periods span 5 years (up until 2015). From 2016, the construction period is computed from the construction year. See OFS, catalogue des caractères, registre fédéral des bâtiments et des logements, version 4.1, p. 69. 38′255 polygons have a GBAUP value. They are generally the same as those with a value in Dataset I, but not only. This attribute is more often given than GBAUJ but does not provide any precise year, only a construction period. For construction before 2016, there are a total of only 13 different construction periods in the dataset: No info, before 1919, 1919–1945, 1946–1960, 1961–1970, 1971–1980, 1981–1985, 1986–1990, 1991–1996, 1996–2000, 2001–2005, 2006–2010, 2011–2015, after 2015.

Values from dataset 'II' mostly come from the 2000 building census, which is known to be relatively flawed. They are therefore considered less reliable than dataset 'I'.

As the majority of GBAUJ values come from previous building censuses, some decades are overly represented (1920, 1960, 1970, 1990, and 2000). In addition, as the construction period GBAUP is computed from the construction year GBAUJ, the periods are biased following a threshold effect.

Years 1919 and 1946 are also overrepresented due to the threshold defined with the period categories in GBAUP.

Dataset 'III' comprises the following useful attributes.

- 'PHB' are values complementary to MUTORI values, but their reliability cannot be assessed.

Dataset 'IV' comprises the following useful attribute.

- **'CONS_PERIOD'** is a construction period that has been manually extracted from Dataset 'IV' and digitized manually for this study. It concerns buildings in the 16 central communes of the Geneva Canton, i.e. 51′535 polygons. Construction periods were grouped in six categories: no data (19′171 buildings), 1851–1919 (6′608 buildings), 1920–1945 (3′413 buildings), 1946–1975 (11′030 buildings), 1976–2000 (6′717 buildings), 2001–2019 (4′596 buildings).

Two dates define the construction period attribute. The oldest possible date of the end of the construction (C_YR_MIN) and the newest possible date of the end of the construction (C_YR _MAX).

The 'EGID' attribute is used to match identities between datasets. The goal followed when merging attributes from the various datasets was to (1) provide a value for the maximum number of entries and (2) prioritize values from the more reliable sources. Values have been combined according to the following prioritized conditions for each EGID entry.

```
› If GBAUJ exists:
    › C_YR_MIN=GBAUJ;
    › C_YR_MAX=GBAUJ;
› else, if ANNEE_CONS exists:
    › C_YR_MIN=ANNEE_CONS;
    › C_YR_MAX=ANNEE_CONS;
› else, if EPOQUE_CON exists:
    › C_YR_MIN=EPOQUE_CON.start;
    › C_YR_MAX= EPOQUE_CON.end;
› else, if GBAUP exists:
    › If GBAUP='après 2015':
        › C_YR_MIN=2015;
    › If GBAUP='avant 1919':
        › C_YR_MAX=1919;
    › else:
        › C_YR_MIN=GBAUP.start;
        › C_YR_MAX=GBAUP.end;

› If C_YR_MIN is not equal to C_YR_MAX
  and MUTORI exists
  and MUTORI is between C_YR_MIN and C_YR_MAX:
    › C_YR_MIN=MUTORI;
    › C_YR_MAX=MUTORI;

› If C_YR_MIN and C_YR_MAX remain undefined
  and MUTORI exists:
    › C_YR_MIN=MUTORI;
    › C_YR_MAX=MUTORI;

› If C_YR_MIN
  and C_YR_MAX remain undefined
  and PHB exists:
    › If PHB='avant 1919':
        › C_YR_MAX=1919;
    › else:
        › C_YR_MIN=PHB.start;
        › C_YR_MAX=PHB.end;

› If C_YR_MIN
  and C_YR_MAX remain undefined
  and CONS_PERIOD exists:
    › C_YR_MIN= CONS_PERIOD.start;
    › C_YR_MAX= CONS_PERIOD.end;
```

The post-industrial history of Geneva is characterised by six main periods (Lamuniè and re, 2007; Lamuniè et al., 2015a; Lamuniè et al., 2015b) whose transition years correspond to major changes in construction practices.

- 1850 – destruction of the external defensive walls of the city;
- 1919 – end of World War I, new development in the building industry;
- 1945 – end of World War II, modernist concepts take a prevalent role in the construction of Geneva;
- 1975 – change of building market due to the oil crises of 1973 and 1979;
- 2000 – globalisation and first federal law on energy efficiency in buildings.

The development of the city (Figure A1) presents a typical growth from its centre, with more recent buildings in suburban areas. Concentrations of old buildings outside the city centre correspond to historical village centres. The largest buildings have all been built in recent years.

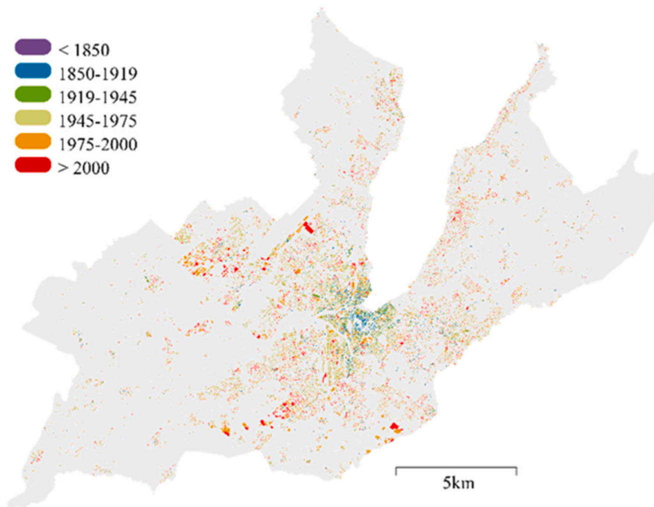

Fig. A.1. Location of all buildings by approximated construction period.

A.8 Approximated Construction Year

After the merging process, a total of 18,405 buildings (21.8% of all buildings) had a construction period longer than a year. For each entry, an approximated construction year C_YR_APP is computed as.

