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# A novel approach to establishing bottom-up LCA-based limit values for new construction

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A B S T R A C T

The global construction industry, a significant contributor responsible for 37 % of greenhouse gas emissions (GHGe), necessitates immediate and relevant policies to reduce emissions. Consequently, several countries are implementing GHGe limit values in building regulations to initiate mitigation measures. To support this development and the efforts to mitigate GHGe, this study provides a method for defining a representative case sample of conventional practice and bottom-up Life Cycle Assessment (LCA)-based limit values for policy measures. Based on a dataset of 291 actual building projects, a representative case sample of 163 conventional case studies is defined, and their related life cycle GHGe is calculated with LCA, resulting in a variation from 8.3 to 11.8 kg $CO_2e/m^2$/year. Cumulative distribution functions are computed with share factors, which consider the construction activity in a country and reflect the physical output of completed construction work from which limit values are derived. A general limit value is calculated at 9.0 kg $CO_2e/m^2$/year, corresponding to the median where the ambition level targets 50 % of new construction to perform mitigation efforts. Across building types, limit values vary between 8.2 and 11.5 kg $CO_2e/m^2$/year, and more ambitious limit values for residential buildings are derived starting at 4.9 kg $CO_2e/m^2$/year based on examples of best practice case studies. Comparing the general bottom-up limit value against top-down targets reveals a gap, suggesting a necessary increase in the ambition level. Yet, limit values should be introduced and gradually tightened to reach net zero in 2050 across several building typologies to support the adaptation of mitigation strategies.

## 1. Introduction

The escalation of the climate crisis emphasizes the importance of mitigating greenhouse gas emissions (GHGe). Effective strategies for the immediate mitigation of GHGe must be implemented in countries committed to the Paris Agreement, which aims to limit the temperature increase to 1.5 °C above the pre-industrial level [1]. Industries should pursue more significant efforts to mitigate their contribution to global GHGe, including the building and construction sector, which is responsible for 37 % of emissions, of which 27 % relates to the energy demand and 10 % to the manufacture of building materials [2]. To ensure an effective pursuit of mitigation efforts, understanding the contribution to GHGe from new buildings must be gained through building materials, components and systems implemented [3]. In this context, Life Cycle Assessment (LCA) emerges as a useful method whereby valuable insights into the environmental impacts caused by the building's production, construction, use and end-of-life can be achieved [4–7]. Collecting several projects can aid further in estimating bottom-up benchmarks, which provide an understanding of new buildings' environmental impacts. To that end, benchmarks offer a measure for assessing the environmental performance of buildings and identifying the reduction possibilities in resource consumption and related environmental impacts. For instance, in sustainability certification schemes for buildings, environmental performance is assessed by comparing it to a benchmark or limit value [8]. Finally, benchmarks can act as a tool for setting realistic limit values in building regulations aiming to initiate mitigation efforts [9]. In research, several studies investigate the possibility of establishing benchmarks based on the bottom-up approach for various categories of environmental impact [10–17].

Meanwhile, some countries have begun implementing the requirements for documenting the environmental impacts with LCA and

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compliance limit values. Regulation by means of limit values were introduced early in the Netherlands, where LCA has been a requirement since 2013 [18]. Furthermore, in 2018, the Netherlands implemented limit values for the eleven aggregated impact categories [11]. France implemented the RE2020 regulations, which state that limit values, varying from 640 to 900 kg $CO_2e/m^2$, are valid between 2022 and 2024 for several building typologies and that compliance must be documented by conducting LCA [19]. Note that these limit values include all life cycle stages of embodied emissions. In Sweden, several limit values have been proposed depending on the building typology, varying from 130 to 460 kg $CO_2e/m^2$. However, these limit values only include upfront emissions corresponding to A1-5 and may be introduced by 2025 at the earliest [20]. The Danish regulations were recently updated with new requirements, such as LCAs being valid for all new buildings and a general limit value of 12 kg $CO_2e/m^2$/year that applies to buildings larger than 1000 $m^2$ [21]. In addition, regulations that document and regulate the GHGe of new buildings are expected in several Nordic countries, e.g., Finland, Iceland and Norway [22]. Furthermore, the implementation of limit values of GHGe for new buildings is a positive trend that is expected to gain momentum with the enactment of the revised Energy Performance of Buildings Directive (EPBD) of the European Commission, which calls for calculating the life cycle GHGe of all new buildings in Europe from 2027 [23].

Although the importance of defining benchmarks and potential limit values is recognized, and several political initiatives are being made in that direction, the literature still needs studies demonstrating a robust methodology for establishing bottom-up LCA-based limit values to support policy-making.

### 1.1. State of the art

Limit values calculated using a bottom-up approach and expected to be implemented in the regulations must reflect today's technologies as implemented in building construction [24]. In support of this, a sample of actual buildings is preferred and must be collected [25,26]. In previous studies, building archetypes were often used to determine bottom-up-based benchmarks. While archetypes can accurately represent building typologies, the environmental impacts of the choice of material data and energy use may not represent actual building projects [27,28]. For instance, in a study by Hoxha et al. [3], the bottom-up limit value has been developed with scenarios for building archetypes indicating variabilities in environmental impacts. In Lavagna et al. [17], environmental benchmarks for European housing are calculated on a representative building stock defined with statistics about size, type, period of construction, technical characteristics, energy consumption and climatic zones. Ensuring the representativeness of a sample allows for generalization [29], and while these studies include several relevant parameters to ensure representativeness, only archetypes have been developed. Thus, no actual building projects have been examined which would induce the generalization of environmental impacts. Moreover, the number of building projects significantly influences the robustness of limit values based on the bottom-up approach [30]. However, since LCAs of buildings can be time-consuming and are not easily accessible, studies that investigate bottom-up-based benchmarks or limit values typically include small sample sizes, which can be crucial for further harmonization [27]. In a study by Rucinska et al. [12], a preliminary LCA-based bottom-up benchmark for Polish office buildings is proposed with a sample size of eleven case studies resulting in a mean value of approximately 5000 kg $CO_2e/m^2$/year over sixty years. Although they considered actual building projects, the sample size seems insufficient to define limit values, especially for other typologies. In addition, the process of selecting the case studies did not take into account the representativeness of materials, type of office building, construction method, or other aspects [12]. In another study by Röck et al. [31], a large sample of European buildings was collected, resulting in 762 case studies, of which LCA-based bottom-up benchmarks were determined at an average of 600 kg $CO_2e/m^2$ [27]. However, in this study, the representativeness of the cases has not been investigated in detail, as the focus was creating a large sample of case studies. Thus, the bottom-up-based benchmark values represented in the literature do not necessarily consider case studies that reflect which building types are typically built or their material composition, as also highlighted in Ref. [17].

Furthermore, the bottom-up-based benchmarks and limit values do not take into account the construction activity of a country in which building typologies constitute a substantial quantity of square meters constructed historically. Frequently constructed building typologies are responsible for a larger portion of GHGe, as was recently shown in the case of Denmark [32]. Thus, taking account of construction activity in establishing GHGe limit values will reflect these building typologies. Doing so will further ensure that efforts to mitigate emissions are mainly targeted towards these.

While bottom-up-based limit values for new buildings can ensure mitigation efforts for most constructed new buildings, they should also be aligned with climate targets to ensure their effectiveness. However, bottom-up limit values may not necessarily align with top-down climate targets such as the Paris Agreement, which are rooted in the state of Earth system processes. The standard ISO 21678:2012 *Sustainability in buildings and civil engineering works — Indicators and benchmarks — Principles, requirements and guidelines* acknowledges that limit values can also incorporate a top-down approach that takes climate targets into account [30,33]. Yet, most countries still rely on the bottom-up approach to determine possible emissions requirements [33]. The Danish limit value of 12 kg $CO_2e/m^2$/year over fifty years (600 kg $CO_2e/m^2$) is defined such that 10 % of new buildings must perform better than currently, which does nothing to encourage the necessary mitigation efforts. This is also demonstrated in a study by Horup et al. [34], where the Danish legislation providing for 306 kg $CO_2e/m^2$ is compared to estimated top-down limits for upfront emissions in 2023, which varied between 96.4 and 237.8 kg $CO_2e/m^2$. Thus, a clear gap of 220 % was shown between the bottom-up-based limit value and the top-down limit for the Danish context. This gap is also demonstrated by the Reduction Roadmap, which provides potential limit values for the Danish residential stock that is aligned with the Paris Agreement [35]. Here, a limit value for buildings in 2025 is proposed at 5.8 kg $CO_2e/m^2$/year over fifty years, and the expected limit value in 2025 is 7.1 kg CO2e/$m^2$/year [36]. While significant gaps between bottom-up GHGe limit values and climate targets may be present, a balance in introduced gradual limit values should be prioritized to allow stakeholders to adopt mitigation strategies toward reaching net zero by 2050. In addition, the current limit value needs to be differentiated between typologies, allowing easier compliance for some building types, and therefore initiating effective mitigation efforts.

