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Resch, Eirik; Lausselet, Carine; Brattebø, Helge; Andresen, Inger

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An analytical method for evaluating and visualizing embodied carbon emissions of buildings

Eirik Resch [a,b,*], Carine Lausselet [c], Helge Brattebø [c], Inger Andresen [a]

[a] Department of Architecture and Technology, Norwegian University of Science and Technology, Trondheim, Norway
[b] Department of Applied Mathematics and Computer Science, Technical University of Denmark, Kgs. Lyngby, Denmark
[c] Industrial Ecology Programme, Norwegian University of Science and Technology, Trondheim, Norway

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ABSTRACT

Greenhouse gas emissions associated with buildings constitute a large part of global emissions, where building materials and associated processes make up a significant fraction. These emissions are complicated to evaluate with current methodologies due to, amongst others, the lack of a link between the material inventory data and the aggregated results.

This paper presents a method for evaluating and visualizing embodied emission (EE) data of building material production and transport, including replacements, from building life cycle assessments (LCAs). The method introduces a set of metrics that simultaneously serve as a breakdown of the EE results and as an aggregation of the building's inventory data. Furthermore, future emission reductions due to technological improvements are modeled and captured in technological factors for material production and material transport. The material inventory is divided into building subparts for high-resolution analysis of the EE. The metrics and technological factors are calculated separately for each subpart, which can then be evaluated in relation to the rest of the building and be compared to results from other buildings. Two methods for evaluating and visualizing the results are presented to illustrate the method's usefulness in the design process.

A case study is used to demonstrate the methods. Key driving factors of EE are identified together with effective mitigation strategies. The inclusion of technological improvements shows a significant reduction in EE (−11.5%), reducing the importance of replacements. Furthermore, the method lays the foundation for further applications throughout the project phases by combining case-specific data with statistical data.

1. Introduction

Buildings account for 32% of the total global final energy use, 19% of energy-related greenhouse gas (GHG) emissions and approximately one-third of black carbon emissions [1] and thus represent one of the critical pieces of a low-carbon future. In order to reduce energy use in buildings through country-level regulation, the Energy Performance of Buildings Directive [2] and the Energy Efficiency Directive [3] has been established by the European Commission. This has motivated research, new building codes, and the development of concepts that provide guidance for high energy efficiency and low carbon emissions from buildings.

Life-cycle assessment (LCA) is a standardized method [4] frequently used to give an overview of how various types of environmental impacts accumulate over the different lifecycle phases and elements of a system. It provides a basis for identifying environmental bottlenecks of specific technologies and for comparing a set of alternative scenarios with respect to environmental impacts [5,6]. LCAs have been increasingly used to evaluate the environmental performance of buildings [7] and is the method of choice for quantifying building-related GHG emissions from raw material extraction, building material production, transportation, operation, and decommissioning over the building lifetime.

Embodied emissions (EE) embedded in the production and maintenance of buildings become increasingly important in construction projects where energy efficiency is prioritized [8–11]. For the eight analyzed Norwegian cases in Ref. [12], embodied impacts were found to be 60–75% of total emissions, confirming the importance of embodied impacts in Norwegian low-carbon buildings. For the Swiss national building stock, the contribution of construction material to total life cycle emissions of residential buildings has been estimated to increase from 19% in 2015 to 39% in 2050 [13] due to reduced building energy

* Corresponding author. Department of Architecture and Technology, Norwegian University of Science and Technology, Trondheim, Norway.
E-mail address: eirik.resch@ntnu.no (E. Resch).

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consumption. Since low operational energy demand is already a regulatory priority in most countries, a stronger focus should be set on EE from materials [14]. While country-level regulation has led to strict building codes on operational energy performance, the EE is yet to be regulated. Pilot initiatives exist for the inclusion of EE in Norwegian building codes [15], but relevant unsolved problems include a lack of representative reference EE values and low transparency and comparability of the assessment methodology [16,17].

EE and embodied energy are closely related. Although there is large variation between studies, in a recent literature review transportation energy is found to be on average 6%, construction energy 10%, and demolition energy 3% of the energy embodied in building materials. The recurrent embodied energy due to replacements and maintenance is approximately 25% of total lifecycle embodied energy (excluding demolition energy) in a building with 50-year service life [8]. In a comprehensive building stock model from 2018 [13], Swiss 2015 residential GHG emissions from material use are found to be caused mostly by the input of concrete (31%), insulation material (23%), minerals (18%), brick (12%), and wood (6%), and material end-of-life is dominated by the disposal of insulation material (4%) and wood (1%).

The most influential material-related parameters for environmental performance have been identified as material choice, building lifetime, and material service life [11,18,19]. In addition, better design, increased reuse of materials, and stronger policy will help the transition to a low-carbon built environment [20–24]. The EE from future replacements can be expected to decrease with time due to technological improvements in material technology, production technology, recycling rate, prefabrication, automation, transportation technology, and the electrification of those processes together with decarbonization of the energy grid. The influence of material service life is affected by future technological improvements, and previous research [25] has pointed out the importance of including such improvements in future work.

LCA methodology for quantifying the EE requires large amounts of case-specific data from each lifecycle phase investigated. Due to the difficulty of interpreting this data and the numerous mathematical operations that go into LCA calculations, it is customary to only interpret the resulting EE at building or building element level, leaving out important information on the background for the results. This lack of a link between the background inventory data and the results reduces the usefulness of the LCA by leaving out information relevant for interpretation. Thus, there is a need for an improved methodology to provide simplified analytical relations describing the system mathematically with links to the background inventory data.

The number of LCA studies on buildings is large [26], and opens up huge potential to make use of data from previous studies. In a previous paper by the authors, a database tool for systematically organizing and storing previously conducted building LCAs at full resolution was presented [16]. The building LCA database tool (bLCAd-tool) stores the data used in the original LCA calculations in an SQL database tailored for EE analysis of buildings. This method makes all data easily accessible and available for analysis and further use in a range of applications. This data can be used to produce statistical reference values that can be used as a proxy in early-phase LCA calculations, to supplement missing data throughout the project phases, and to create benchmarks by which a case study can be compared. However, to make such statistics useful and representative, there is a need for a method that categorizes the building inventory into subparts of the building and then extracts useful metrics for each subpart.

This study presents an efficient, structured and parametrized assessment of EE in LCAs of buildings, that gives a better understanding of driving factors of the building's GHG emissions related to material production, transport, and replacements. In this paper, we present a method for linking the background inventory data of an LCA with the EE results through the following metrics: (1) the total quantity of the subpart, (2) the emission factors of the subpart, (3) the replacement factors of the subpart over the study period (material lifetime factor), (4) the transport distance of the subpart from the factories to the building site, (5) the transport emission intensity, and (6) the replacement emission factors of the subpart over the study period. The metrics simultaneously serve as a breakdown of the EE results and as an aggregation of the background inventory data. The EE of future replacements of materials is implemented in this method by adjusting future emissions for each subpart by a technology factor for production and another for transport. These factors take into account the year of replacement for each material and the time-development of the emission factors.

The utilization of the method is dependent on procedures for systematically evaluating and visualizing the results, and the paper presents two methods of visualization that can be used as tools to evaluate the EE of a case-building or a statistical building type. As proof of concept, the method and its visual applications are exemplified with case-specific values from a case building. The applications based on statistical values will be further elaborated on and applied on a statistical set of case buildings in a future paper.

The analytical framework, the methods for evaluation and visualization, and the case study building are presented in section 2, the applications for design improvements are demonstrated with a case study in section 3, and the method and model are discussed in section 4.

2. Methods

This section first presents a novel methodology for working with EE data from building LCAs in 2.1–2.4. Tools for visualizing results from the methodology are introduced in 2.5 and the case building is presented in 2.6. The method in the case study is implemented as an add-on feature of the bLCAd-tool [16] but is here formalized to be universally applicable.