〉C_YR_APP = randomValueBetween(C_YR_MIN, C_YR_MIN)

which ensures a uniform distribution of construction years among building entries that had a construction period longer than a year.

A.9 Demolition Period

Available GIS data only records existing buildings. In order to identify past buildings that have been demolished, historical maps from dataset 'IX' have been compared manually, following a similar procedure as the one used for the original creation of maps from dataset 'VIII'. Basically, building parcels from two chronologically successive maps are compared to identify new and lost parcels. The latter map provides the upper bound for the construction period. The lower bound corresponds to the year of the oldest map containing the parcel. Since this process has not been automated and is time-consuming, only a reduced geographical scope of 16 central districts (75 km^2) of the Canton of Geneva (282 km^2) is analyzed. A total of 32,364 buildings are concerned by these 16 municipalities.

Table A.1
Distribution of demolished buildings across time.

year min	year max	# of buildings	total surface [m^2]
0	**1818**	830	203,162
1728	**1840**	72	13,557
1818	**1959**	519	254,364
1840	**1911**	436	50,740
1911	**2018**	681	77,885
1959	**2018**	569	504,288
	total:	3107	1,103,996

None of the 3107 identified demolished buildings has been included in this study for two reasons: they represent a small fraction of the building stock; no information related to their height or use could be collected.

It might be that other sources of data, e.g. municipal records or historical accounts on demolitions, reveal additional demolition sites or challenge our understanding of their dynamics. Currently, the map suggests that most demolished buildings were industrial buildings originally built at the direct periphery of the city but later demolished or replaced by other buildings as the city grew around them.

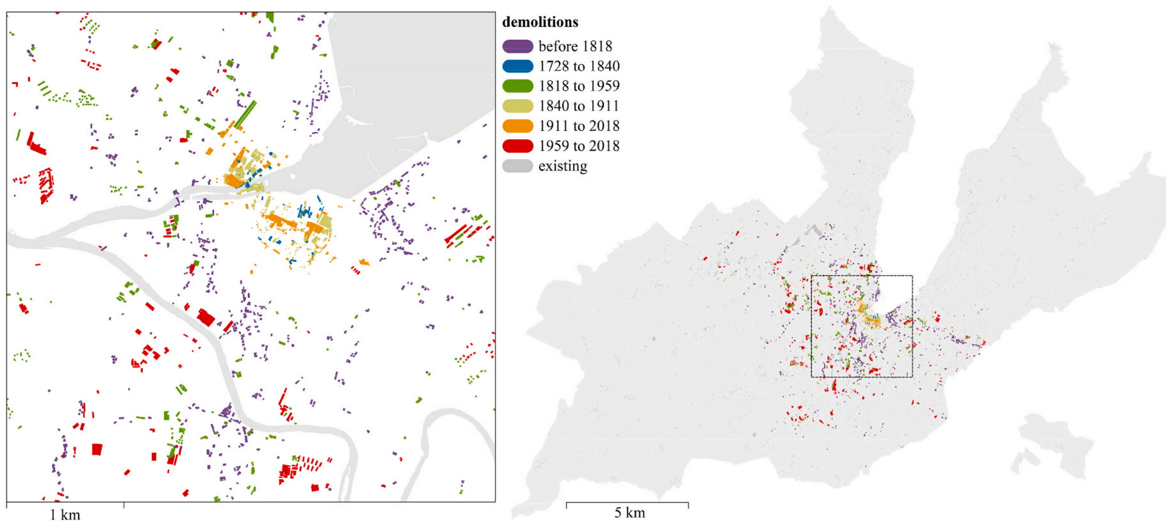

Fig. A.2. Demolished buildings in the 16 central districts of the Canton of Geneva.

A.10 Use Category

Dataset I provides information about the function of each building under the 'NOMENCLATURE' attribute. There are 33 different categories and 117 sub-categories, from housing to shopping malls, to schools or agricultural buildings.

In this study, building uses are grouped in seven categories, each being characterised by typical structural demands.

- single-dwelling buildings: low volumes, short spans, and low residential load cases (e.g., houses)
- multi-dwelling buildings: high volumes, short spans, and high residential load cases (e.g., apartment buildings, hotels, prisons, residences for the elderly, boarding residences)
- office & educational buildings: medium spans and medium office load cases (e.g., business offices, public administrative services, hospitals, schools, libraries, research centres)
- industrial & retail buildings: long spans and high load cases (e.g., factories, workshops, shopping malls, restaurants, industrial hangars, gas stations, warehouses, depots)
- community buildings: diverse structural systems, high design quality, high construction quality, and long spans (e.g., sport, leisure, cultural, and worship buildings, train stations, airports, urban infrastructure buildings)
- appendices: low dimensions, low design quality, low construction quality, and short spans
- unknown

A building use category has been assigned to each building, as a function of the 'NOMENCLATURE' attribute in dataset I. The precise assignment from 117 original categories to 7 new categories is described in Table A2.

Table A.2
Assignment of new building use categories to the building use provided in dataset I, together with corresponding numbers of buildings, footprint areas, ratios of footprints, gross floor areas, and ratios of gross floor areas.