The state of the art shows that studies investigating benchmarks and limit values exist. However, more studies using methods of establishing a representative sample and robust bottom-up LCA-based limit values are needed to support the development of regulations that require LCA and compliance with bottom-up limit values. The representative case sample must be large and represent real building projects to ensure robustness, while the method of establishing a limit value should be aligned with the construction activity. Developing such limit values would allow GHGe to be gradually limited, initiating mitigation strategies in the construction sector, and paving the way for achieving climate targets. Therefore, this study provides a novel method of establishing robust and representative bottom-up limit values for GHGe for new buildings. Based on a dataset encompassing 291 actual buildings across several building typologies and their related life cycle GHGe, the method is developed by answering the following research question:

1. How can robust GHGe limit values be established on a representative basis while considering a country's construction activity and enabling the introduction of gradual limit values?

Furthermore, the research outcome contributes to identifying mitigation strategies by establishing robust GHGe limit values relevant to policy-makers and researchers.

## 2. Materials and methods

This section outlines the approach applied in the study, which aims to provide a comprehensive understanding of the processes. The overall process illustrated in Fig. 1 follows three steps: (i) establishing representative case samples, (ii) assessing their environmental impacts, and (iii) defining the limit values.

### *2.1. Method for establishing a representative sample of case studies*

The first step in establishing a representative sample is to collect data for a group of building projects. Ideally, the update of limit values in regulations would be facilitated by a centralized and open collection of building LCAs that are conducted to document compliance with regulations [37]. If such a source does not exist, the collection of building projects can originate from several research projects that aim to conduct life cycle assessments of real buildings, or they can be provided by stakeholders in the construction industry. This implies the necessity to establish contact with organizations or companies in academia and the private and public sectors. A study by Röck et al. [38], describes the challenges in comprehensive data-collection processes based on the experience of collecting fifty case studies from five EU member states. Since the sample of buildings needs to be representative, the project collection must undergo a conformity check.

To ensure that the case studies reflect conventional practices, deselecting experimental case studies that deviate from the norm is essential. This criterion applies to case studies where mitigation strategies initiated from the project's beginning have reduced GHGe. Moreover, buildings with specialized functions must be excluded from the sample, necessitating increased resource use and, consequently, increased GHGe. For instance, laboratories requiring double sandwich constructions to reduce vibrations during production will require the consumption of resources beyond that of conventional buildings. However, this may entail allowing a supplement to the limit value to ensure they are still built in the future [39]. Such information can be gathered from the stakeholders of the building projects, since they possess valuable insights into the project's objective and potential challenges. Moreover, the representativeness of the selected case studies must be assessed by investigating whether the data cover a sufficient share of actual constructed square meters and if the materials used in these case studies reflect the general practice. The case studies are considered in the final representative case sample provided they align with national records of constructed areas and utilized materials to an acceptable degree for a chosen period. Achieving 100 % alignment may not be possible. If substantial variations (e.g., more than 20 %) [40] between the statistics and the case studies become apparent, whether they cause extremes or outliers in the statistical distribution in the life cycle of GHGe must be checked. If no extremes are evident, the variations in the comparison are deemed acceptable.

Preferably, statistics that match the period when the case studies are constructed should be examined. To support this, the statistics to be compared could be narrowed down to a specific time. This period could be defined based on the recordings of TABULA [41]. If the generic building types of a country change every decade, cases representing the construction technology of the latest decade are included in the case sample. In addition, the case sample should only include buildings that have been constructed and are in use to ensure that the life cycle GHGe value is as representative of the building as possible. In addition, to ensure that the case studies reflect the conventional practice of a specific time, the case studies are selected based on when they were constructed to ensure that the year fits into the chosen period.

As the final sample of case studies is defined, it is possible to distinguish between residential- and non-residential building typologies depending on the type of limit value that is wanted. If distinguishing between building typologies, differentiated GHGe limit values are determined. From this, it is possible to distinguish further between specific building use types to define GHGe limit values for single-family, multi-family, etc.

### *2.2. Life cycle assessment*

An LCA is performed to assess the GHGe of the case studies, since this method is chosen in the Danish regulations to check compliance with the GHGe limit values. To ensure comparability, the LCA of the case studies is aligned with the Danish Building Regulations (BR18), valid since 2018; however, updated in 2023 with LCA requirement, which follows EN 15978:2012 *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* [42,43]. The LCAs consider life cycle stages: Production (A1-3), Use (B4 and B6), and End of Life (C3-4), as only these modules are included in the limit values in BR18. Moreover, only the environmental impact category 'Global warming potential' (GWP) is reported (measured in kg $CO_2$ equivalents).

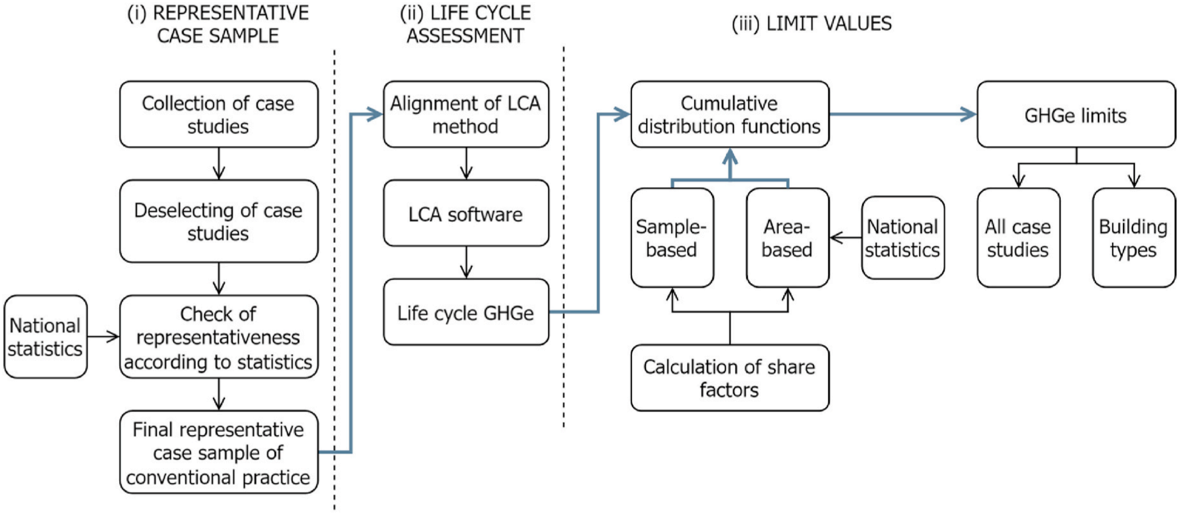

**Fig. 1.** Illustration of the methodology applied in the study. It includes defining a representative case sample, calculating the GHGe of all case studies with LCA, and outlining a cumulative distribution function with share factors to determine GHGe limit values.

According to BR18 §§ 297–298, the functional unit of the LCAs is defined as one square meter per reference floor area (RFA; cf. BR18) over a reference study period (RSP) of fifty years. Thus, the GHGe limit values will be expressed in kg $CO_2e/m^2$/year. Life cycle GHGe is determined with LCAbyg 2023 (5.3.1.0), where all case studies were modelled using the available database and following the BR18 methodology. The cases were checked for conformity to ensure the same level of detail and comprehensiveness. However, modifications to the method are applied to the LCA method of BR18, as the background environmental data of building materials and emissions factors of the energy grid are expected to be updated in 2025. This modification is required to ensure GHGe limit values reflect the future methodological aspects of LCA in BR18 and to ensure their comparability with new buildings' GHGe in the future. The environmental data consist of Ökobaudat 2023 and a newly developed Danish generic database of GHGe of the thirty most applied building materials [44,45]. In this GHG database for Danish building materials, generic values are determined based on environmental product declarations (EPD) according to both EN 15804:2012+A1:2013 *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products* and EN15804:2013+A2:2019 [46,47]. Environmental data in Ökobaudat 2023 is in accordance with EN15804+A2. Emission factors of the energy grid are from Ref. [48], which shows the progression of the energy grid from 2025 to 2075. These emission factors are expected to be obligatory in LCA's in the upcoming update of Danish building regulations from 2025. The LCAs of case buildings include the following building elements: external and internal walls including finishings; ground-floor slab including flooring; floor slabs including flooring and ceiling constructions; roof including ceiling and roofing constructions; stairs, ramps, elevators, windows and doors, beams and columns, and foundations. The level of detail of technical installations such as water, heat, drainage, ventilation and cooling differ significantly across the building models. To avoid the variation in detailing and the uncertainties in the results, it was decided to apply default values of GHGe from installations. These have been developed by the Danish Housing Authority and are validly applicable in LCAs aligned with BR since they are considered representative of typical installations [49,50]. However, these values are updated with Ökobaudat 2023.

### 2.3. Establishing bottom-up LCA-based GHGe limit values

Establishing a GHGe limit value at a specific level of ambition involves cumulative distribution functions (CDF). These are developed from a policy perspective, allowing definitions of GHGe limit values in building regulations and updating them regularly, e.g., every second year. The CDFs can consider the probability of which building types have been built based on the construction activity of a particular country and their corresponding GHGe. This enables limit values to be established that reflect the activities of the construction industry. The cumulative distribution function is defined as shown in Equation (1) [51].

$$y(x) = P(X \leq x) \text{ where } x \in [x_{min}, \cdots, x_{max}] \tag{1}$$

Here, y represents the accumulated probability of the case studies as a function of x, where x represents the GHGe of the case studies in ascending order. The right-hand side describes the probability of a case study, X, resulting in GHGe less than or equal to x, where x belongs to the range within $x_{min}$ and $x_{max}$. Ideally, $x_{min}$ should equal zero to ensure GHGe limit values gradually decrease towards net zero in 2050. This may not be feasible for a sample of case studies with GHGe greater than zero. The unit of the x-axis depends on the chosen functional unit of the LCA.