The European standard EN 15978 [27] describes a calculation method for LCA of buildings. In it, the lifecycle phases are divided into modules A-D. In this paper, the system boundary is set on modules A1-A3 (production of building materials, cradle-to-gate), A4 (transportation of building materials to the building site), and B4 (replacements of building materials throughout the building lifetime/study period). In this paper, B4 is further divided into material production, B4m, and material transport, B4t, analogous to the two initial lifecycle modules (see Table 1). This division allows for performing calculations on and evaluating production and transportation separately also for replacements.

The method is outlined in a flowchart in Fig. 1. The building specific data (green) is used together with additional model definitions (blue) to calculate the model results (grey).

Building specific data. The building specific data includes building and study information (building lifetime/study period and heated floor area (HFA)), and the lifecycle inventory (LCI). For the lifecycle phases related to material production (A1-A3, B4m), the inventory data needed for each material or component are the (1) quantity, (2) emission intensity, and (3) lifetime. For the transport of materials (A4, B4t), the additional data needed are the (4) traveled distances and the (5) specific emissions of the transport modes.

Model definitions. The model definitions include (1) defining building subparts as subsets of the inventory and (2) defining technology development vectors.

Model results. The results are calculated for all subparts. The EE results per m^2 are capturing the final effect of all choices on the resulting EE, including design choices, construction technologies, and material choices. The metrics Q, F, L_F, D, T, and L_{DT} (see Table 2) are a breakdown

Table 1
Material use lifecycle phases according to the adjusted European standard EN 15978 [27].

	Initial material use	Replacements
Material production, cradle-to-gate	A1-A3	B4m
Transport from factory to building site	A4	B4t

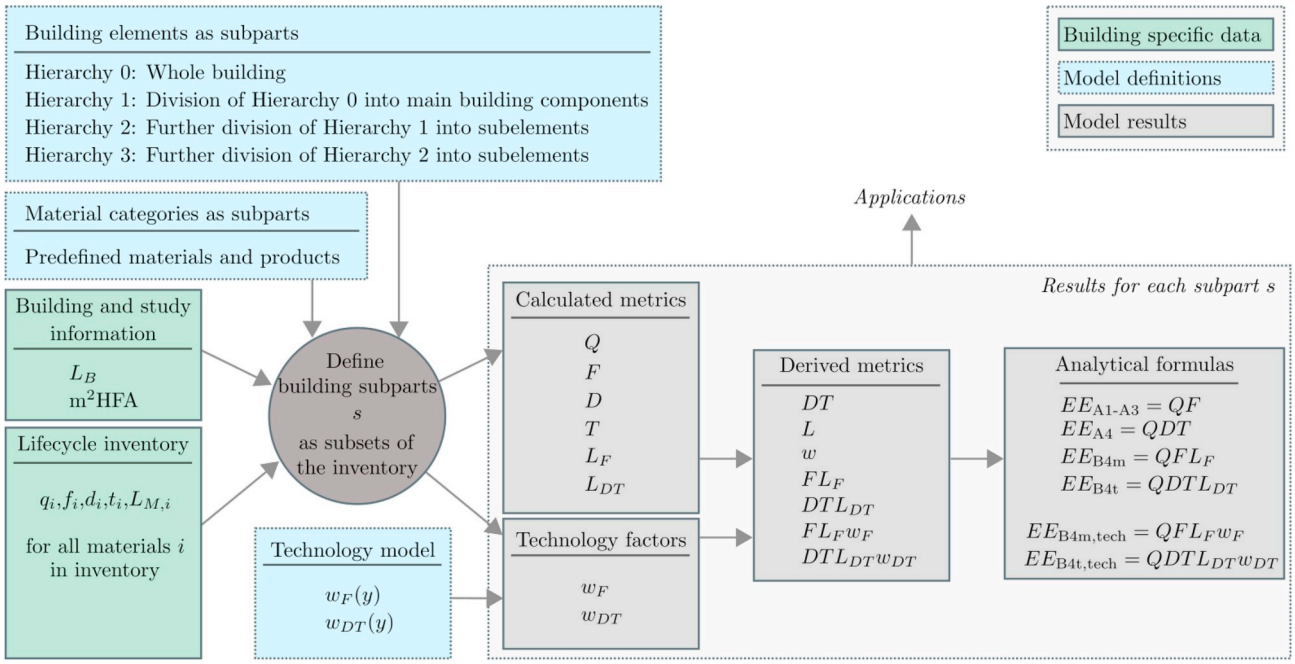

Fig. 1. Flowchart of the method.

of the EE and are thus isolating the contribution from individual factors. The technological factors w_F and w_{DT} are additional measures of the effect of future technological developments. Combinations of these metrics lead to a set of derived metrics. The metrics are related to EE by analytical formulas. Analyzing the metrics for a building and its subparts clarify what the potential of alternatives for reduced EE are.

Table 2
The metrics and technological factors, their units, and interpretation.

	Factor	Unit	Interpretation
EE	EE	$kgCO_2e./m^2$	Embodied emissions; the final effect of all choices, indicates where the focus should be when aiming for reduced impact
Metrics	Q	kg/m^2	Quantity; the total mass of building materials per heated floor area
	F	$kgCO_2e./kg$	Production emission factor; emission intensity of material production
	DT	$kgCO_2e./kg$	Transport emission factor; emission intensity of material transport. Product of distance, D, in km and emission intensity of transportation, T, per kg and km
	L_F	Multiplier, fraction	Production lifetime factor; the fraction of material production EE added due to material replacements throughout the building's lifetime
	L_{DT}	Multiplier, fraction	Transport lifetime factor; fraction of material transportation EE added due to material replacements throughout the building's lifetime
	L	Multiplier, fraction	Total lifetime factor; the fraction of total emissions added due to replacements
Technology factors	w_F	Multiplier, fraction	Production technology factor; the change in future emissions from material production due to technological improvements
	w_{DT}	Multiplier, fraction	Transport technology factor; the change in future emissions from material transport due to technological improvements
	w	Multiplier, fraction	Total technology factor; the total change in future EE due to technological improvements

2.1. Defining the metrics

The building specific data (see Fig. 1) is linked with the EE results through the metrics in Table 2. The metrics simultaneously serve as a breakdown of the EE results and as an aggregation of the building specific data. The metrics are calculated for building *subparts*. The subparts are in this study defined as building elements (BE), according to the Norwegian standard NS 3451 Table of Building Elements [28], and additionally, as material categories (MC), according to a set of predefined material and product groups. Yet, the subparts can be any arbitrary subset of the material inventory. For example, building subparts can be the whole building, individual BE, individual MC, MC within a BE, BE within an MC, etc. The metrics are calculated based on the data used in the original LCA calculation, and summarize amongst others the quantity, emission factors, and replacement emission factors of subparts.

The quantity Q of the subpart is the sum of the quantities q_i of each material i that goes into the subpart

$$Q = \sum_i q_i. \tag{1}$$

The specific emissions from material production F of the subpart is the quantity-weighted average of the specific emissions f_i of all materials i in the subpart

$$F = \frac{\sum_i q_i f_i}{\sum_i q_i}. \tag{2}$$

The production lifetime factor L_F is the quantity- and specific emission-weighted average of the lifetime factors

$$L_F = \frac{\sum_i q_i f_i l_i}{\sum_i q_i f_i}, \tag{3}$$

where l_i is the lifetime factor of the material, $l_i = L_B/L_{M,i} - 1$; L_B being the lifetime of the building (study period) and $L_{M,i}$ the service lifetime of the material. The transport distance D of the subpart is the quantity-weighted average distance from the factory to the building site of the materials i in the subpart

$$D = \frac{\sum_i q_i d_i}{\sum_i q_i} \tag{4}$$

where d_i is the distance for material i. The transport emissions per kg and km, T, is the quantity- and distance-weighted average transport emission factor of each material i in the subpart

$$T = \frac{\sum_i q_i d_i t_i}{\sum_i q_i d_i} \tag{5}$$

where t_i is the transport emissions per kg and km of material i. If the material is transported by several transport modes with differing transport emission factors, then an additional distance-weighted averaging of the transport emission factors t_i must be performed. The transport lifetime factor L_{DT} is the quantity-, distance-, and transport emission-weighted average replacement factor of the materials in the subpart

$$L_{DT} = \frac{\sum_i q_i d_i t_i l_i}{\sum_i q_i d_i t_i}. \tag{6}$$

Similarly, as for T, if there are several transport modes with differing emission factors, an additional distance weighted averaging of the transport emission factors t_i is necessary. Multiplying D with T gives a specific emission factor for the transport analogous to what F is for material production. DT and F have the same units, which is useful because they can then be compared directly. In the calculations, however, it is beneficial to keep D and T separate since this retains the original information of the material inventory data, and thus can be evaluated independently.