description from 'NOMENCLATURE' attribute in dataset I (In French)		new use category	# of buildings	footprint (m^2)	% of footprint	GFA (m^2)	% of GFA
1	habitation		38,109	5,684,034	39.3%	21,363,535	33.1%
1_1	habitation individuelle		26,893	2,994,590	20.7%	7,147,681	11.1%
1_1_1	habitation à un seul logement	single-dwelling	26,893	2,994,590	20.7%	7,147,681	11.1%
1_2	**habitation à deux logements**		**1874**	**262,758**	**1.8%**	**682,426**	**1.1%**
1_2_1	habitation à deux logements	multi-dwelling	1874	262,758	1.8%	682,426	1.1%
1_3	**habitation à plusieurs logements**		**9063**	**2,278,891**	**15.7%**	**12,807,686**	**19.8%**
1_3_1	habitation à plusieurs logements	multi-dwelling	9063	2,278,891	15.7%	12,807,686	19.8%
1_4	**hébergement collectif ou communautaire**		**279**	**147,794**	**1.0%**	**725,741**	**1.1%**
1_4_1	etablissement medico-social	multi-dwelling	109	81,508	0.6%	423,041	0.7%
1_4_2	foyer	multi-dwelling	59	21,427	0.1%	80,801	0.1%
1_4_3	colonie de vacances	multi-dwelling	0	0	0.0%	0	0.0%
1_4_4	internat	multi-dwelling	8	2659	0.0%	11,454	0.0%
1_4_5	autre hébergement collectif ou communautaire	multi-dwelling	44	17,689	0.1%	66,943	0.1%
1_4_6	résidence meublée	multi-dwelling	59	24,511	0.2%	143,503	0.2%
2	**mixte: logements + activités ou équipement collectif**		**5513**	**1,579,952**	**10.9%**	**10,106,809**	**15.6%**
2_1	**habitation à plusieurs logements avec rez-de-chaussée commercial/activités ou équipement collectif**		**3024**	**800,020**	**5.5%**	**5,072,875**	**7.8%**

(*continued on next page*)

Table A.2 (*continued*)

description from 'NOMENCLATURE' attribute in dataset I (In French)		new use category	# of buildings	footprint (m^2)	% of footprint	GFA (m^2)	% of GFA
2_1_1	habitation à plusieurs logements avec rez-de-chaussée commercial/ activités ou équipement collectif	multi-dwelling	3024	800,020	5.5%	5,072,875	7.8%
2_2	**habitation à plusieurs logements avec activités**		**2394**	**745,118**	**5.1%**	**4,912,149**	**7.6%**
2_2_1	habitation à plusieurs logements avec activités	multi-dwelling	2394	745,118	5.1%	4,912,149	7.6%
2_3	**ferme**		**95**	**34,813**	**0.2%**	**121,785**	**0.2%**
2_3_1	ferme	single-dwelling	95	34,813	0.2%	121,785	0.2%
3	**activités**		**7107**	**3,946,682**	**27.3%**	**18,735,949**	**29.0%**
3_1	**bâtiment agricole**		**1161**	**684,940**	**4.7%**	**1,509,863**	**2.3%**
3_1_1	serre	industrial & retail	560	578,071	4.0%	1,218,323	1.9%
3_1_2	silo	industrial & retail	112	5955	0.0%	45,732	0.1%
3_1_3	poulailler	industrial & retail	96	7579	0.1%	11,318	0.0%
3_1_4	porcherie	industrial & retail	10	4721	0.0%	12,818	0.0%
3_1_5	hangar agricole	industrial & retail	67	26,548	0.2%	26,247	0.0%
3_1_6	autre bâtiment de production agricole	industrial & retail	316	62,064	0.4%	195,425	0.3%
3_2	**bâtiment industriel/artisanal**		**1449**	**1,061,468**	**7.3%**	**5,099,042**	**7.9%**
3_2_1	usine	industrial & retail	286	494,829	3.4%	2,831,058	4.4%
3_2_2	atelier	industrial & retail	939	451,678	3.1%	1,885,609	2.9%
3_2_3	garage	appendices	217	112,899	0.8%	376,901	0.6%
3_2_4	chantier naval	industrial & retail	7	2062	0.0%	5474	0.0%
3_3	**bâtiment commercial**		**490**	**345,736**	**2.4%**	**1,614,014**	**2.5%**
3_3_1	centre commercial	industrial & retail	29	142,006	1.0%	749,822	1.2%
3_3_2	station-service	industrial & retail	88	11,419	0.1%	21,399	0.0%
3_3_3	commerce	industrial & retail	373	192,310	1.3%	842,792	1.3%
3_4	**bâtiment administratif**		**1374**	**788,920**	**5.4%**	**5,714,810**	**8.8%**
3_4_1	bureaux	office & educational	1374	788,920	5.4%	5,714,810	8.8%
3_5	**entrepôt**		**2003**	**753,063**	**5.2%**	**3,183,094**	**4.9%**
3_5_1	dépôt	industrial & retail	1241	534,482	3.7%	2,397,479	3.7%
3_5_2	hangar	industrial & retail	762	218,582	1.5%	785,615	1.2%
3_6	**hôtel/restaurant**		**354**	**128,001**	**0.9%**	**765,693**	**1.2%**
3_6_1	hôtel	multi-dwelling	147	80,039	0.6%	623,336	1.0%
3_6_2	restaurant	industrial & retail	206	47,767	0.3%	142,358	0.2%
3_6_3	divertissement	community	1	195	0.0%	0	0.0%
3_7	**autre bâtiment d'activités**		**276**	**184,554**	**1.3%**	**849,434**	**1.3%**
3_7_1	autre bâtiment d'activités	unknown	276	184,554	1.3%	849,434	1.3%
4	**equipement collectif**		**4368**	**2,174,954**	**15.0%**	**11,998,510**	**18.6%**
4_1	**enseignement et recherche**		**719**	**705,318**	**4.9%**	**3,137,671**	**4.9%**
4_1_1	université	office & educational	54	72,161	0.5%	708,460	1.1%
4_1_2	collège	office & educational	102	177,362	1.2%	634,411	1.0%
4_1_3	ecole primaire	office & educational	323	300,904	2.1%	1,179,797	1.8%
4_1_4	ecole privée	office & educational	80	54,085	0.4%	242,071	0.4%
4_1_5	jardin d'enfants	community	84	32,535	0.2%	84,472	0.1%
4_1_6	autre école	office & educational	76	68,270	0.5%	288,459	0.4%
4_2	**culture**		**133**	**206,083**	**1.4%**	**2,065,763**	**3.2%**
4_2_1	musée	community	29	20,076	0.1%	124,240	0.2%
4_2_2	théâtre	community	12	10,551	0.1%	94,337	0.1%
4_2_3	bibliothèque	office & educational	13	7206	0.0%	43,789	0.1%
4_2_4	salle communale	community	39	27,980	0.2%	116,902	0.2%
4_2_5	salle de spectacle	community	20	16,051	0.1%	87,944	0.1%
4_2_6	halle d'exposition	community	11	119,294	0.8%	1,567,186	2.4%
4_2_7	cinéma	community	7	3625	0.0%	22,595	0.0%
4_2_8	conservatoire de musique	office & educational	2	1301	0.0%	8771	0.0%
4_3	**culte**		**208**	**78,416**	**0.5%**	**473,588**	**0.7%**