Fig. 2 illustrates the principle of determining a GHGe limit value based on the cumulative distribution function. The starting year is n = 2025, and the final year is n. The GHGe limit value, $x_{2025}$, at a specific probability, e.g., y = 50 %, is determined by linear interpolation. Doing so will define a limit value that aims to target 50 % of the new buildings to perform better than currently.

Suppose $x_{2025}$ is valid in building regulations at a given year or period, e.g., from 2025 to 2027: a new or updated limit value can be determined in 2027. This can be based on the same sample or an updated one. The life cycle GHGe of the case sample will be reduced due to the regulating limit values. However, they vary between $x_{min}$ and the previous limit value, $x_{2025}$. This process is repeated until year n, where the limit value $x_n$ is determined and the life cycle GHGe will vary between $x_{min}$ and $x_{n-1}$, while $x_{min}$ must reach zero by 2050.

#### 2.3.1. Share factors concerning the number of buildings

This study applies two parameters to describe the probability y of a case study over the cumulative distribution functions. These are called share factors, which are distinguished as sample-based and area-based. These factors are applied to consider the building typologies of the sample and constructed activity in a country. Equation (2) calculates an equal share factor, $S_{w,c}$, for each case study within the sample, $n_c$ [52]. Doing so will result in all building types or building use types having an equal share of and thus equal influence on the GHGe limit value. For instance, given a sample $n_c$ of 13 case studies of a building-use type, the sample-based share factor will equal $S_{w,c} = 7.7$ % (1/13), and each case study will be distributed equally over the CDF. This approach can generally be applied for an entire sample as a total or be differentiated into smaller samples between building types, e.g., residential and non-residential, or building-use types, e.g., single-family houses, multi-family houses, etc.

$$S_{w,c} = \frac{1}{n_c} \bullet 100 \ [\%] \tag{2}$$

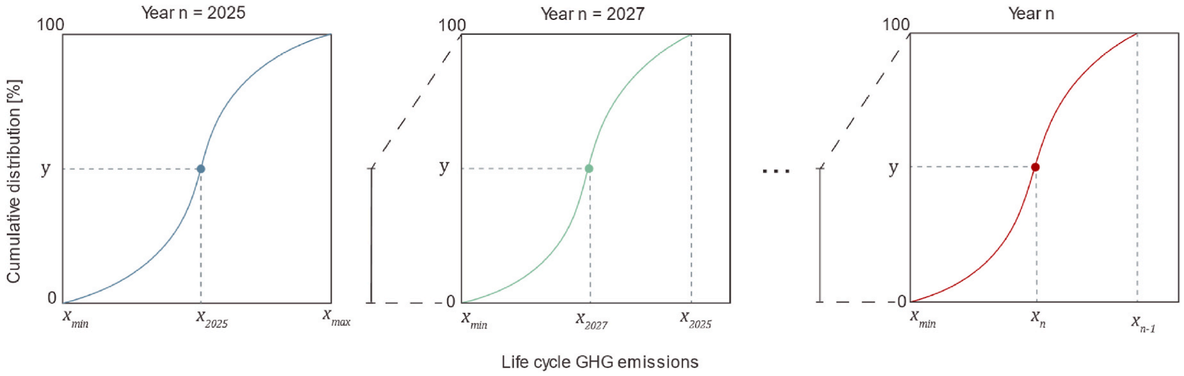

**Fig. 2.** Illustration of the cumulative distribution function to establish GHGe limits at a certain level of ambition. The x-axis displays each case's life cycle GHGe within the case sample in ascending order. At the same time, the y-axis shows the accumulated share of each case study in the respective scenario. The illustration shows an example at the 50th percentile that aims to affect the life cycle GHGe of 50 % of new construction.

### 2.3.2. Share factors concerning the construction activity

Equation (2) considers only the number of case studies included in the sample, resulting in equal influence from all case studies on the final GHGe limit values. Since the number of case studies will be random, share factors that relate to reality are defined by considering the construction activity. Therefore, instead of distributing the case studies based on the sample size, area-based share factors are determined that ensure that the GHGe limit value accurately relates to building typologies that account for a significant portion of a country's constructed areas. To do so, statistics of historically constructed building use types must be examined for a chosen period. Upon reviewing the statistics, area-based share factors can be determined based on the percentage of newly constructed areas of building-use typologies. This allows the life cycle GHGe of the respective building-use types to be weighted according to the gross square meters constructed within each building-use typology of a given period. The area-based share factors are determined with Equation (3), which corresponds to determining the share of the areas constructed of a building typology over the total constructed area [52].

$$A_w = \frac{A_c}{\sum_c A_c} \bullet 100\ [\%] \tag{3}$$

where $A_w$ is the area-based share factor for the building use types, c, and $A_c$ is the average constructed area for the building-use typologies. Depending on the availability of statistics for newly constructed areas, the heated floor area, gross floor area, or other area measures can be used to determine area-based share factors. The type of area measure can influence the area-based weighting. The area-based share factor corresponds to a building typology's share of constructed areas. For instance, given a building of type c representing 9000 m$^2$ of constructed area out of 100,000 m$^2$ in the whole of a period, the area-based share factor, $A_w$ equals 9.0 %.

To consider the sample size established for the limit value, the area-based weighting factor is divided by the number of case buildings, $n_c$. This results in the exact share factor for each case building of the considered building-use types in the sample, $A_{w,c}$, and is determined using Equation (4) [52].

$$A_{w,c} = \frac{A_w}{n_c}\ [\%] \tag{4}$$

For instance, $n_c$ of a building-use type consists of thirteen case studies, and the share of newly constructed square meters is 9.0 % of a chosen period. The area-based share factor for each case study will equal y = 0.7 % (9/13). In this case, case studies are accumulated using this factor in the CDF. This method calculates a general GHGe limit value across all building-use typologies and a differentiated limit value for residential and non-residential use.

### 2.4. Case studies

This study selected the representative sample from a pool of case studies comprising 291 projects encompassing primarily new constructions in Denmark from 2007 to 2023, some yet to be finalized. The information on building projects was obtained through a collection of data from various research projects [39,53–56], and external sources, such as the DGNB certification scheme, the Voluntary Sustainability class, and the case collection of the Knowledge Hub for Buildings' Climate Impact [57–59].

These projects represent the latest construction techniques, since they were built during the last ten years. Private companies provided architectural plans, BIM models and other documentation about building product quantities. A summary of the materials-intensity coefficients (MICs) is provided in Fig. 3, representing the total weight per reference floor area (according to the Danish building regulations). Within the MICs, the materials utilized in the external envelope, internal walls and floors, roof, foundations, technical systems and equipment are included. The projects are categorized into row houses, multi-family houses, single-family houses, day care, offices, health facilities, education and production, based on the classification provided in the Central Register of Buildings and Dwellings (BBR) [60]. The building typologies sport, logistic, cultural, retail and military are grouped into the other category due to the limited number of case studies and the representativeness of less than 5 % of floor areas newly constructed [32]. In general, the distribution of the MICs varies across the building typologies, indicating potential differences in related GHGe. Across the building categories, the average MIC ranges from 727 to 1395 kg/m$^2$. Row houses exhibit the lowest average MICs, while production buildings exhibit the highest. In particular, education buildings present a relatively narrow range from 1104 to 1686 kg/m$^2$, while multi-family houses present the broadest range from 243 to 2514 kg/m$^2$. Supplementary Materials Table 1 presents the MICs of each building for various typologies.