2.2. The metrics analytical relations to embodied emissions

The LCA calculation methodology can be reformulated into simplified formulas consisting of the metrics. These metrics can then be used to gain insights into the driving factors of the LCA results. The metrics' relations to the initial EE and future EE with and without technological factors are shown in Table 3. In the following, the EE calculation of a building or a building subpart based on the quantities and weighted average parameters of subparts is formalized. The equations give the same results as a standard attributional LCA calculation.

The EE from the production of initial building materials (A1-A3) in subpart s are

$$EE_{\mathrm{A1-A3},s} = f(Q_s, F_s) = Q_s F_s, \tag{7}$$

and the EE from production of replacements (B4m) are

$$EE_{\mathrm{B4m},s} = f(Q_s, F_s, L_{F,s}) = Q_s F_s L_{F,s} = EE_{\mathrm{A1-A3},s} L_{F_s}. \tag{8}$$

The EE from the transport of initial building materials (A4) are

$$EE_{\mathrm{A4},s} = f(Q_s, D_s, T_s) = Q_s D_s T_s, \tag{9}$$

and the EE from the transport of replacements (B4t) are

$$EE_{\mathrm{B4t},s} = f(Q_s, D_s, T_s, L_{DT,s}) = Q_s D_s T_s L_{DT,s} = EE_{\mathrm{A4},s} L_{DT,s}. \tag{10}$$

Combining these equations, we get the total emissions for the subpart for these four lifecycle phases

$$\begin{aligned} EE_s &= EE_{\mathrm{A1-A3},s} + EE_{\mathrm{A4},s} + EE_{\mathrm{B4m},s} + EE_{\mathrm{B4t},s} \\ &= Q_s F_s + Q_s F_s L_{F,s} + Q_s D_s T_s + Q_s D_s T_s L_{DT,s} \\ &= Q_s [F_s(1 + L_{F,s}) + D_s T_s (1 + L_{DT,s})]. \end{aligned} \tag{11}$$

Counterintuitively, the fractions of emissions added due to replacements, L_F and L_{DT}, are not the same, since the metrics are weighted by the parameters of each material. The lifetime factors L_F and L_{DT} can alternatively be combined into a single lifetime factor L by an emission-factor weighted averaging which gives the following alternative formula for the total emissions

$$EE_s = Q_s(F_s + D_s T_s)(1 + L_s), \tag{12}$$

where $L = \frac{FL_F + DTL_{DT}}{F + DT}$. This metric is, for instance, useful for determining the total additional EE added throughout the lifetime.

2.3. Technological factors

The emissions related to the production of materials as well as emissions from their transport can be expected to decrease in the future due to technological improvements in material technology, production technology, recycling rate, transportation technology, and the electrification of those processes together with the decarbonization of the energy grid. The technological factors presented in Table 2 are introduced to take these future emission reductions into account. Both technological factors are calculated based on vectors of assumed developments in emission reductions of material production emission factor F, $w_F(y)$, and in transport emission factor DT, $w_{DT}(y)$, for each year y in the study period. This time-dependent emission reduction in the expected year(s) of replacement for each material is then used in the calculation of an average weighted by the initial EE, and thus giving more importance to materials with high initial EE. This results in two factors that adjust the future emissions by the expected emission reductions in the year(s) of replacement for each material inventory in the subpart

$$w_F = \frac{\sum_i q_i f_i w_F(y_i)}{\sum_i q_i f_i} \tag{13}$$

$$w_{DT} = \frac{\sum_i q_i d_i t_i w_{DT}(y_i)}{\sum_i q_i d_i t_i}, \tag{14}$$

where $w_F(y_i)$ and $w_{DT}(y_i)$ are the fractional emission reductions in the year of replacement y_i, from material production and transport of material i, respectively. For materials that are replaced more than once, the reductions $w_{F,>1}(y)$ and $w_{DT,>1}(y)$ are the average $w_F(y)$ and $w_{DT}(y)$ from all replacement years. To take into account future reductions in emissions of material production and transportation, the EE equation above is expanded to include the additional technological factors for adjusting B4m and B4t. The equation for calculating the EE of the material production and transportation including technology estimation for future replacements then becomes

$$EE_s = Q_s[F_s(1 + L_{F,s} w_{F,s}) + D_s T_s (1 + L_{DT,s} w_{DT,s})] \tag{15}$$

The technology factors w_F and w_{DT} can alternatively be combined into a single technology factor w by a replacement emission-factor weighted average which gives the following alternative formula for the total emissions

Table 3
The emission factors and how they relate to EE with and without future developments in technology taken into account. The initial and future EE refer to the lifecycle phases of Table 1.

	Emission factors	Lifetime factors	Tech factors	Replacement emission factors wo/tech impr.	Replacement emission factors w/tech impr.	Initial EE	Future EE wo/ tech impr.	Future EE w/tech impr.
Production	F	L_F	w_F	$F{\cdot}L_F$	$F{\cdot}LF{\cdot}w_F$	$Q{\cdot}F$	$Q{\cdot}F{\cdot}L_F$	$Q{\cdot}F{\cdot}L_F{\cdot}w_F$
Transport	DT	L_{DT}	w_{DT}	$DT{\cdot}L_{DT}$	$DT{\cdot}L_{DT}{\cdot}w_{DT}$	$Q{\cdot}DT$	$Q{\cdot}DT{\cdot}L_{DT}$	$Q{\cdot}DT{\cdot}L_{DT}{\cdot}w_{DT}$

$$EE_s = Q_s(F_s + D_s T_s)(1 + L_s w_s), \tag{16}$$

where $w = \frac{FL_F w_F + DTL_{DT} w_{DT}}{FL_F + DTL_{DT}}$. This metric is, for instance, useful for determining the total reduction of replacement EE due to the technological factors.

2.4. Interpretation

The metrics and equations have physical interpretations that can be used for evaluation of the EE of a building subpart. The methodology treats any chosen subpart of the building as a unified product that has its own metrics. This means that for any subpart of the building, or the whole building, the EE can be broken down into these components and an interpretation of what is causing the emissions is available for identifying potential improvements.

The metrics can give insights into how well choices are made in the design and planning of the building, in terms of their impact on EE. The design of the building, the quantities of materials needed per functional unit, the emission intensity of the production of the materials and products chosen, their transport distance and transport emission intensity, as well as their durability and the need for replacements, can all be interpreted for individual building subparts and for the building as a whole. The metrics thus provide information on how well the building and its subparts are planned in terms of EE.

The technological factors are calculated based on a projection of the change in future emission intensities compared to those of the initial year and can be interpreted as how much technological improvements will affect replacement EE, taking into account the year of replacement and which materials are replaced and at what rate.

To make the EE results comparable to other buildings, one can apply a normalization. In this paper, the normalization used is the heated floor area (HFA). This is done by dividing the metric Q by the HFA of the building. The remaining metrics are already directly comparable since they do not depend on the quantities.

2.5. Methods for evaluating and visualizing results

Visualizing the results is important for making them practical and comprehensible for the analyst. The two visualization and evaluation methods described here can be equally used for statistical metric values and case-specific metric values.