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Table A.2 (*continued*)

description from 'NOMENCLATURE' attribute in dataset I (In French)		new use category	# of buildings	footprint (m^2)	% of footprint	GFA (m^2)	% of GFA
4_3_1	eglise	community	103	51,143	0.4%	338,069	0.5%
4_3_2	temple	community	36	11,227	0.1%	78,175	0.1%
4_3_3	chapelle	community	25	5804	0.0%	23,667	0.0%
4_3_4	mosquée	community	4	2134	0.0%	4948	0.0%
4_3_5	synagogue	community	4	1675	0.0%	7703	0.0%
4_3_6	autre lieu de culte	community	36	6434	0.0%	21,025	0.0%
4_4	**santé/soins/aide sociale**		**116**	**141,898**	**1.0%**	**969,316**	**1.5%**
4_4_1	hôpital, clinique	office & educational	68	109,988	0.8%	827,224	1.3%
4_4_2	etablissement de soins	office & educational	48	31,910	0.2%	142,092	0.2%
4_5	**sports/loisirs**		**519**	**280,547**	**1.9%**	**1,018,908**	**1.6%**
4_5_1	stade	community	10	2519	0.0%	5462	0.0%
4_5_2	salle de sport	community	116	115,074	0.8%	426,743	0.7%
4_5_3	centre sportif	community	44	37,846	0.3%	142,470	0.2%
4_5_4	piscine	community	9	14,536	0.1%	64,407	0.1%
4_5_5	patinoire	community	4	19,879	0.1%	119,636	0.2%
4_5_6	manège	community	84	34,062	0.2%	90,101	0.1%
4_5_7	centre de loisirs	community	90	28,175	0.2%	89,226	0.1%
4_5_8	autre bâtiment destiné aux loisirs	community	88	23,516	0.2%	75,275	0.1%
4_5_10	ecurie	community	74	4942	0.0%	5589	0.0%
4_6	**sécurité**		**149**	**57,706**	**0.4%**	**253,271**	**0.4%**
4_6_1	police	office & educational	6	4358	0.0%	37,458	0.1%
4_6_2	etablissement pénitenciaire	multi-dwelling	22	15,547	0.1%	69,868	0.1%
4_6_3	caserne	office & educational	3	1795	0.0%	7199	0.0%
4_6_4	arsenal	industrial & retail	7	8676	0.1%	25,831	0.0%
4_6_5	pc	community	11	3278	0.0%	12,178	0.0%
4_6_6	stand de tir	community	13	5035	0.0%	18,383	0.0%
4_6_7	service du feu	community	34	12,358	0.1%	62,695	0.1%
4_6_8	douane	office & educational	53	6659	0.0%	19,659	0.0%
4_7	**communications**		**47**	**14,789**	**0.1%**	**61,410**	**0.1%**
4_7_1	central de télécommunications	office & educational	40	14,711	0.1%	61,335	0.1%
4_7_3	installation de téléphonie mobile	community	7	78	0.0%	74	0.0%
4_8	**transports routiers et urbains**		**12**	**48,566**	**0.3%**	**368,623**	**0.6%**
4_8_1	parking public	community	8	23,134	0.2%	120,028	0.2%
4_8_2	dépôt tpg	industrial & retail	3	25,424	0.2%	248,586	0.4%
4_8_3	abri tc	industrial & retail	1	9	0.0%	9	0.0%
4_9	**autres transports**		**175**	**166,721**	**1.2%**	**1,050,186**	**1.6%**
4_9_1	gare	community	27	22,957	0.2%	96,972	0.2%
4_9_2	port-franc	community	2	2696	0.0%	14,834	0.0%
4_9_3	voirie-entretien	community	42	24,951	0.2%	92,546	0.1%
4_9_4	ouvrage aéroportuaire	community	104	116,117	0.8%	845,834	1.3%
4_10	**approvisionnement**		**1892**	**147,779**	**1.0%**	**759,043**	**1.2%**
4_10_1	**ouvrages sig**		**1079**	**50,040**	**0.3%**	233,367	0.4%
4_10_1_1	bâtiment eau	community	27	17,554	0.1%	107,174	0.2%
4_10_1_2	installation technique eau	community	17	2578	0.0%	12,744	0.0%
4_10_1_3	bâtiment gaz	community	5	1866	0.0%	10,234	0.0%
4_10_1_4	installation technique gaz	community	43	1063	0.0%	2956	0.0%
4_10_1_5	bâtiment électricité	community	176	13,328	0.1%	69,334	0.1%
4_10_1_6	installation technique électricité	community	811	13,651	0.1%	30,925	0.0%
4_10_2	**ouvrages privés**		**341**	**18,154**	**0.1%**	**77,435**	**0.1%**
4_10_2_1	bâtiment eau	community	10	374	0.0%	457	0.0%
4_10_2_2	installation technique eau	community	42	4623	0.0%	16,712	0.0%
4_10_2_3	bâtiment gaz	community	6	1054	0.0%	3131	0.0%
4_10_2_4	installation technique gaz	community	14	455	0.0%	1689	0.0%
4_10_2_5	bâtiment électricité	community	41	4754	0.0%	37,962	0.1%
4_10_2_6	installation technique électricité	community	228	6895	0.0%	17,485	0.0%
4_10_3	installation de chauffage	community	90	7478	0.1%	22,409	0.0%
4_10_4	chauffage à distance	community	5	1035	0.0%	1846	0.0%
4_10_5	réservoir	community	296	30,916	0.2%	229,887	0.4%
4_10_6	déchetterie	community	12	8187	0.1%	20,588	0.0%
4_10_7	compostage	community	1	6	0.0%	6	0.0%
4_10_8	station d'épuration	community	33	30,905	0.2%	171,254	0.3%
4_10_9	citerne mazout	community	8	116	0.0%	87	0.0%
4_10_10	citerne gaz	community	6	629	0.0%	1861	0.0%
4_10_11	installation de climatisation	community	21	314	0.0%	304	0.0%
4_11	**administration publique**		**96**	**70,848**	**0.5%**	**293,619**	**0.5%**