## 3. Results

### 3.1. Selection of representative case studies

Analyzing buildings to conform to their representativeness in the Danish context will require the validation of several inclusion criteria. The criteria to be met enable a project to be classified as conventional, representing a significant number of newly constructed buildings over a year and the materials utilized proportionately to materials used in construction. The first criterion is the ability to classify a project as a representative case study. After the conformity check, only 163 out of 291 projects were able to meet the criteria. From the 128 excluded projects, three were cases that were not built in Denmark, eight were cases with extended material consumption due to special conditions [39], four were building types not covered by LCA requirements in

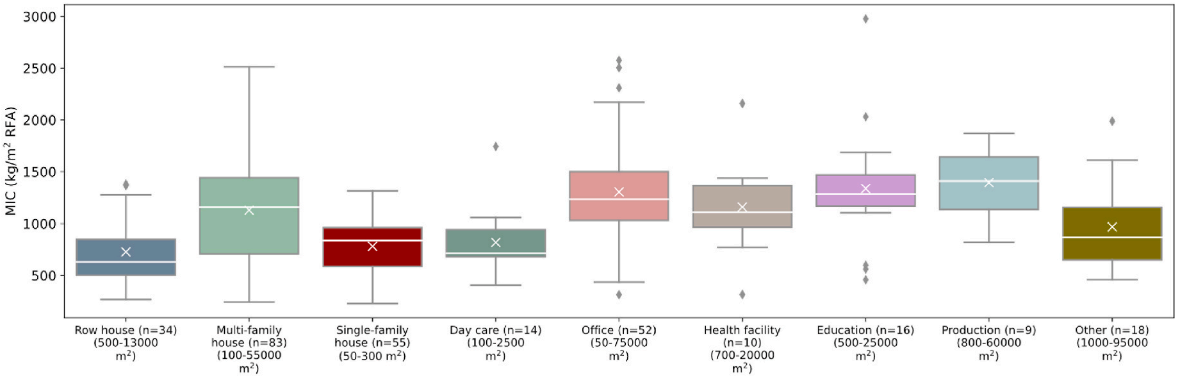

**Fig. 3.** Material intensity coefficients (kg/m$^2$ reference floor area) of 291 building projects.

building regulation (BR), fourteen were not registered in BBR or in use, and seventeen could not be identified or were anonymous and therefore too uncertain to be included in the sample. Finally, the remaining 82 case studies were excluded due to alternative construction principles deviating from conventional practice, using alternative materials, or explicitly focusing on strategies for reducing GHGe.

Among the projects that met all the criteria and were identified as conventional case studies, the final case sample comprised 64 non-residential and 99 residential buildings built in Denmark between 2013 and 2023. Moreover, related to their typology, 35 were single-family houses, 42 multi-family houses, 22 row houses, 35 offices, seven day care institutions, six educational buildings, eight health facilities, and a final category of eight other buildings, which included one cinema, three supermarkets, three logistics hubs and one production building. The process of creating the presentative case sample is illustrated in Fig. 4.

The second criterion is related to the representativeness of the total area constructed within the case sample, compared to annual recordings of the constructed area. National statistics are examined to assess the representativeness of the 163 case studies, specifically statistics on which the feasibility study is considered for comparison, on which the update of GHGe limit value in 2025 in Danish building regulations are based. This statistic considers the average heated floor area (HFA) and the number of buildings constructed annually and registered in BBR between 2015 and 2020, illustrated in Fig. 5. Residential building typologies represent a significant portion (67.7 %) of the constructed HFA and 93.2 % of the buildings. While office buildings and other buildings represent approximately the same share of 12.5 % and 12.7 % of constructed HFA respectively, the number of buildings constructed annually is 2.2 % and 3.3 %. Finally, the building typologies that are built less frequently are day care institutions, and education and health facilities, representing 7.1 % and 1.2 % of HFA and the number of buildings, respectively. More detailed statistics are provided in the Supplementary Material Table 2.

The representative case sample covers 31.7 % of constructed HFA compared to records from 2015 to 2020 (Fig. 6). Thus, the case sample represents a significant percentage of the yearly constructed area of buildings. The share of case buildings represented in the recordings of the constructed area varies from 0.7 % to 72.2 %, where single-family houses cover the smallest share and offices the largest. Concerning the number of buildings, only 1.5 % of the number of case studies is covered with the sample, given that it only considers 163 case studies, which, compared to a total of 11,071 new buildings constructed between 2015 and 2020, is significantly less. The best-represented building type is health facilities, while single-family houses are the least represented in the number of buildings constructed. More than 5000 case studies would be needed to represent single-family houses fully. Since Danish single-family houses are repetitive in terms of the materials they use and their shape, the importance of the final criterion becomes evident, which relates to checking the representativeness of materials employed in the case sample compared to national records.

Since BBR provides this information on the façade and roofing materials utilized in Danish buildings, the façade and roof-cladding materials of the representative case sample registered in BBR are compared against materials used according to the BBR of all new constructions built in 2016–2020. The comparative result is shown in Fig. 7, and more detailed results are given in Supplementary Materials Table 3. The categories Education, Daycare institution, Health facility and Other are collectively analyzed as *Other* since this category from BBR represents the aggregated statistics for these building typologies.

Brick is the preferred material for the façades of residential housing, which is well represented in general, as the difference between the case sample and BBR is only 14.4 %, 26.7 %, and 21.4 %. However, there is an over-representation of 56 % and 137 % for offices and other buildings respectively, meaning that the case sample includes more buildings with brick façades than the actual reporting of BRR. Moreover, case studies with concrete on the façade are lacking for multi-family houses and other buildings. However, only a 16.8 % difference is evident for offices. Wood cladding is generally over-represented, especially for single-family houses, row houses and other buildings, as 261 %, 580 % and 393 % differences are seen respectively. Finally, while there is over-representation of other materials for single-family houses of only 203 % and a lack of 67.4 % for offices, there is a difference of only 20.6 % for row houses, multi-family houses and other buildings. Regarding roofing materials, bitumen is preferred for several building typologies. Only 5.6 %, 1.0 % and 1.4 % differences are evident for row houses, multi-family houses and offices respectively. However, bitumen is over-represented for single-family houses and other buildings by 57.3 % and 99.2 % respectively. Case studies with roof tiles and concrete roof tiles are lacking, especially in single-family and row houses and other buildings, which may be caused by the over-representation of other materials, which are 308 % and 676 % for single-family and row houses respectively, and a lack of 57.8 % for other buildings. Overall, there is a good representation of brick in the façade and bitumen on the roof, as the case sample represents a significant percentage of those materials.

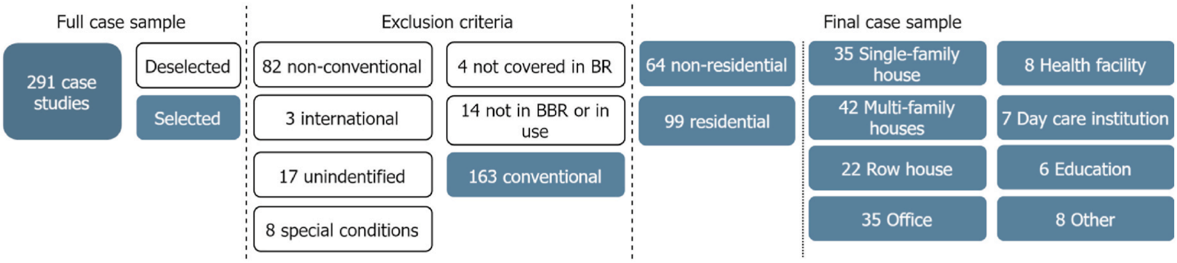

**Fig. 4.** Process diagram of selecting a representative case sample based on 291 case studies.

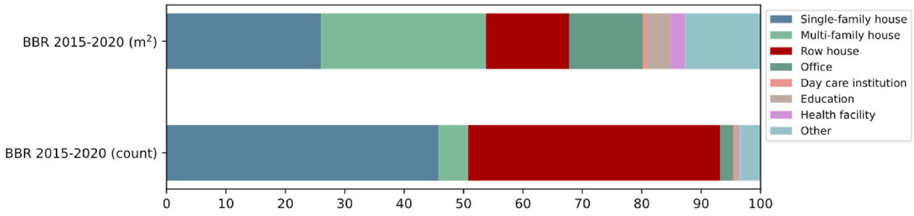

**Fig. 5.** National records in BBR of heated floor area (m$^2$) and number of buildings (count) for the given building typologies between 2015 and 2020.

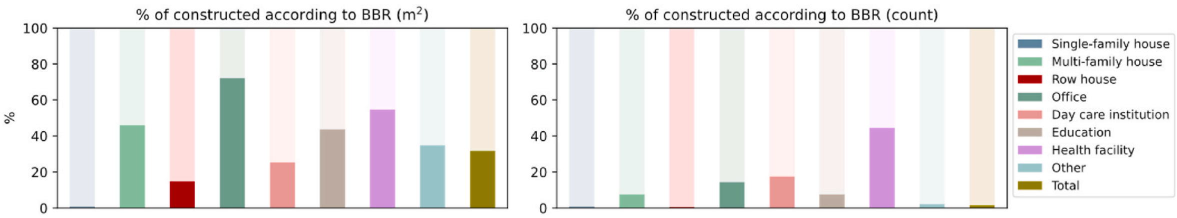

**Fig. 6.** Comparison of constructed HFA and number of buildings in the representative case sample against the national records in BBR between 2015 and 2020.