The Metrics chart is visualizing the EE and the breakdown into metrics for a set of defined subparts of the building. Fig. 2 shows an example of a Metrics chart. In the first column, the EE of each lifecycle phase is presented in a stacked bar where each lifecycle phase is color-coded by the metric associated with it. All lifecycle phases, and thus the total EE, are linearly dependent on quantity Q of the second column. The initial emissions, A1-A3 and A4, are in addition linearly dependent on the emission factors F, DT of the third column. By multiplying the emission factors F, DT by lifetime factors L_F, L_{DT}, and by the technology factors w_F, w_{DT}, we get the technology adjusted replacement emission factors $FL_F w_F$ and $DTL_{DT} w_{DT}$ in the fourth column. The replacement emissions, B4m and B4t, are linearly dependent on the replacement emission factors. For case-specific data, the chart will show the calculated metrics for that building. For statistical data, the metrics chart can, for instance, show the average values, in addition to their distributions as error bars for each BE and metric. The metrics chart can also display both types of data at once, to compare and benchmark a case building against statistical values represented by error bars.

The *Q-F-DT* Plot and the *EE-L_F-L_{DT}* Plot are two-dimensional representations of the metrics. Fig. 3 shows an example of each plot. Each connected line shows metrics from one subpart which is identified by a number. The resulting EE is shown along the curved contour lines. The *Q-F-DT* Plot shows the initial EE, with a breakdown of the emissions into quantity Q along the horizontal axis and emission factors F and DT along the vertical axis. The *EE-L_F-L_{DT}* Plot shows the replacement EE, with a breakdown of the emissions into initial EE along the horizontal axis (and is thus dependent on the *Q-F-DT* Plot) and the technology adjusted lifetime factors $L_F w_F$, $L_{DT} w_{DT}$, and Lw, along the vertical axis. Minimizing the values along both axes for both plots will reduce EE, and the focus for design improvements should be on the subparts with highest values on the contour line axes. Moreover, their horizontal and vertical values show how to theoretically reduce the EE most efficiently by the relative magnitudes of each metric along the two axes. Both case-specific data and statistical building type data can be presented in *Q-F-DT* and *EE-L_F-L_{DT}* plots to visualize case results or the emission profiles of building types.

2.6. The case study building

The method requires building specific data, model definitions for subparts, and a technology model, as shown in Fig. 1. The case study building is the single-family residential building ZEB Living Lab, which was built as a living laboratory by the Research Centre for Zero Emission Buildings [29] in 2014. This case was chosen because its inventory is fairly complete, and it has been well documented in the literature [11, 12,25,30–32]. The one-story (no basement), 102 m^2 HFA timber building was intended to have net zero GHG emissions from the production of building materials and their transportation to the building site, including replacements of materials, and operational energy use throughout its postulated lifetime of 60 years, by compensating for its emissions by renewable onsite energy generation from PV-panels on its roof that would substitute grid electricity. An LCA of the building was performed on the final design by the research centre. The building specific data was acquired by the authors and inserted into the bLCAd-tool which stores the data used in the original LCA calculations in an SQL database tailored for EE analysis of buildings [18]. The methodology presented in this paper was then applied to that data. The

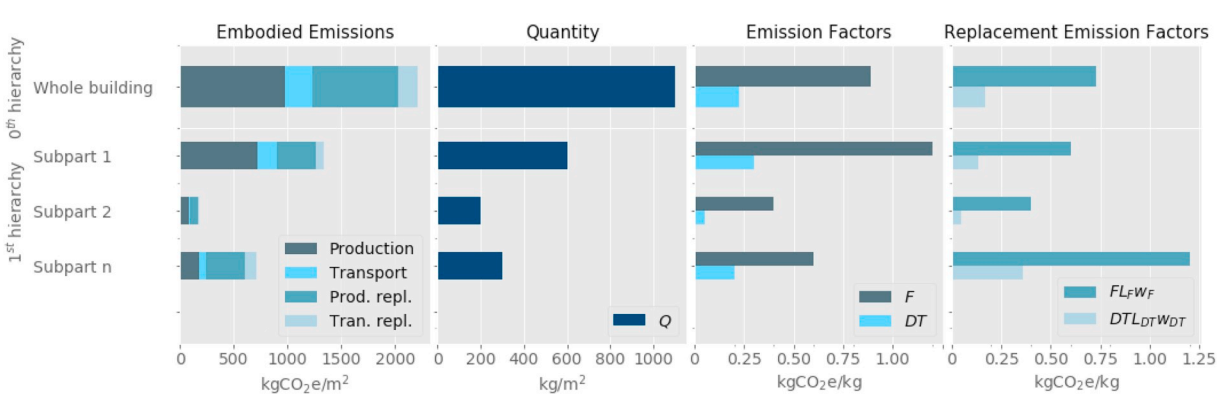

Fig. 2. Example of a Metrics chart visualization showing the EE of each lifecycle phase and a breakdown into the metrics.

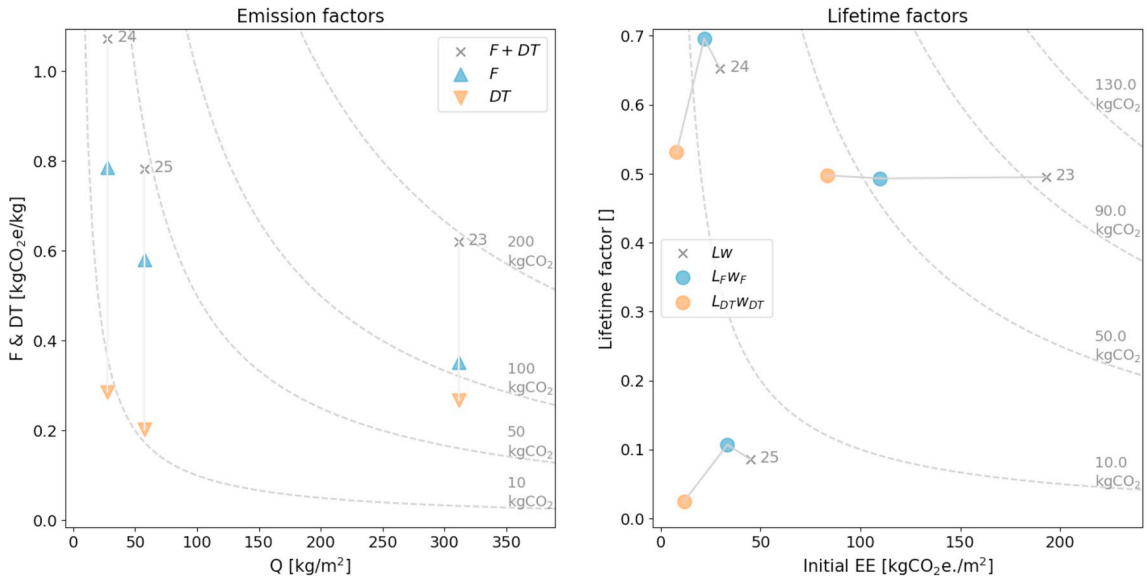

Fig. 3. Example of the *Q-F- DT* plot (left) and the *EE* - L_F - L_{DT} plot (right). The numbers next to the connected lines refer to subparts of the building.

original study included dishwasher, fridge and freezer, washing machine, tumble drier, hob, and oven; these are in this study not considered as parts of the building and are not included. All remaining inventory items except one, aluminum sealing tape, are included in the calculations. This item was excluded due to missing density value and accounts for 0.1% of the EE. In a comparative study of similar low-carbon buildings, the case building had the highest EE/m^2 [12].

The subparts are defined as BE and as MC. The BE subparts are divided into four hierarchies of BE (see Fig. 1) according to the standard NS 3451 [28] with all the BE that was included in the original assessment of the building. The 0th hierarchy includes all materials included in the inventory of the study, while the 1st, 2nd, and 3rd hierarchies have an increasing resolution on the specificity of the BE. A higher hierarchy includes all materials from lower hierarchies, with the exception of the 3rd hierarchy which only includes the BEs that are specified at this resolution; in this case study, those are sub-elements of 23 Outer walls and 26 Outer roof. The MC subparts are categorized by a list of predefined materials and products, where each material inventory item of the original assessment gets assigned to a category. This means that although some products consist of more than one material, such as the hot water tank, they are organized as separate MCs. Conversely, other products are included in the inventory as several materials. Windows and doors, for example, are in the case study divided across aluminium, steel, timber, plastics, rubber, paint, glass, and so on.