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Table A.2 (*continued*)

description from 'NOMENCLATURE' attribute in dataset I (In French)		new use category	# of buildings	footprint (m^2)	% of footprint	GFA (m^2)	% of GFA
4_11_1	bureaux des administrations publiques	office & educational	35	19,195	0.1%	135,743	0.2%
4_11_2	mairie	office & educational	38	10,843	0.1%	38,958	0.1%
4_11_3	poste	office & educational	23	40,810	0.3%	118,918	0.2%
4_12	**organisations internationales**		**260**	**250,102**	**1.7%**	**1,524,633**	**2.4%**
4_12_1	mission permanente	office & educational	49	22,623	0.2%	83,677	0.1%
4_12_2	consulat	office & educational	8	5811	0.0%	24,712	0.0%
4_12_3	bureaux des oig	office & educational	33	48,406	0.3%	394,719	0.6%
4_12_4	ONU	office & educational	28	34,068	0.2%	186,327	0.3%
4_12_5	CERN	office & educational	142	139,194	1.0%	835,199	1.3%
4_13	**autre équipement collectif**		**42**	**6180**	**0.0%**	**22,480**	**0.0%**
4_13_1	wc public	community	16	137	0.0%	83	0.0%
4_13_2	autre équipement collectif	office & educational	26	6043	0.0%	22,397	0.0%
5	**autre bâtiment (non rattaché ailleurs)**		**29,380**	**1,092,132**	**7.5%**	**2,431,359**	**3.8%**
5_1	bâtiment plus grand que 20 m2 non classé ailleurs	unknown	5806	411,584	2.8%	1,195,818	1.9%
5_2	garage privé	appendices	12,756	555,321	3.8%	1,055,054	1.6%
5_3	bâtiment plus petit que 20m2	appendices	8426	83,669	0.6%	121,914	0.2%
5_4	véranda	appendices	2268	39,295	0.3%	48,024	0.1%
5_5	cheminée	appendices	101	1787	0.0%	9537	0.0%
5_6	cabine t + t	unknown	23	477	0.0%	1011	0.0%
		total	**84,477**	**14,477,754**	**100.0%**	**64,636,161**	**100.0%**

In comparison, Table A3 shows the distribution of the new building use categories among all 84′477 entries.

Table A.3
Distribution of building uses across all entries.

	# of buildings	% of buildings	footprint (m^2)	% of footprint	GFA (m^2)	% of GFA
single-dwelling	26,991	32.0%	3,031,455	20.9%	7,136,615	12.0%
multi-dwelling	16,804	19.9%	4,330,714	29.9%	24,731,760	41.5%
office & education	2624	3.1%	1,972,968	13.6%	10,753,311	18.1%
industrial & retail	5103	6.0%	2,810,161	19.4%	9,391,834	15.8%
community	3084	3.7%	946,448	6.5%	4,894,325	8.2%
appendices	23,768	28.1%	792,971	5.5%	1,009,535	1.7%
unknown	6103	7.2%	593,321	4.1%	1,656,769	2.8%

The city core is mainly occupied by multi-dwelling, office, and education buildings (Figure A3). Outside, buildings are mainly grouped in patches of similar use categories.

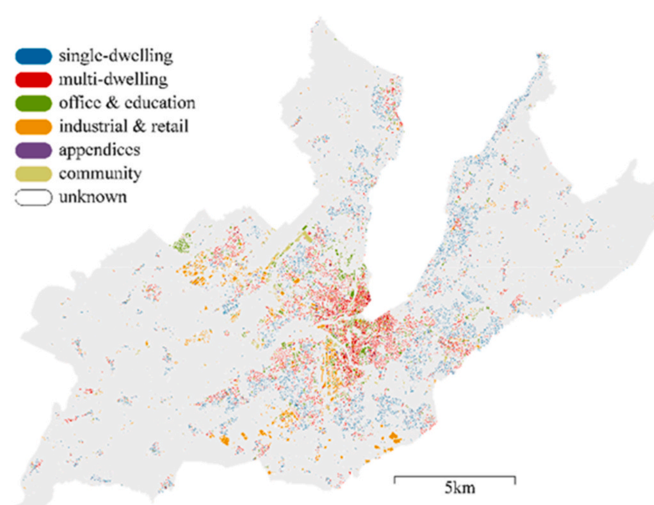

Fig. A.3. Location of all buildings by use category.

A.11 Data Cleaning

When multiple entries share the same EGID, same building use, and same construction periods, they are removed and replaced by a new entry with all the same attributes except the footprint area. The new footprint area is the sum of the footprint areas of the removed duplicates. 5′168 duplicates have been identified. The resulting dataset contains 84′477 entries.

Entries with unknown building use OR no construction period OR (zero height AND zero underground floors) OR zero area, are deemed unusable. They amount to 20′111 buildings (23.8%), corresponding to 11.7% of the total footprint area and 7.2% of the total gross floor area.

Appendix B. Sample Buildings Description

Sample buildings are selected from analyses of Geneva's architectural heritage (Lamuniè and re, 2007; Lamuniè et al., 2015a; Lamuniè et al., 2015b; Graf et al., 2010; Graf et al., 2015). Floor plans, building sections and construction specifications are obtained from specialized architecture publications and original hard copies retrieved from the Office du Patrimoine et des Sites, Geneva. Missing information on construction materials is collected from specialized construction books and site visits. During data collection, a specific care we given to select buildings that would feed the diversity of the set in terms of use category, construction period and building height. Out of the 48 studied buildings, 7 are located outside Geneva Canton but still within Romandie, more specifically in the Cantons of Vaud and Fribourg, where similar construction techniques are employed (Schwab and Rinquet, 2018b). Sample buildings located in the Canton of Geneva are mapped on Figure B1, and described in Table B1.