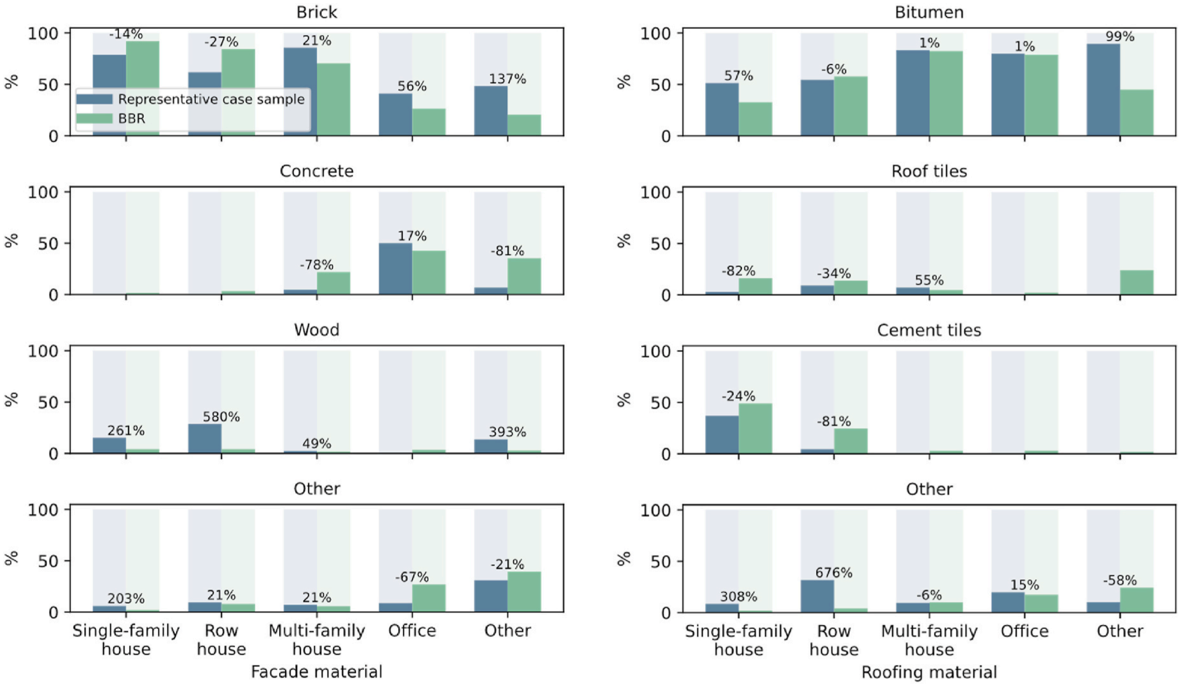

**Fig. 7.** Comparing the utilization of façade and roofing material of the case sample against the registered building materials in BBR in 2016–2020.

### *3.2. Life cycle GHG emissions*

The total GHGe from the representative case sample distinguished between building-use types is provided in Fig. 8. The average values of GHGe vary from 8.3 to 11.8 kg $CO_2e/m^2$/year. Here, row houses have the lowest mean in GHGe, education the highest. Within building types, the most significant variation in emissions is for offices, while the smallest variation is for education. Moreover, statistical distributions of building-use type are compared with expanding the sample to include all case studies, excluding the nine buildings with special conditions, as these are handled differently in the regulations [39]. Concerning all case studies (291), the most significant variation is found for education, and the smallest variation is for daycare institutions. The mean for all case studies across all building typologies varies from 7.3 to 11.9 kg $CO_2e/m^2$/year over a reference period of fifty years, where row houses have the lowest mean and health facilities the highest. Eliminating case studies to define the representative case sample influences the mean in GHGe of several building-use types as they either increase or decrease. However, the range of boxplots also decreases in general. For some building types, the means seem similar, e.g., day care institutions, while there are significant differences for other building types, e.g., education. Whether the mean in GHGe is statistically significant is investigated by comparing group means with T-tests (T distributions) within each building-use type across the two samples and different building-use types within the same sample. These T-tests are performed in R version 4.2.2 and RStudio version 2023.12 [61,62].

The statistically significant difference within and across the building-use types is validated if the p-value is less or greater than a significance level of 5.0 %. In Table 1, a significance level below 5.0 % indicates a significant difference between the means of the compared groups. Moreover, the diagonal shows whether statistical significance can be detected within the same building-use type across the two samples. Notice that Production is not included here, as no production facilities are considered in the representative case sample. The only building type with statistically significant group means across the two samples is row houses. Also, residential building types are not statistically different in GHGe within the representative case sample, and there are no statistical differences between daycare institutions and residential buildings. However, several of the remaining building typologies are statistically significant. Finally, taking all case studies together, instances of statistically significant increases as row houses are significantly different from single-family, multi-family houses and day care institutions. The table's results support the possibility that the effort to establish a representative sample is meaningful in this case, as the GHGe can differ significantly across the two samples for some building typologies. Nonetheless, the table indicates that GHGe limit values should be distinguished between building typologies to ensure mitigation efforts are performed for all building typologies. If only a general limit value is determined, there may be a risk of missing the mitigation potential in those building typologies that emit less than the limit values. Overall, the results of the T-tests support the finding that the GHGe are different across building-use types. Therefore, this also supports determining GHGe limit values for

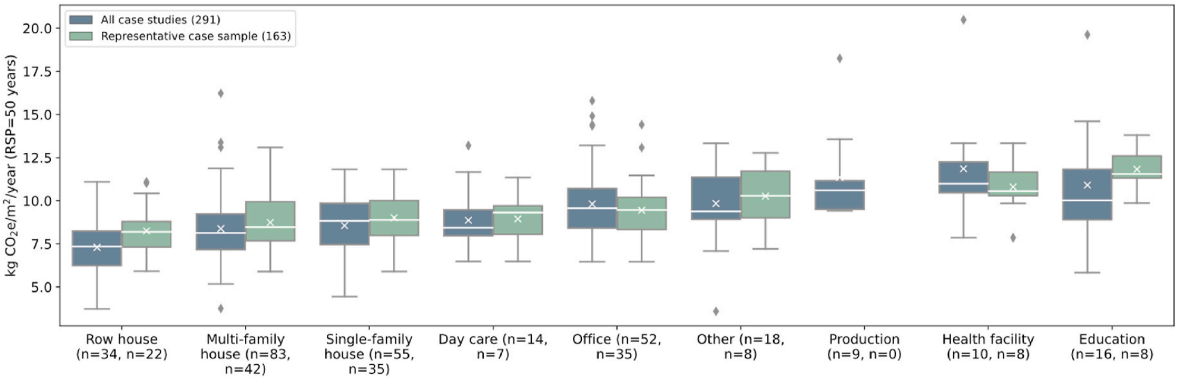

**Fig. 8.** Comparing the life cycle GHGe (A1-3, B4, B6, C3-4) of 291 case studies (blue) and the representative case sample of 163 case studies (green). Mean values are shown by 'x,' and the number of case studies within each sample is indicated by 'n'. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**

Statistical significance (p-values less than 5.0 %) of group means indicated by numerical values below the significance level. If the numerical call value is less than 0.05, the mean values between the building typologies are significantly different. More details are given in Supplementary Table 5. The T-tests are performed in R version 4.2.2 and RStudio version 2023.12.1.

| The p-value of T-test | | All case studies | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Single-family house | Multi-family house | Row house | Office | Day care institution | Education | Health facility | Other |
| Representative sample | Single-family house | 1.8E-01 | 5.9E-01 | 1.7E-03 | 1.6E-03 | 5.8E-01 | 1.2E-02 | 1.3E-02 | 5.3E-02 |
| | Multi-family house | 4.3E-01 | 2.7E-01 | 5.6E-03 | 2.3E-04 | 3.7E-01 | 7.5E-03 | 1.0E-02 | 2.8E-02 |
| | Row house | 7.0E-02 | 2.4E-01 | 4.9E-02 | 8.4E-08 | 1.1E-02 | 4.7E-04 | 1.9E-03 | 5.9E-04 |
| | Office | 2.6E-01 | 6.5E-02 | 9.0E-03 | 9.4E-01 | 1.1E-01 | 2.2E-01 | 9.4E-02 | 9.7E-01 |
| | Day care institution | 9.2E-01 | 7.5E-01 | 3.3E-01 | 4.7E-01 | 7.8E-01 | 4.0E-02 | 2.5E-02 | 2.1E-01 |
| | Education | 2.4E-03 | 1.5E-03 | 4.1E-04 | 5.5E-03 | 4.8E-03 | 1.2E-01 | 1.2E-01 | 2.9E-01 |
| | Health facility | 1.9E-02 | 9.3E-03 | 2.7E-03 | 6.3E-02 | 4.5E-02 | 2.3E-01 | 1.0E+00 | 1.2E-01 |
| | Other | 1.3E-01 | 7.6E-02 | 2.9E-02 | 3.2E-01 | 1.8E-01 | 1.1E-01 | 5.7E-01 | 5.0E-01 |

each building-use type. Moreover, the results suggest that establishing a representative sample influences GHGe and potentially influences GHGe limit values.

Differences between the materials utilized in the façade and roof were detected in the case sample and compared to BBR records. Whether the choice of material influences the life cycle GHGe in the sample, the emissions are examined concerning the façade and roof materials utilized in each case study, as shown in Fig. 9. Naturally, material types with the highest number of instances, e.g., brick in the façade and bitumen in roofing, influence the distributions, as the related case studies are distributed evenly along the boxplots. However, this also means that the choice of cladding materials for the façade and roof does not directly influence the GHGe, as no clear indication of lower or higher emissions is found. Concerning the over-representation of wood cladding (e.g., single-family houses), brick façade and wood cladding can exhibit varying emissions, indicating that this over-representation does not influence the GHGe. However, buildings with wood cladding exhibit lower GHGe than the median.