The technology factors w_F for production and w_{DT} for transport are included in the calculations of replacement EE and is here modeled as a linear interpolation between today's emission factor (100% of initial values both for production and transport) and the assumed reduction in the final year of the study (50% of initial value for production and 10% for transport in year 2074).

3. Case study results

This section applies the method to the case study to demonstrate its use in the design and evaluation phases of a building construction project. Two applications for evaluation through visualization are presented: the Metrics chart, and the *Q-F- DT* and *EE* - L_F - L_{DT} plots. The same visualizations can also be used for statistical data from building types which may be useful in other project phases. The results in this section are a demonstration of the methodology and the visualization tools applied to case-specific data. Numerical results are provided in a spreadsheet in the supplementary materials.

3.1. Metrics chart

The Metrics chart for the case building is shown for BE in Fig. 4 and for MC in Fig. 5.

The first row in Fig. 4 shows the overall EE for the 'Whole building' and the distribution among the lifecycle phases, the total quantity per HFA, and the building's overall performance of emission factors and replacement emission factors. The lower hierarchies show how these EE and metrics are distributed among the BE.

On the 1st hierarchy, the majority of EE fall into 'Envelope, foundations, and structure'. This is regardless of the observation that it has the lowest emission factors and the lowest replacement emission factors, and is due to practically all material quantity going into this BE. On the contrary, more than a quarter of EE come from 'Electric power', not due to large quantities, but due to very high material production emission factor (F) and replacement emission factor (FL_Fw_F). 'Heating, ventilation, and sanitation' has low quantity and also lower emission factors and replacement emission factors and therefore low EE. The emissions from the BE on the 1st hierarchy can be further investigated by looking at their sub-elements on the 2nd hierarchy.

On the 2nd hierarchy, among the sub-elements of 'Envelope, foundations, and structure' (beginning with the digit 2), the 'Outer walls' and 'Outer roof' stand out as having the highest emissions followed by 'Stairs and balconies'. These are thus the most important BE to focus on in the main building construction. 'Outer walls' has a large quantity, which can be expected given that outer walls make up a large area of the building envelope. The emission factor for 'Outer walls' is small relative to the other BE, however, a further reduction in the emission factor will have a great impact on overall emissions due to the large quantities. 'Outer roof' has large quantities, but also high production emission factor. Reducing any of those, or reducing them in combination, will impact the building's EE significantly. 'Stairs and balconies' has surprisingly large quantities for a one-story building, and the production emission factor is also of significance. This BE could therefore also be an area of focus for design improvements. Among the sub-elements of 'Electric power' (beginning with the digit 4), 'Other tech: Photovoltaic' is responsible for nearly all the EE, due to having the highest production emission factor and production replacement emission factor of all materials in the entire building. This BE includes technical components and mounting board in addition to the PV panels. Of particular note is that the replacement emission factor is higher than the emission factor, even after technological improvements. This is due to a short lifetime of 15

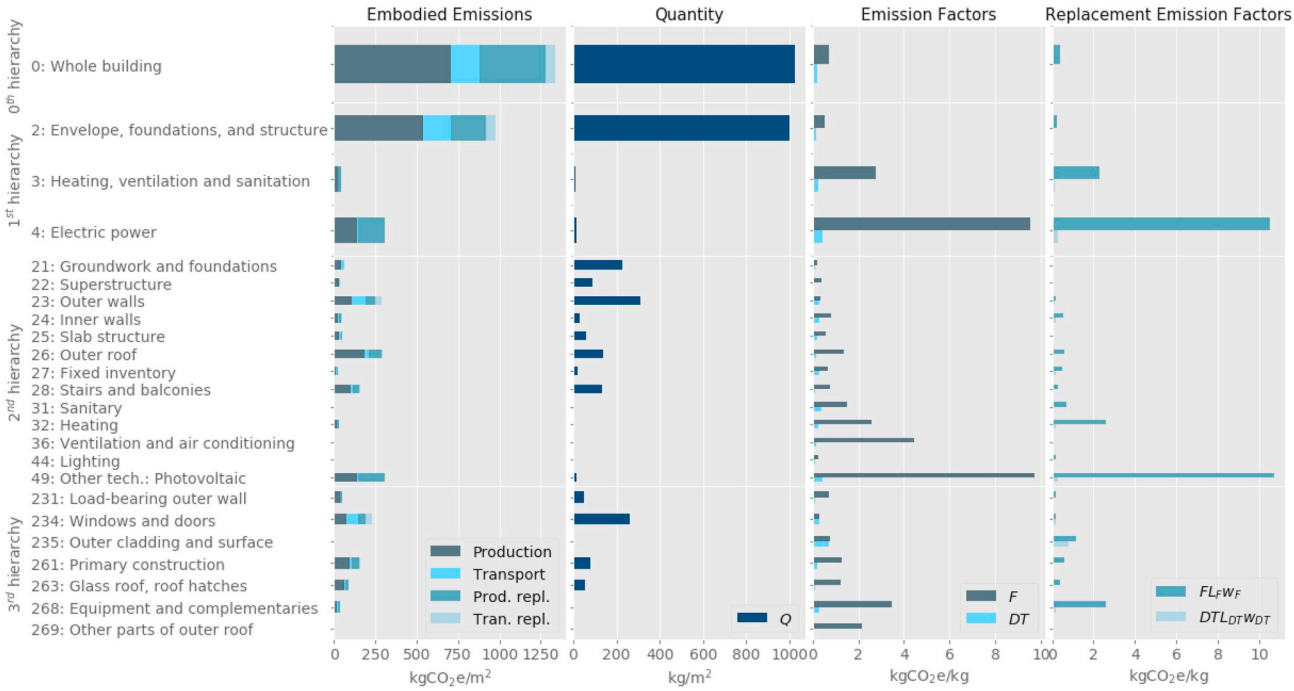

Fig. 4. Metrics chart for the case building with subparts defined as BE. The columns show from left to right (1) the EE of lifecycle phases A1-A3 material production, A4 material transport, B4m replacement-material production, and B4t replacement-material transport; (2) quantity of materials per heated floor area Q; (3) emission factor for material production F and for material transport DT; (4) replacement emission factors FL_Fw_F and $DTL_{DT}w_{DT}$.