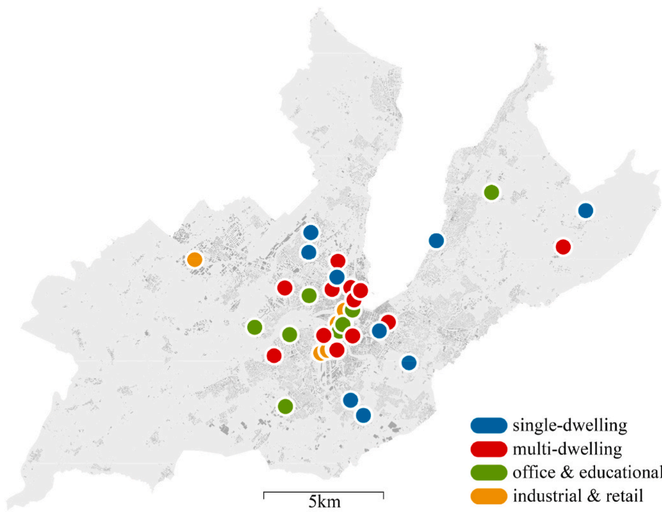

Fig. B.1. Sample buildings currently located within the canton of Geneva by use category.

Table B.1
Description of all analyzed sample buildings.

	Category of building use at the time of construction	Height [m]	Footprint [m^2]	Gross Floor Area [m^2]	# Underground Levels	# Upper Levels (excl. attics)	Construction date	Volume of Materials [m^3]	Mass of Materials [T]	Greenhouse Gas Emissions [TCO2e]	Volume of Materials per GFA [m^3/m^2]	Mass of Materials per GFA [kg/m^2]	Greenhouse Gas Emissions per GFA [kgCO2e/m^2]
01	Single-dwelling	13.5	430	1582	1	2	1830	954	1222	164	0.60	772	104
02	Single-dwelling	11.1	99	360	1	2	1837	252	332	44	0.70	922	121
03	Single-dwelling	12.5	214	856	1	2	1843	462	589	78	0.54	688	91
04	Multi-dwelling	20	235	1645	1	5	1898	1007	1373	216	0.61	835	131
05	Multi-dwelling	25.5	285	2460	1	6	1901	1388	1853	280	0.56	755	114
06	Industrial & Retail	13.2	318	954	0	3	1909	781	1292	229	0.82	1354	240
07	Multi-dwelling	23	281	1872	1	5	1910	1214	1676	240	0.65	896	128
08	Office & Educational	16	240	1200	1	4	1910	795	1245	212	0.66	1049	176
09	Multi-dwelling	27.3	444	3555	1	7	1930	1741	3415	506	0.49	922	132
10	Office & Educational	29	782	4667	1	5	1930	2764	6564	820	0.59	1407	176
11	Industrial & Retail	10	167	247	0	2	1930	72	159	47	0.29	645	191
12	Single-dwelling	5.7	160	392	1	2	1931	237	562	70	0.60	1433	179

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Table B.1 (*continued*)

	Category of building use at the time of construction	Height [m]	Footprint [m²]	Gross Floor Area [m²]	# Underground Levels	# Upper Levels (excl. attics)	Construction date	Volume of Materials [m³]	Mass of Materials [T]	Greenhouse Gas Emissions [TCO2e]	Volume of Materials per GFA [m³/m²]	Mass of Materials per GFA [kg/m²]	Greenhouse Gas Emissions per GFA [kgCO2e/m²]
13	Multi-dwelling	9	246	904	1	3	1932	485	1008	143	0.54	1115	158
14	Single-dwelling	7.65	60	180	1	2	1933	106	249	30	0.59	1382	167
15	Multi-dwelling	18	380	2447	1	6	1934	1134	2250	330	0.46	920	135
16	Multi-dwelling	24.5	400	2885	1	6	1939	1440	1987	305	0.50	738	107
17	Multi-dwelling	11	356	1424	1	3	1954	848	1457	247	0.60	1023	173
18	Industrial & Retail	15.6	492	2859	1	4	1955	1245	2955	368	0.44	1034	129
19	Office & Educational	12	1030	3352	1	3	1956	2373	5435	815	0.71	1621	243
20	Multi-dwelling	23	572	4523	1	7	1957	2148	4515	628	0.47	998	139
21	Multi-dwelling	17.5	380	1675	1	4	1960	893	1281	195	0.53	802	116
22	Office & Educational	23	454	1840	1	4	1963	1114	2647	332	0.61	1438	181
23	Multi-dwelling	31.4	390	3483	1	9	1970	1716	4068	504	0.49	1168	145
24	Industrial & Retail	9	1250	3430	1	2	1970	1444	3435	434	0.42	1002	126
25	Single-dwelling	8.4	193	499	1	2	1971	303	537	91	0.61	1077	182
26	Multi-dwelling	15	374	1660	1	4	1971	735	1514	220	0.44	912	133
27	Multi-dwelling	13	382	1386	1	3	1972	708	1638	216	0.51	1182	156
28	Office & Educational	64	856	17,981	3	18	1972	7481	18,611	3063	0.42	1035	170
29	Multi-dwelling	32	426	5625	5	10	1976	2743	6507	807	0.49	1157	144
30	Multi-dwelling	24.2	315	2143	1	7	1980	790	1874	232	0.37	875	108
31	Single-dwelling	8.4	320	790	1	2	1986	484	774	131	0.61	979	166
32	Office & Educational	24	382	2556	1	6	1989	996	2468	396	0.39	965	155
33	Industrial & Retail	10	1172	4142	2	2	1990	3417	8110	1010	0.82	1958	244
34	Multi-dwelling	25.5	350	2701	1	7	1993	1082	2570	321	0.40	951	119
35	Multi-dwelling	18.5	940	4873	1	5	1996	2122	4836	635	0.44	992	130
36	Single-dwelling	6	106	292	1	2	1998	135	321	40	0.46	1098	137
37	Single-dwelling	5.8	116	343	1	2	1999	151	359	45	0.44	1046	131
38	Industrial & Retail	25.4	1900	12,168	1	5	1999	3884	9912	2003	0.32	815	165
39	Office & Educational	10.5	774	3096	1	3	2006	1415	3373	432	0.46	1089	140
40	Multi-dwelling	17.7	484	3388	1	6	2008	1453	3455	434	0.43	1020	128
41	Multi-dwelling	23	550	4050	1	7	2010	1730	4106	511	0.43	1014	126
42	Office & Educational	27	2730	22,570	2	5	2010	10,909	25,998	3322	0.48	1152	147
43	Single-dwelling	6.9	82	240	1	2	2014	112	265	33	0.46	1104	138
44	Industrial & Retail	25	2017	14,035	1	5	2014	8221	19,557	2471	0.59	1393	176
45	Industrial & Retail	8.9	985	2219	0	3	2015	1092	2598	329	0.49	1171	148
46	Single-dwelling	6	143	366	1	2	2017	228	540	68	0.62	1477	185
47	Single-dwelling	5.8	102	254	1	2	2017	143	339	42	0.56	1337	166
48	Multi-dwelling	27.5	600	5670	1	9	2018	2477	5884	737	0.44	1038	130