### 3.3. Establishing GHGe limit values

### 3.3.1. GHGe limit values

General limit values are determined at the 50th percentile to demonstrate the GHGe corresponding to the median. These values indicate the standard. However, they may not ensure that buildings' climate loads will move towards compliance with the Paris Agreement. The results of the cumulative distribution functions of 163 conventional case studies in Fig. 10(a) and (b) show that the general GHGe limit values at the 50th percentiles are 9.0 kg $CO_2e/m^2$/year for both sample-based and area-based share factors (provided in Supplementary Materials Table 6). Although the share factors of the two methods vary for each type of building within the sample, there is no significant difference between the potential GHGe limit values. This indicates that the case sample represents the construction activity from 2015 to 2020. The general limit values reflect the individual share factor and GHGe of case studies within each building typology, resulting in a limit value applicable to all building types. Consequently, buildings with mean values in GHGe, which are lower than the general limit value, e.g., residential buildings, will not be immediately affected, unlike those with greater mean values, such as health facilities and educational buildings. However, the statistically significant differences in mean values across building typologies support the establishment of differentiated limit values. Fig. 10(c) illustrates GHGe limit values for each building type at the 50th percentile (numerical values in Supplementary Materials Table 10). These distributions show that the lowest GHGe limit value would be for row houses at 8.2 kg $CO_2e/m^2$/year, and the highest GHGe limit value would be for educational buildings at 11.5 kg $CO_2e/m^2$/year. Thus, the differentiated limit values vary within this span, resulting in a difference of up to 3.3 kg $CO_2e/m^2$/year. The differentiated limit values demonstrate how the individual distribution is placed compared to the general limit value, that is, on either the lower or upper boundary. This approach will ensure that efforts to mitigate GHGe are explored for building typologies, representing the most significant proportion of new construction.

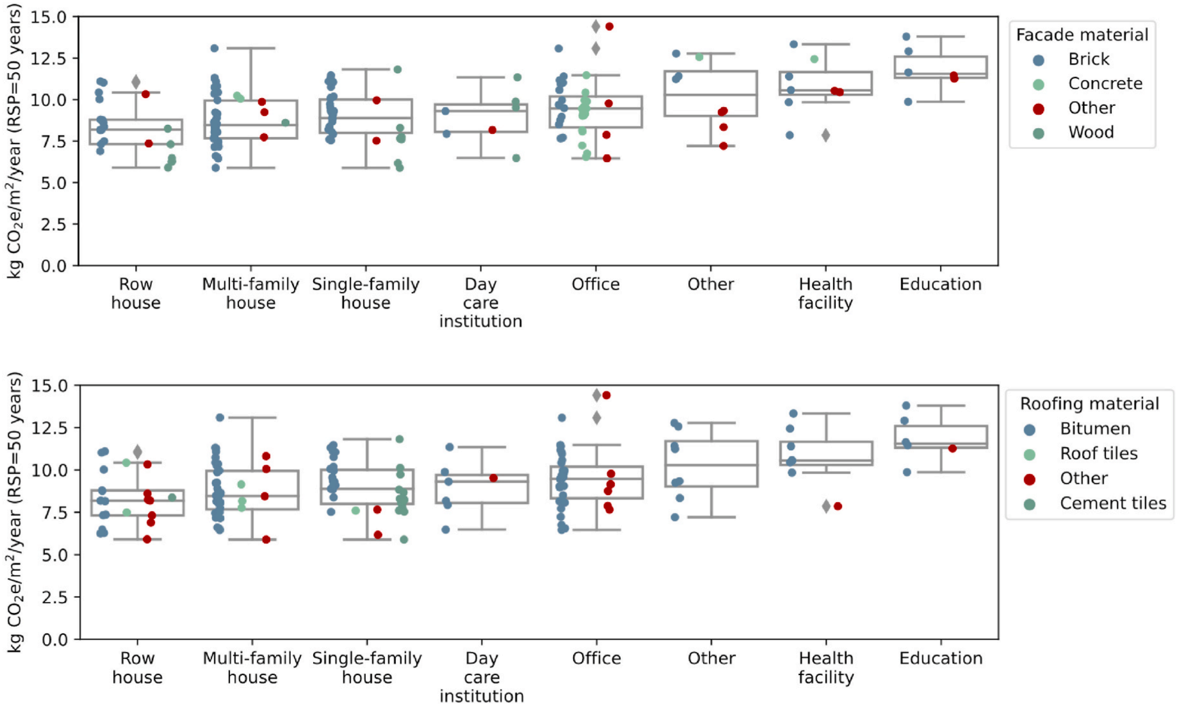

**Fig. 9.** Life cycle GHGe (modules A1-3, B4, B6, C3-4) of representative case samples differentiated in building-use type and the façade and roofing material of the buildings respectively.

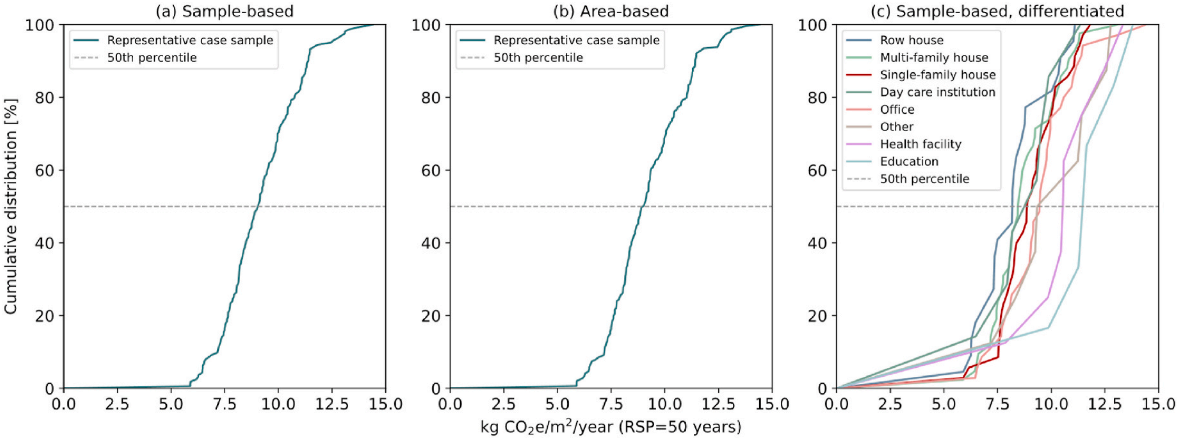

**Fig. 10.** Cumulative distribution function of the representative case sample of 163 case studies for both sample- and area-based share factors.

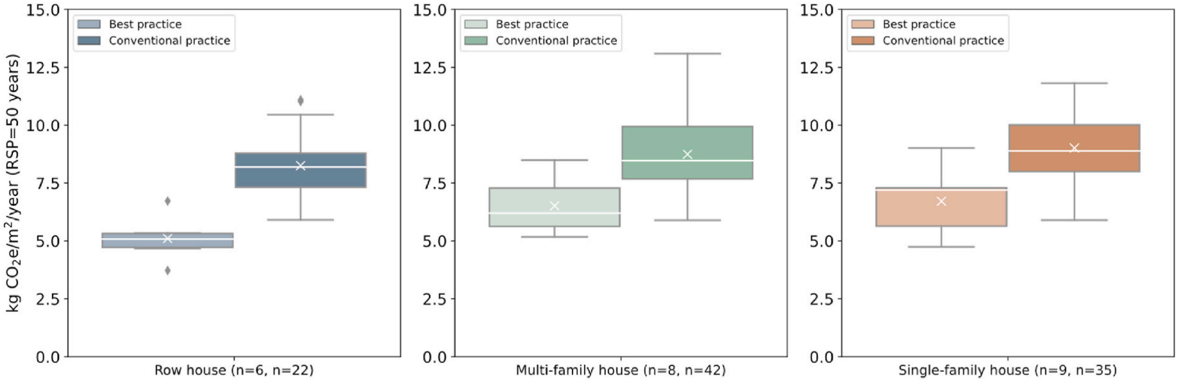

**Fig. 11.** Comparing the life cycle GHGe (A1-3, B4, B6, C3-4) of best practice conventional case studies for residential building-use types row houses, multi-family houses and single-family houses.

#### 3.3.2. GHGe limit values for best practices of residential buildings

A significant proportion (67.7 %) of all newly constructed heated floor areas were for residential buildings, and most were multi-family houses (27.8 % of the 67.7 %). If new floor areas are constructed as usual in the future, a large proportion of GHGe from residential areas is expected [32]. Thus, there must be a focus on mitigating GHGe from residential buildings. Fig. 11 compares the conventional practices identified in this study with examples of best practice from Garnow et al. [63]. The best practice examples are a collection of case studies demonstrating mitigation efforts integrated into the projects. Thus, it showcases the possibilities of today's technologies that can reduce GHGe over buildings' life cycles. Garnow et al. describe the comprehensive process of collecting and aligning the case studies with BR18, which enables the comparison performed in this study. The mean values for best practice are 5.1, 6.5, and 6.7 kg $CO_2e/m^2$/year for row houses, multi-family houses and single-family houses respectively, while they are 8.3, 8.7 and 9.0 kg $CO_2e/m^2$/year for conventional practice. Generally, less variation in GHGe for best practice is evident, where the smallest variation is in row houses, and the largest is for single-family houses. T-tests of the mean values prove there are statistically significant differences. Thus, this difference indicates significant mitigation potential by setting GHGe limit values that consider best practice case studies.