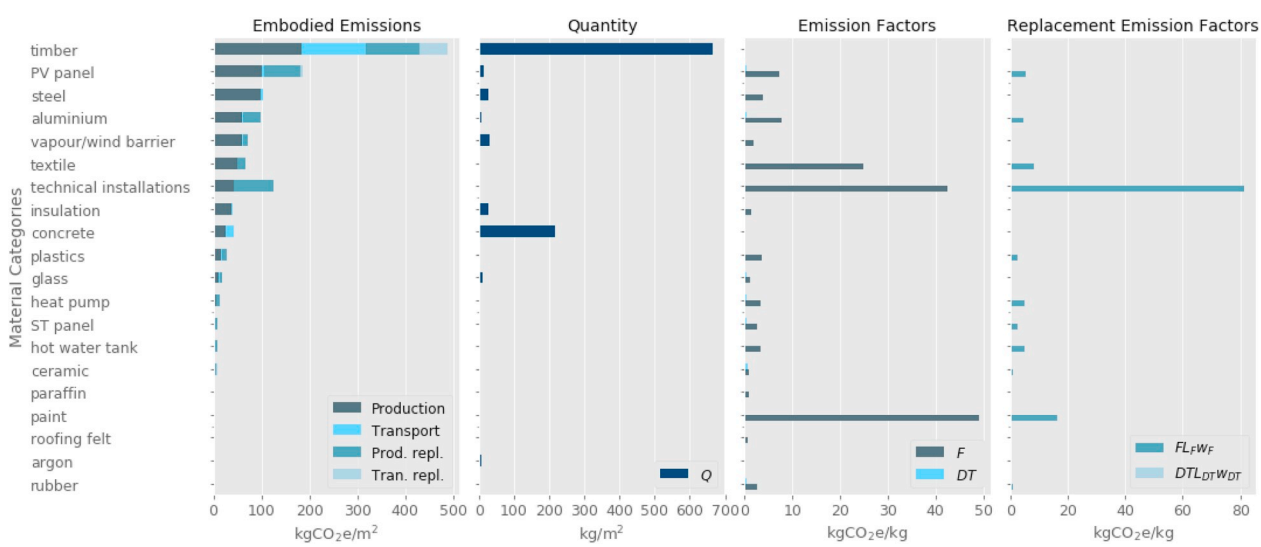

Fig. 5. Metrics chart of the case building with subparts defined as the whole inventory separated into MC. The columns show from left to right (1) the EE of lifecycle phases A1-A3 material production, A4 material transport, B4m replacement-material production, and B4t replacement-material transport; (2) quantity of materials per heated floor area; (3) emission factor for material production F and for material transport DT; (4) replacement emission factors FL_Fw_F and $DTL_{DT}w_{DT}$.

years for the 'inverter' component, which has high EE. Among the sub-elements of 'Heating, ventilation, and sanitation', none are of particular importance.

'Outer walls' and 'Outer roof' are further separated into their sub-elements on the 3rd hierarchy (beginning with digits 23 and 26, respectively). For 'Outer walls', 'Windows and doors' dominates emissions mostly due to the large quantity. For 'Outer roof', the 'Primary construction' is dominating, followed by 'Glass roof, roof hatches'. These both have significant quantities, emission factors, and replacement emission factors.

The effect of building design on EE can be indirectly interpreted from the same figure. The 2nd hierarchy shows 'Outer walls' to be responsible for the largest quantity, and the 3rd hierarchy further shows that 'Windows and doors' is the main reason for the high quantity. Since the quantity is given per m^2 HFA, the building design is indirectly contained in this metric and is an indication of large areas of windows and doors relative to the HFA. The information obtained from analyzing the Metrics chart should, however, be used in conjunction with architectural drawings and will together inform the analyst on where the greatest potentials for EE reductions lie.

Fig. 5 shows the Metrics chart for the case building's MC. It shows that the top categories are responsible for most of the EE, while the bottom categories are insignificant and can be ignored.

Among the categories that do matter, there are two main trends. The

first includes 'timber' and 'concrete', which together make up most of the building mass. It is mainly due to their large quantities, and not their emission factors, that EE is high. The building is a timber building, and the quantity of wood is thus high. Concrete is used only in the foundation, and because of its high density, its EE is high despite its low emission factor. The other trend applies to the remaining categories, which, relative to timber and concrete, have smaller quantities but high emission factors. Notably, 'technical installations' has high emission factor and also high replacement emission factor due to a short material lifetime (high L_F). The exact balance between quantity, emissions factors, and replacement emission factors varies and determines the possibilities for emission reductions.

3.2. Q-F- DT and EE - L_F- L_{DT} plots

The culprits among the metrics in terms of their contribution to the EE can be further explored by two-dimensional plots that show the contribution of each metric and the resulting emissions. In the Metrics chart in Section 3.1, it was established that '2 Envelope, foundations, and structure' is responsible for most of the EE. In the following, the focus is on that BE only. The *Q-F- DT* and *EE* - L_F - L_{DT} plots for this BE on hierarchies 1, 2, and 3 are shown in Fig. 6.

On the 1st hierarchy, the first column shows the emission factor for production *F* and for transport *DT* together with their total emission factor along the contour lines for the resulting EE. The quantity is the same for all three, and reducing the quantity will reduce emissions proportionally. However, by following the contour lines one can see that reducing the quantity will have a larger effect on EE from *F* than from *DT*. The EE from production dominates, and a fractional reduction in *F* will have a larger effect than a reduction in transport emission factor *DT*. The second column shows the emissions from replacements, where the technology adjusted lifetime factors determine how much EE is added to the initial EE during the lifetime of the building (shown on the contour lines). The largest fraction added is for future production of materials, and a smaller fraction is added for transport.

On the 2nd hierarchy, the value of the methodology applied to design improvements becomes apparent. Here, the BE '26 Outer roof' and '23 Outer walls' stand out as the most important contributions to initial EE, followed by '28 Stairs and balconies'. Although the two former have about the same amount of EE, '26 Outer roof' EE is mainly caused by a high emission factor *F*, while '23 Outer walls' EE is mainly caused by a large quantity. However, a reduction of EE for both is achieved along the gradients of the contour lines, emphasizing the importance of keeping the focus on reduction along both axes. The theoretically most efficient way of reducing EE is therefore along the gradients of the contour plot. For '26 Outer roof', this gradient is directed mostly towards lower quantities, while the gradient for '23 Outer walls' is directed mostly toward lower emission factors. The EE from replacements are dominated by the same BE as for the initial emissions, but not because they have the highest lifetime factors, rather as a consequence of the initial EE being high. The gradients, and therefore the optimal reductions, are in the directions of a reduction of both initial EE (quantities of materials used in the design and their emission factors) and the lifetime factors (reducing the need for replacements).

The 3rd hierarchy is only showing the BE specified at this hierarchy, which for this building is sub-elements of '23 Outer walls' and '26 Outer roof'. Here, '234 Windows and doors' (of the outer walls) and '261 Primary construction' (of the outer roof) dominate EE. Following the same logic as above, the EE from '234 Windows and doors' will have the largest reduction by reducing the emission factors, while '261 Primary construction' would benefit the most from a combined reduction of both quantity and production emission factor. The replacement EE of these BE can be reduced by reducing the need for replacements, as well as reduced quantities and emission factors in the initial EE.

3.3. Importance of the technological factors

Including the technological factors w_F and w_{DT} for the replacement EE leads to a more realistic estimation of the EE than excluding the effect of future emission reductions, as is normal to see in building LCAs. Fig. 7 shows the total reductions in future EE per BE and MC. The production replacement emission factor and thus also the production replacement EE is reduced by 18.6%. Likewise, the transport replacement emission factor and thus also the transport replacement EE is reduced by 59.4%. The total reduction in replacement EE is 27.8%, leading to an overall EE reduction for all four lifecycle phases of 11.5%. The replacement EE is 71.2% of initial EE without technological factors and significantly less at 51.4% when included.

4. Discussion of method and model

4.1. Added value

A number of shortcomings in current methodologies for reduction of EE in the planning of buildings were discussed in the introduction. The methodology presented in this paper addresses several of those by breaking down EE of material production, transport, and replacements into subparts (BE and MC) and a further breakdown into the metrics. This hierarchical structure allows for EE analysis across many levels of detail; from the aggregated to the specific. Furthermore, the breakdown into metrics allows for evaluating the importance of different driving factors for each subpart. The effect of future technological emission reductions in material production and transport is quantified by technological factors. This effect is significant and including it increases the validity of the results. Two visualization tools are introduced to evaluate the EE of a case building. These visualizations imply the theoretically optimal way of reducing emissions. In practice, it may prove difficult to achieve these metric reductions. However, this information can guide the analyst in the direction of optimal improvements, and in combination with architectural drawings and BIM models serve as a valuable tool for design improvements. The methodology does not only highlight which subparts of the building to focus the reductions, but more importantly, how to best address the emission reduction. The results from the case study clarify (1) which subparts that are of importance and (2) to what extent the quantity, choice of material, and transport of materials are driving factors for the EE of the subpart. Once a subpart has been singled out, the metrics provide information on how to approach the emission reduction.