Appendix C. Material Coefficients

The EGHGHE computed in this paper rely on process analysis as a life cycle inventory technique. The main limitation associated with this technique is its truncation error (Stephan and Athanassiadis, 2017; Lenzen, 2000; Suh et al., 2004; Majeau-Bettez et al., 2011), which underestimates embodied environmental flows, including EGHGE, compared to more comprehensive techniques such as hybrid analysis (Crawford et al., 2018b).The only database of hybrid embodied environmental flows coefficients for construction materials that is currently available is the EPiC database for

Australia (Crawford et al., 2019, 2022).Given the lack of a readily available database of hybrid EGHGE coefficients of construction materials in the Swiss context, a process-based database is used. Another limitation of this method is that wastage during construction is not considered.

Embodied Carbon (EC) values for Table C1 are obtained from (Miatto et al., 2019). Coefficients of composite components such as hollow-core slabs are weighted from composing materials (Table C2). Reinforced concrete components such as slabs, beams, walls and piles are computed based on the appropriate quantity of reinforcing steel (Table C2).

Table C.1
Density and embodied greenhouse gas emission coefficients (EC) for all materials used in this study.

	density [kg/m^3]	EC [kgCO_2e/kg]
concrete	2300	0.099
steel for reinforced concrete	7850	0.682
steel	7850	0.734
timber	675	0.126
stone	1400	0.138
terracotta	900	0.258
masonry (full)	2000	0.258
masonry (hollow)	1000	0.258
slate	2500	0.034
copper	8900	2.19
metal sheet	7850	1.83
zinc	7200	4.04
tile	1700	0.375
aluminium	2690	5.62
aluminium (80% recycling content)	2690	2.94

Table C.2
Embodied greenhouse gas emission coefficients (EC) for building components used in this study.

	density [kg/m^3]	EC [kgCO_2e/m^3]	steel/volume of reinforced concrete [kg/m3]	concrete [% vol.]	steel rebars [%vol.]	steel [%vol.]	timber [%vol.]	stone [% vol.]	terracotta [%vol.]	void [% vol.]
Slabs (joist/plank/screed)										
Timber/Stone/ Concrete	1561	**187**	125	30.0%	0.0%	0.0%	15.0%	55.0%	0.0%	0.0%
Timber/Reinf. Concrete/Concrete	1269	**126**	125	49.7%	0.3%	0.0%	15.0%	0.0%	0.0%	35.0%
Timber/Terracotta/ Concrete	971	**128**	125	30.0%	0.0%	0.0%	15.0%	0.0%	20.0%	35.0%
Steel/Stone/ Concrete	1972	**375**	125	42.0%	0.0%	3.0%	0.0%	55.0%	0.0%	0.0%
Steel/Reinf. Concrete/Concrete	1679	**313**	125	61.7%	0.3%	3.0%	0.0%	0.0%	0.0%	35.0%
Steel/Terracotta/ Concrete	1382	**315**	125	42.0%	0.0%	3.0%	0.0%	0.0%	20.0%	35.0%
Reinf.Concrete/ Stone/Concrete	1814	**208**	125	44.8%	0.2%	0.0%	0.0%	55.0%	0.0%	0.0%
Reinf.Conc./Reinf. Conc./Concrete	1522	**147**	125	64.5%	0.5%	0.0%	0.0%	0.0%	0.0%	35.0%
Reinf.Concrete/ Terracotta/ Concrete	1224	**149**	125	44.8%	0.2%	0.0%	0.0%	0.0%	20.0%	35.0%
Reinforced Concrete	2388	**309**	125	98.4%	1.6%					
Timber	675	**85**								
Beams										
(Reinforced) concrete	2357	**280**	80	99.0%	1.0%					
Timber	675	**85**								
Steel	7850	**5762**								
Posts										
(Reinforced) concrete	2385	**306**	120	98.5%	1.5%					
Timber	675	**85**								
Steel	7850	**5762**								
Stone	1400	**193**								
Masonry (full)	2000	**516**								
Masonry (hollow)	1000	**258**								
Aluminium	2690	**15,118**								

(continued on next page)