Distinguished limit values for the three types of residential buildings are provided in Fig. 12. The distributions show significant differences between the potential limits, especially since the limit value in the 50th percentile for row houses is significantly lower. Here, the limit value is 4.9 kg $CO_2e/m^2$/year, while it is 6.0 and 6.6 for multi-family and single-family houses respectively. Overall, there is considerable mitigation potential in residential building types, which are responsible for a substantial proportion of new buildings in Denmark, by establishing limit values that take into account today's technological possibilities within the construction industry. Ultimately this analysis shows that the outcome at any percentile depends greatly on the life cycle emissions of the chosen sample of case studies.

## 4. Discussion

### 4.1. Robustness of method

#### 4.1.1. Representativeness of case studies

This study has presented an extensive collection of 291 actual case studies. Due to the vast number of cases, another large sample of case studies was defined, comprised of 163 case studies that reflect building typologies and materials used in construction. While a large sample of case studies representative of a specific country does not exist in the literature, this study further provides an understanding of GHGe of 291 actual case studies. Consequently, the method depends on data availability to ensure the representative case sample's robustness in establishing GHGe limit values. The large case sample results from multiple research projects performed over several years. Currently, Denmark lacks a centralized data collection of building LCAs performed to document GHGe and compliance with the limit value. A centralized collection of LCAs in an open database is necessary to facilitate the updates and tightening of future limit values [37].

The approach to establishing a representative case sample generally applies to other countries but may be limited due to a lack of relevant data and national statistics. Denmark has an extensive publicly available registry of both the new and existing building stock in the BBR, which enables relevant analyses of the building stock, such as checking the utilization of cladding materials on the façade and roof. The correctness of the BBR data in the analyses does contain uncertainty since it was found that BBR contains incorrect information or lacks general information on more than half of the buildings [64]. Similar data on those provided in BBR may not be available in other countries. However, two sources that may provide relevant data are EU Horizon projects H2020 Hotmaps and AmBIENCe, which provide information regarding the EU27 building stock, such as physical characteristics and thermal behavior [65,66]. A study by Callegher et al. [67], provides statistics for, e.g., materials utilized to construct walls, roofs and floors in residential buildings in EU member states. This study reveals that since 2010, a large proportion of residential buildings have had brick, concrete and wood on the façade, which aligns with the findings of this study.

An important aspect of the representativeness of the case studies in the representative case sample was whether they were in use or not. Buildings in use are considered legal, as occupancy permits have been provided by the authorities. This also implies that the buildings comply with regulations concerning transmittance, acoustics, fire, load-bearing structure, indoor climate, etc. However, compliance with these regulations cannot be guaranteed for case studies that are not finalized. While this study compares conventional practices with best practices to define more efficient limit values for residential buildings, it is essential to consider that the best practice case studies are all constructed using bio-based materials [63]. Therefore, these case studies are biased towards bio-based materials such as wood, as they comprise larger quantities of wood than conventional practices. Although constructing buildings with more bio-based materials is one strategy to mitigate GHGe, there may be a risk of burden-shifting if only a single environmental impact is considered, such as the global warming potential [55]. Furthermore, if limit values that reflect cases of best practice are implemented instead of conventional practices when defining limit values, stakeholders will implement and explore existing wood-based construction in their building projects, under the impression that a significant mitigation potential may be reached. However, from a consequential perspective, shifting to wood-based construction can increase GHGe [68]. One of the influential aspects of this increase relates to the substitution of

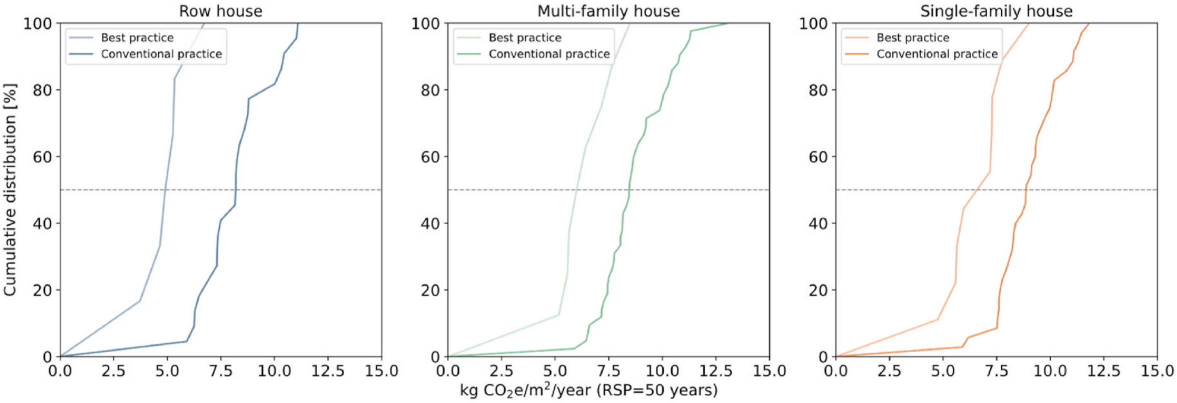

**Fig. 12.** Cumulative distribution functions of best and conventional practices for residential building-use types.

co-products from wood production, which affects the climate impact of wood used in construction.

### 4.1.2. Limit values

The study provides a robust method for defining GHGe limit values based on a representative case sample. The method's robustness lies in its ability to define GHGe limit values based on a representative case sample while considering the construction activity by calculating the share of constructed areas of different building typologies. Moreover, it supports the development of general and differentiated limit values for buildings based on several environmental indicators.

The share factors allowed for the life cycle emissions to be weighted to ensure that buildings with higher GHGe, which are built less frequently than others, should not dominate the distribution of the GHGe. The study results showed that the area-based share factors had minimal influence on the general limit value. Therefore, sample-based share factors are deemed feasible. However, in this case the heated floor area was an area-based share factor; thus, the distribution function may change if other measures of the constructed area are considered instead.

Representative or best practice case samples can consider the current situation with GHGe by considering representative case studies of a country; likewise, it can consider today's best practice examples to initiate more extensive mitigation efforts. Consequently, the distribution functions of the GHGe are highly dependent on the chosen case sample, as significantly different GHGe limit values can be obtained. This underlines the importance of selecting cases as has been done in this study, mainly only if conventional building practices are targeted by policies. The case sample can include case studies that include technological innovations. However, due to the dependence on case studies' life cycle GHGe, potentially biased results can be obtained if certain case studies are chosen intentionally.

Depending on data availability, the method can be used in other countries to develop bottom-up LCA-based GHGe limit values. Data availability is crucial, given that the method's robustness is embedded in the extensive data collection of case studies and national recordings concerning construction activity and materials utilized in new construction.

Finally, the method enables the establishment of GHGe limits at various levels of political ambition. This further enables the introduction of gradual limit values, allowing stakeholders to gradually adapt and deliver the necessary reductions to reach net zero in 2050.

Based on this study's presented method, similar studies were compared to gain a perspective on the validity of the life cycle assessments' results and limit values. The limit values of the Danish BR are based on [69], where GHGe varied between 6.3 and 13.8 kg $CO_2e/m^2$/year of sixty case studies. This aligns with the spread in GHGe of this study, although the representative case sample has increased by 103 case studies.

Trigaux et al. [70], critically review European benchmark studies and systems and investigate the variation in benchmark numerical values. Here, benchmark values considering the full life cycle of both residential and non-residential buildings vary between 14.0 and 33.7 kg $CO_2e/m^2$/year. These values are greater than those defined in this study; however, the Danish reference values cited vary between 7.9 and 14 kg $CO_2e/m^2$/year [13,71], which are of the same order of magnitude as the distinguished limit values of the representative case sample. Rasmussen et al. [27] give an overview of existing benchmarks from case studies performed in IEA Annex 72. The benchmarks consider the full span of the life cycle, varying from 5 to 90 kg $CO_2e/m^2$/year. This significant variation indicates a wide variation in emissions factors applied to calculate the GHGe from energy demand between countries since the embodied emissions vary between 1 and 12 kg $CO_2e/m^2$/year. Nevertheless, these values approximate those found in this study. It is important to note that directly comparing benchmarks and LCA results across studies involves uncertainties due to the differences in the methodology, e.g., scope, RSP, data, assessment methods, etc.

## 4.2. Methodological implications and limitations of LCA

Transparency is crucial in conducting LCA, as defining the system boundaries, the life cycle inventory and the functional unit influence the outcomes [72]. LCAs are carried out in this study according to the Danish Building Regulation BR18. It is important to note that BR18 does not encompass all life cycle stages and the corresponding modules, as only modules A1-3 in the Production stage, B4 and B6 in the Use stage and C3-4 in the End-of-life stage are declared. This poses a challenge for upfront emissions, as a significant proportion of emissions occurs during the production and construction stage of new buildings [73,74]. Including the construction stage in upfront emissions can drastically change GHGe limit values. Recent studies by Kanafani et al. [75,76], indicate that the construction site alone constitutes approximately 1.8 kg $CO_2e/m^2$/year (upper quartile, RSP = 50 years) for Danish sites. Furthermore, certain modules in the use and end-of-life stages (B1, B2, B3, B5, C1, and C2) are addressed in BR18. Research by Baloutski et al. [77], has revealed that including these modules can increase the GHGe for Danish buildings by approximately 1 kg $CO_2e/m^2$/year (upper quartile). Naturally, this inclusion will also influence the GHGe limit value.