From equations (11) and (15) it can be read that EE is linearly dependent on the material quantity *Q*, i.e. reducing the quantity will reduce the EE of the subpart proportionally, and will do so for all four lifecycle phases. Reducing the specific emissions from material production, *F*, will reduce the first term in the bracket proportionally, while a reduction in the specific emissions from material transportation, *DT*, will reduce the second term proportionally. A reduction in the lifetime factors, L_F and L_{DT}, (or in $L_F w_F$ and $L_{DT} w_{DT}$ if the technological factors are included) will not reduce the EE linearly but will depend on their initial value. An initial value close to or larger than 1 will mean a relatively larger reduction, while a small value compared to 1 will have little impact on EE. Based on the above, and previous studies showing the production term to be larger than the transportation term [8,11], the metrics can be ordered by their potential for reduction in EE when there is a proportional reduction of each metric: *Q*, *F*, *DT*, L_F, L_{DT}. This ordering is generally true for the building level and for many subparts, however, the ordering will depend on the initial values of the metrics.

In this study, the presented method is applied to buildings. Buildings are complex products and therefore a good area of application. The method would, however, be the same for any product. Furthermore, this study applies the method only to the impact category Global Warming Potential (GWP). The methodology would, however, be the same for any impact category.

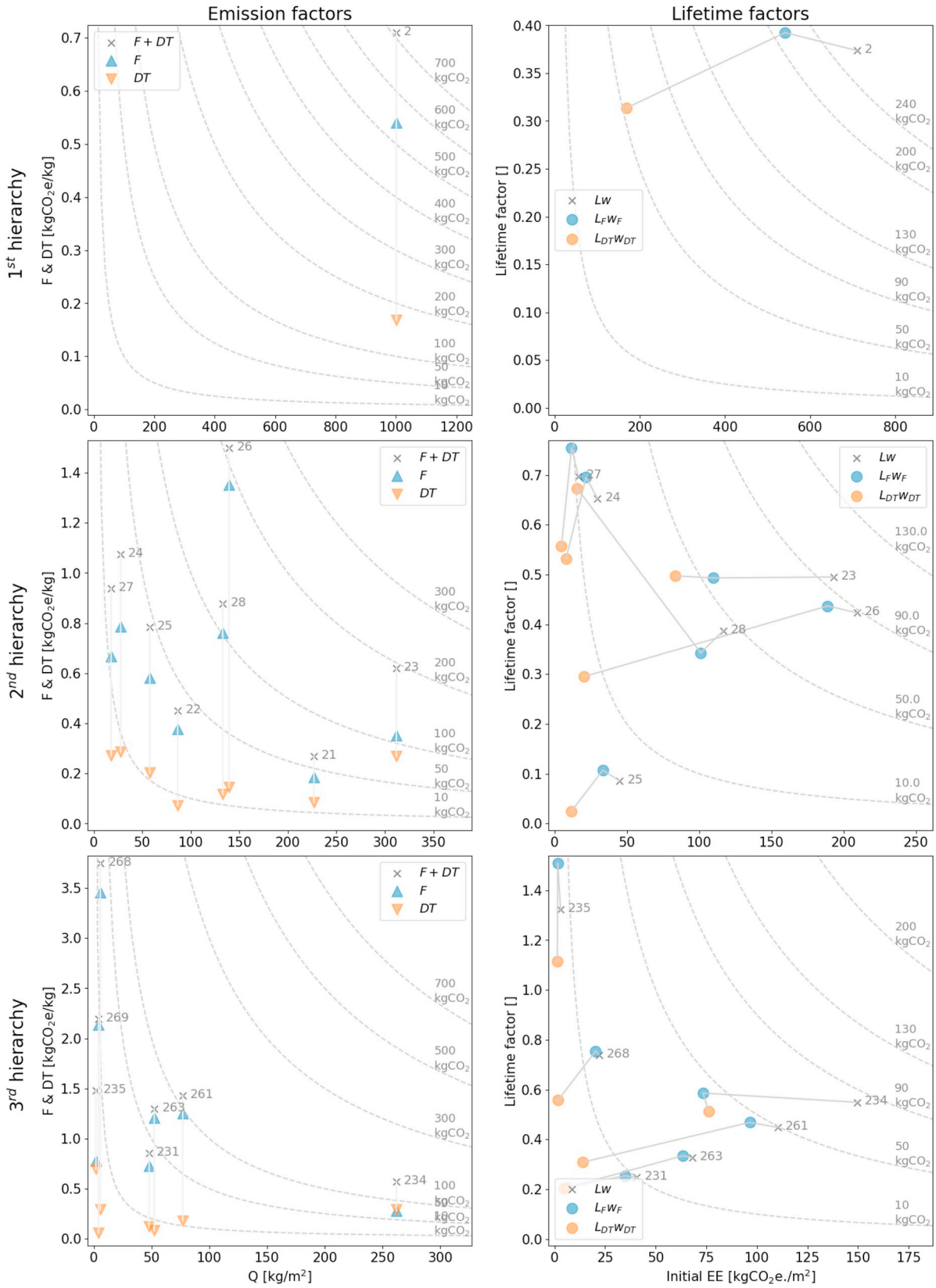

Fig. 6. The *Q-F- DT* plots in the left column show the EE in $kgCO_2e./m^2$ of the initial lifecycle phases broken down by quantities and emission factors. The *EE* - L_F - L_{DT} plots in the right column show the EE of the replacement lifecycle phases broken down by initial EE and lifetime factors. The dashed contour lines are the products of the horizontal and vertical axes and show the resulting EE. The plots show results from building element '2 Envelope, foundations, and structure' from the case building at the 1st, 2nd, and 3rd hierarchies, where BE are numbered according to NS3451. Building element names for the numbering can be found in Fig. 4.

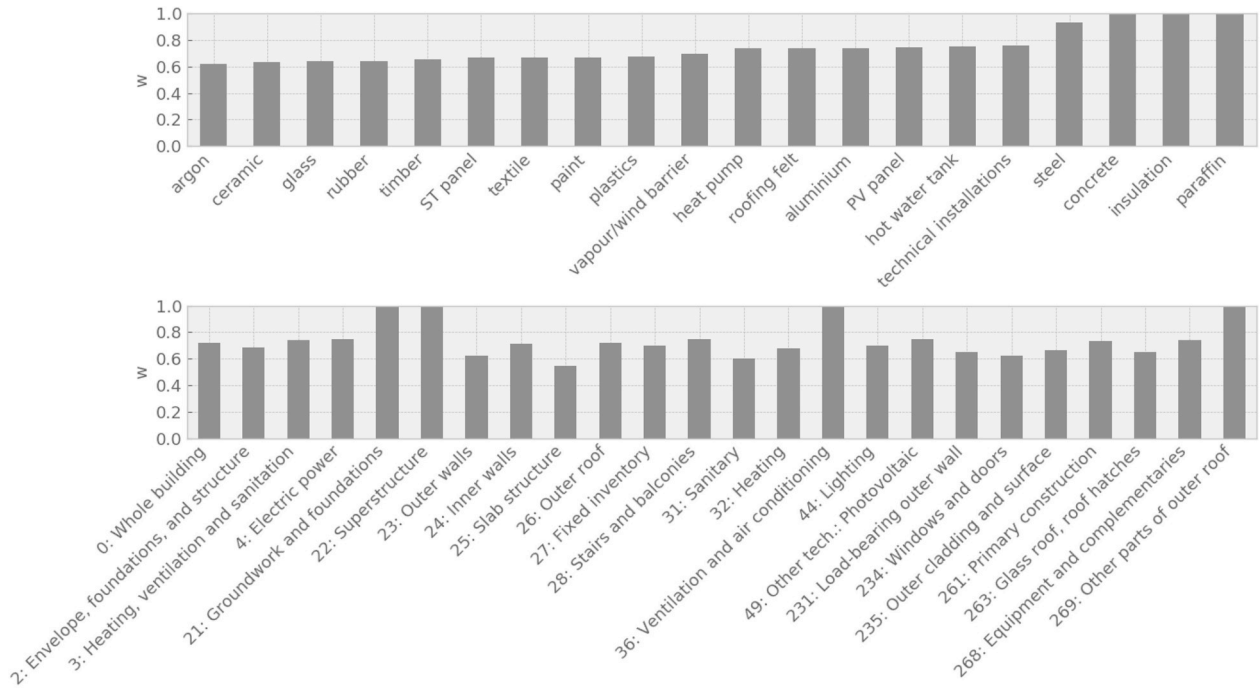

Fig. 7. Total technology factor *w*. The reductions in future EE from replacements due to technological improvements, shown for MC (top) and for BE (bottom). A value of 1 signifies that the subpart is not replaced during the study period.