Table C.2 (*continued*)

	density [kg/m^3]	EC [kgCO_2e/m^3]	steel/volume of reinforced concrete [kg/m3]	concrete [% vol.]	steel rebars [%vol.]	steel [%vol.]	timber [%vol.]	stone [% vol.]	terracotta [%vol.]	void [% vol.]
Walls										
(Reinforced) concrete	2357	**280**	80	99.0%	1.0%					
Stone	1400	**193**								
Masonry (full)	2000	**516**								
Masonry (hollow)	1000	**258**								
Roof Framework										
(Reinforced) Concrete	2388	**309**	125	98.4%	1.6%					
Timber	675	**85**								
Steel	7850	**5762**								
Roof cover										
(Reinforced) concrete	2388	**309**	125	98.4%	1.6%					
Tile	1700	**638**								
Slate	2500	**85**								
Zinc	7200	**29,088**								
Copper	8900	**19,491**								
Metal sheet	7850	**14,366**								

Appendix D. Data Validation

D.1 Data coverage

Following Section 2.3, data are interpolated on a building if at least one sample building is sufficiently similar to that building. The absence of sample buildings in three building use categories – i.e., 'community', 'appendices', and 'unknown' – contributes the most to building entries not being interpolated (Fig. D.1a). The remainder of discarded buildings are built more than $C_{thr} = 25$ years and $H_{thr} = 8$ m apart from any known sample building. As a result, 47.1% of buildings are not studied, corresponding to only 20.7% of total GFA (Fig. D.1c). This considerable variation is explained by the fact that most dismissed buildings are appendix buildings – e.g., garages, storage rooms – typically characterised by a small footprint and no upper stories.

For fixed thresholds – e.g., thresholds on construction years C_{thr} and building heights H_{thr} – data coverage can only be improved by increasing the number and variety of studied sample buildings. Despite very tight thresholds, the high coverage ratio (79% of total GFA) is significant, given the relatively tiny proportion of sample buildings: $\frac{48}{84'477} = 0.06\%$. This is explained by a selection of sample buildings that present a diversity of use, construction year, and height (Fig. 4c).

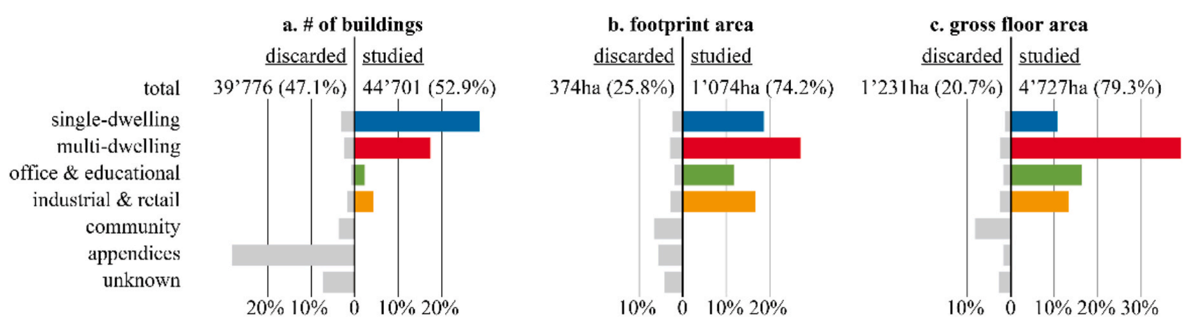

Fig. D.1. Ratio of buildings whose environmental effects could be obtained after the interpolation of values from 48 sample buildings.

D.2 Deviations

In order to estimate interpolation errors, differences between values of EGHGE(b^*) initially measured on sample buildings b^* and interpolated values EGHGE(b) of buildings b with exactly the same features as b^*, confer Table 1, are compared (Fig. D.2). Mean errors on sample buildings are displayed for each building use category in the first four rows of Table 5, and for all building uses in the fifth row. Estimates of mean errors on the entire stock are obtained as a weighted average of errors over building uses, sixth row on Table 5; each weight being proportional to the number of studied buildings in the considered use category. Following this approach, interpolated values of EGHGE per GFA present an error of 13% ± 4.3%, similar to results in (Stephan et al., 2013). More representative deviations would be obtained if additional building samples are used as a control group, i.e. for comparing model predictions to real values on building samples that have not been used for weighing the model. This is a topic for future development.

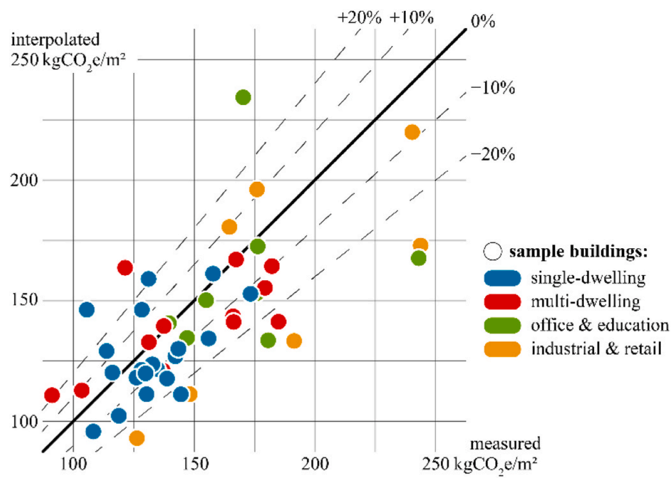

Fig. D.2. Measured EGHGE against interpolated EGHGE for 48 sample buildings.

Table 5
Mean errors between measured and interpolated values.

	# sample buildings	# stock buildings	VOL/GFA	MASS/GFA	EGHGE/GFA
single-dwelling	12	24,339	13.6 ± 6.4%	14.9 ± 5.9%	12.9 ± 5.5%
multi-dwelling	20	14,749	11.6 ± 4.1%	13.8 ± 3.8%	12.6 ± 3.4%
office & edu.	8	1998	17.9 ± 11.0%	17.9 ± 11.1%	15.2 ± 9.3%
indus. & retail	8	3615	18.8 ± 6.2%	19.1 ± 6.4%	19.2 ± 6.0%
sample	48	/	14.4 ± 3.3%	15.6 ± 3.1%	14.2 ± 2.8%
stock	/	44,701	**13.6 ± 5.8%**	**15.0 ± 5.5%**	**13.4 ± 5.0%**

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