The chosen RSP influences the GHGe, as the results are reported and interpreted per year and may not reflect the actual service life of the buildings being assessed. In several European and Nordic countries, the reference study period for LCAs is fifty or sixty years, though, with the revised Energy Performance of Building Directive, the RSP of LCAs is expected to follow the method of Level(s), which is fifty years [23,78–80]. In Denmark, the fifty-year RSP has been practiced in LCAs for DGNB and is now required in the building regulations. The influence of the RSP was not tested in our study, since this would have taken it beyond its intended scope. Rather, it was to apply the national LCA method to a large sample of case studies and to establish limit the values. Naturally, there are uncertainties in the interpreted results. For instance, in a study by Rasmussen et al. [81], a longer RSP will reduce the GHGe over the entire life cycle, but it will also increase the uncertainty of the results. Life cycle modules such as B4 in the Use stage will contribute more to total GHGe than the upfront emissions A1-5, as more replacements will theoretically occur. However, a longer RSP does not necessarily change the conclusions about the building's overall performance compared to others. In addition, a longer RSP exposes ethical issues, as the GHGe of buildings is allocated down the line to future generations. A shorter RSP can support the focus on mitigating GHGs occurring upfront [81], which accounts for 60 % of the Danish situation [52], although the focus on embodied and operational emissions remains important irrespective of the choice of RSP. Nonetheless, the chosen RSP remains an uncertain parameter since it is time-dependent and can influence several aspects of the study, e.g., replacement cycles, building aesthetics and functionality [82,83].

## 4.3. Mitigation effectiveness of bottom-up limit values

### 4.3.1. Possibility of aligning bottom-up limit values with climate targets

Since bottom-up-based limit values are not necessarily aligned with climate targets, there may be a gap between these and top-down targets. A comparison between the general limit value at 9.0 kg $CO_2e/m^2$/year and those proposed in the Reduction Roadmap (RR) at 4.5, 5.8 and 6.8 kg $CO_2e/m^2$/year for three likelihood scenarios at 83.0 %, 67.0 % and 50.0 % [35] respectively reveal an obvious gap. To align with the Paris Agreement, the gap can be closed by increasing the level of ambition of the original example by 50.0 %. If the ambition level is increased to align with the 67.0 % likelihood scenario, a general limit value at the 0.6th percentile may be determined (numerical values in Supplementary Materials Table 11). Limit values based on best practice case studies and related ambition levels do not need to be increased as drastically as conventional practice. The gap is smaller when considering residential case studies exclusively, as the ambition level to become Paris-aligned for conventional practice starts at the 2.3rd percentile, while for best practice it starts at the 38.6th percentile. Nonetheless, since none of the case studies emits zero GHGe over their life cycle, the current pathway will not ensure net zero by 2050.

Overall, the gap indicates that significant mitigation measures, as it can be closed already in 2025, given that the results are based on today's case studies. The comparison with RR may not be complete, as its preconditions are based on older data for emissions factors on the energy mix and environmental data on materials. In a potential update of RR, the percentiles determined in this study may result in different numerical values.

#### *4.3.2. Timing the mitigation of emissions to reach net zero*

Drastic reductions will be needed in the next 26 years, when nations are obliged to become net zero, since the level of ambition in regulation is not aligned with the climate targets. Therefore, limit values should be defined to initiate the necessary mitigation. Although the gap can be closed today by drastically increasing ambition, this may not be the best solution. While increasing the level of ambition may be crucial to ensure effectiveness and circumvent the need for substantial future reductions, a gradual introduction of limit values should be prioritized. It is essential to balance the setting of limit values. Hence, they are not too drastic to avoid potential environmental and systematic consequences such as burden shifting, biodiversity loss, and a lack of demand for certain building materials. Moreover, companies should be allowed to adapt and develop their competencies at a feasible pace. This is a preferred scenario, as limit values uniformly distributed towards 2050 will not ensure net zero will be reached. Thus, the final emissions will depend on technological solutions such as carbon capture.

Another timing aspect concerns determining limit values based on the pathway, like those in Denmark or France, where the limit is tightened every second year. These pathways challenge timing of the necessary mitigation efforts needed to achieve climate targets. Due to building projects' lengthy project timelines, there is a delay between the date of validity of the limit value and the impact on emissions. For instance, in Denmark, if the building permit is granted in 2023, the project must comply with the valid limit value of the same year until building is completed, e.g., two years later in 2025. However, if there is an updated limit value in 2025, it will only affect future projects. Therefore, the impact of the limit value essentially works backwards, as it does not affect emissions that have already happened but instead influences future projects and their compliance efforts. This, therefore, also means that mitigation efforts are not immediately effective, emphasizing that adequate levels of ambition are crucial to achieving the necessary reductions of GHGe.

#### *4.3.3. Differentiating limit values to induce mitigation effectiveness*

Setting general limit values without distinguishing between building types does not impact each building-use type evenly, meaning that the GHGe limit values may not initiate significant efforts to reduce GHGe for specific building types, e.g., residential buildings. In contrast, others may put significantly more effort into achieving GHG reductions. To further ensure the mitigation effectiveness of bottom-up limit values, differentiated limit values for building typologies should be supported to ensure efforts for mitigation are prioritized for all building typologies. The results of this study revealed significant differences in GHGe among building typologies, with residential buildings exhibiting lower emissions compared to other building typologies, especially in the best practice case studies. Given the dominance of residential buildings in the newly constructed areas, increasing the ambition level of limit values for residential buildings is advisable in order to initiate more significant mitigation of GHGe.

## 5. Conclusions

This study provides a novel method for establishing robust bottom-up Life Cycle Assessment (LCA)-based limit values for new construction. The method involves establishing a representative sample of case studies and computing cumulative distribution functions (CDF), which consider the sample- and area-based share factors and the estimated greenhouse gas emissions (GHGe) of the representative case sample. Out of a database comprising 291 actual buildings, 163 are identified as representative of conventional building practice in Denmark. It is found that the representative case sample covers 31.7 % of the heated floor area (HFA) completed between 2015 and 2020, representing a significant proportion of the yearly constructed area of new buildings. Moreover, the representativeness is checked by investigating the utilized materials in the façade and roof, which shows a significant use of bitumen on the roof and of brick on the façade, aligned with utilized materials in conventional practice.

The share factors are derived from the sample size and the construction activity, which represents the measured physical output of new construction, enabling the establishment of limit values that reflect the activity in the construction industry. In this study, no difference between the limit values computed with sample- and area-based share factors was found, indicating that the case sample it considered represents the construction activity in Denmark between 2015 and 2020.

Limit values are computed at the 50th percentile, corresponding to the median, to indicate the current standard of new buildings GHGe. Based on the representative case sample, a general limit value at the 50th percentile is determined at 9.0 kg $CO_2e/m^2$/year, corresponding to a level of ambition targeting 50 % of new construction to perform mitigation efforts. Substantial differences in life cycle GHGe across building typologies are identified, as mean values range between 8.3 and 11.8 kg $CO_2e/m^2$/year. Thus, differentiated limit values are derived for eight building typologies within the representative case sample. The differentiated limit values result in considerable variations, where row houses with the lowest limit value would end at 8.2 kg $CO_2e/m^2$/year, and educational buildings with the highest limit value would end at 11.5 kg $CO_2e/m^2$/year. The study therefore finds that differentiated limit values should be implemented to ensure that mitigation efforts are performed on all building typologies.

The examined statistics show that 67.7 % of yearly constructed HFA consists of residential buildings, which indicates significant GHGe from residential buildings. To focus mitigation efforts on residential buildings, this study determined limit values for residential buildings with best practice case studies, starting from 4.9 kg $CO_2e/m^2$/year and significantly lower than those determined with conventional practice. Thus, residential buildings have considerable mitigation potential.

Nevertheless, the study emphasizes that it is essential to introduce limit values gradually in order to avoid potential environmental and systematic consequences, such as burden-shifting, biodiversity loss etc., and to allow companies to adapt their practices at a feasible pace.

## CRediT authorship contribution statement

**Buket Tozan:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Endrit Hoxha:** Writing – review & editing, Validation, Supervision, Conceptualization. **Christoffer Ole Olsen:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jørgen Rose:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jesper Kragh:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Camilla Ernst Andersen:** Writing – review & editing, Data curation. **Christian Grau Sørensen:** Software, Data curation. **Agnes Garnow:** Writing – review & editing, Data curation. **Harpa Birgisdóttir:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

We acknowledge that the submission declaration of "Building and Environment" journal has been complied with. We also confirm that all necessary permissions have been obtained. The authors declare that there is no conflict of interest regarding the publication of this article.

## Data availability

The authors are unable or have chosen not to specify which data has been used.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111891.

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