4.2. The relevance of future emissions

Material service life and building lifetime are two of the three most influential parameters for environmental performance [18,19]. When designing a building for low material-related EE, the material service life is often brought forward as one of the most important parameters to prioritize. However, one must not ignore the importance of expected future developments in production and transport technologies, and their ongoing decarbonization. While [33] found low-carbon energy production strategies to reduce the total carbon emissions of planned residential Finish area by 10% only, the potential of the decarbonization of the energy mix, which will influence the carbon intensity of the final products is not to be underestimated. The carbon intensity of final products depends on the carbon intensity of all upstream processes in the global and local production chains, and decarbonizing "emission hotspots", typically by replacing coal electricity by low carbon electricity in global production chains will reduce the carbon intensity of the final products significantly [33–35].

Including the technological factors in the calculations significantly reduces the importance of the future replacement lifecycle-phases, and thus emphasizes the importance of keeping the main priority on near-future emissions. Building LCAs should therefore always discount future EE. Not only does this downgrade the importance of the building material lifetime, it also reduces the importance of the much-debated lifetime of the building itself, which is often a rather arbitrarily set study period. This study period is often part of the functional unit, where resulting emissions are divided over the lifetime. This greatly increases the uncertainty and may lead to misleading results. In this study, the building-lifetime parameter is only used for the number of replacements needed. This ensures that initial emissions are far more accurate. With a discounting of future emissions, the importance of the building lifetime is reduced also for future emissions, with decreasing marginal emissions for extra years added.

4.3. Validation of method and model

The results from the method are dependent on the quality of the LCI of the case study, which may have corrupted or uncertain values, and may lack materials in the inventory. The method and model, however, reproduced the previously published case study results. Additional validation was performed on six more case buildings, which also reproduced the results. Thus, the model has been validated, and any systematic or random error must therefore be attributed to the LCI of the original case study.

4.4. Limitations

Our model has a number of limitations. The following aspects should be given attention when applying the model and when evaluating results.

The method includes the lifecycle phases of production, transport, and replacement of construction materials, which is not a holistic picture of the EE in a building's lifecycle. Most notably, the construction and end-of-life phases are not considered. Material waste was not part of this study, but is an important emission source in both of these phases, as well as in the replacements phase [36]. Operational energy use is not part of the EE, but is an important emission source and should be included in a holistic assessment.

Emission reductions from technological improvements in production and transport are uncertain and are here modeled in a simplified way. The technological development vectors (used to calculate technological factors) are in the case study modeled as a linear decrease from the year of construction until the end of the study period, and are the same for all materials. However, the method is independent of this linear development and can be replaced by any development model, for instance, exponential decay. Not only can technological developments be based on more accurate models in future work, but different scenarios can also be explored. Moreover, the technological development vectors are assumed to be the same for all building materials. In reality, the future emissions of each type of material is dependent on its current emission level and its unique production and transport conditions. This implementation is thus a simplification of reality. The same approach can be performed separately for each material or MC to increase accuracy. Doing this will, unfortunately, complicate both the practicality of the

method and its interpretability. It may thus not always be desired, especially considering the inherent uncertainty of future developments. The method leads to independent factors for each subpart that are applied post-assessment. This modular way that the technological factors are implemented in the method, namely by a single development vector for production and one for transport, enables high flexibility for updating and creating different scenarios.

The quantities (mass) of materials do not contain information about their structural qualities, and therefore do not alone describe the benefits of choosing those materials. A material may, for instance, have high structural strength per weight but be widely used in a building and therefore still have high quantities.

A major limitation of the method at its current state is its lack of quantifying the accuracy of the judgments and their probable magnitudes. Results must be sufficiently valid if they are to be used for judgments about how to construct buildings, and quantified uncertainties are necessary for validating results. This can be implemented in the method by calculating error propagation and confidence intervals; it is thus an expansion of the method that is necessary and can be tackled by further developments. The current method does, however, improve the transparency of which BE and lifecycle phases that are included in the system boundary. Moreover, the calculated metrics for each subpart gives insight into the LCI data, which can be evaluated to see if the data is reasonable. The approach presented in this paper, therefore, improves the transparency of the system boundaries as well as of the inventory data and lays the groundwork for verifying each metric against statistics.

4.5. Further work

Uncertainties of case study results should be quantified and can be visualized as error bars. In a future paper, we look at the uncertainty and also look into the optimal improvement strategies for emission reductions by investigating the sensitivity and correlations of the metrics.

By collecting previous building LCAs and producing statistics for the metrics of subparts, further applications can be developed. To be representative for a case study, statistics can be produced based on datasets that are separated into different building types. By use of the analytical formulas, the statistical metrics can be used to calculate EE for subparts of similar buildings. Applications include gaining statistical insights from emission profiles of building types; early-phase EE estimation; increasing the completeness of the assessment by use of proxy values in place of missing values and for subparts outside of the system boundary; two main types of evaluation of environmental performance: evaluation of 'isolated study performance', i.e. analyzing the data of the case study only, and benchmarking the study against statistical reference values; verifying the study design and data against statistical values. These applications together form a workflow throughout the project phases from earliest phase to final operation that reduces uncertainty, increases completeness, and improves the capabilities of EE assessments.

Statistical EE values of building types on a detailed subpart level, and a further split into metrics, will result in representative reference values that enable future building codes to regulate the EE of building materials. Such values can be representative for case-specific conditions that affect EE and have increased transparency and comparability compared to building level EE results. Our efforts should be coordinated with other research groups, by taking part of community driven material intensity research platforms such as proposed by Ref. [37].

This paper applies the method on the building scale, but with a growing focus on neighborhood planning [38], the method can be applied also on bigger scales by introducing an additional hierarchy before the building level. This hierarchy can include the buildings in the neighborhood as well as materials used for transportation and for infrastructure. In such cases, data collection becomes an even bigger issue, and the utility of statistical proxy reference-values therefore increases further.

5. Conclusions

In this paper, we presented a procedure for systematically evaluating and visualizing the EE results of LCAs of buildings' material production, transport, and replacements. This was done by grouping a building's inventory into building subparts and calculating metrics for each. These metrics simultaneously break down the EE into individual driving factors and summarize a data-rich inventory for enhanced interpretation. The method is suited to aid practitioners when designing buildings and in the final evaluation phase. The information obtained from analyzing the metrics can be used in conjunction with architectural drawings and will inform the analyst on where the greatest potentials for EE reductions lie.

This approach has advantages compared to previous classical LCA in that it offers a more structured and efficient assessment of EE. A better understanding of driving factors is provided by parametrization of the EE, which improves interpretation. In addition, future expected emission reductions are taken into account by technology factors for production and transport. Taking future emission reductions into account significantly reduces the importance of the lifetime of the building materials and the replacement EE.

The method will be expanded to include uncertainty in a future paper. Additionally, the method lays the foundation for a multitude of further applications in that it allows for mixing case-specific data with statistical data. This is useful when case-specific data is unavailable, such as in the early project phases, and in later project phases for estimation of building subparts that are outside the system boundary of an assessment. Applications of the method with statistical data can be developed to provide a basis for EE assessment throughout the project phases of construction projects. The current method can be directly applied to case buildings for identifying design and material choice improvements, and for evaluation after construction is completed. In the future, the combination of case-specific and statistical metric values can be useful if EE should be included in building code regulations.

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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.2019.106476.

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