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Embodied emission profiles of building types: guidance for emission reduction in the early phases of construction projects

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Abstract. The embodied emissions of the construction materials in buildings are a significant contributor to climate change but have only rarely been systematically studied by statistical methods. In the early phases of a building project, empirical results of statistical emission profiles of different building types can act as useful guiding information to inform decisions regarding reduced embodied emissions from construction materials. However, engineers and architects do not have such information at disposition. In this paper, the embodied emissions from the production and transport of initial and recurring building material use in 7 Norwegian case studies of low-emission buildings are made comparable and then studied statistically to find out how the impact varies with building types. The building types studied are timber residential, concrete office, concrete school, and concrete swimming hall. Statistics are produced for each building type and are broken down by the impact contribution from different building elements and material categories. This results in embodied emission profiles and material use profiles for these four building types, which, when based on a larger dataset, can be used by architects and engineers to make informed decisions when aiming for reduced embodied emissions in the early phases of a construction project. Additionally, these profiles can be used as benchmarks by which the final building can be compared when the building is constructed. The statistical results are preliminary and based on a limited dataset, which makes them applicable only as an indication for Norwegian low-emission buildings of these four building types. Future work includes expansion of the dataset on which the profiling is based, further development of the statistical method, and applying the methodology to additional building types.

1. Introduction

The construction and operation of buildings is a major source of global greenhouse gas emissions, and with increased energy efficiency due to stricter building codes and a focus on energy renovations, the emissions associated with the building materials are making up an increasing portion [1, 2, 3]. These indirect emissions are often denoted 'embodied emissions', as opposed to the operational emissions from energy and water use. The European standard EN 15978 [4] which is describing a calculation method for life cycle assessment (LCA) of buildings divides the emissions into lifecycle phases. The lifecycle phases for material production from cradle-to-gate are named A1-A3, the transport from the factory to the building site is A4, and B4 is the replacement of building materials. B4 can be further divided into production and transport as is done for the initial lifecycle phases, and can then be denoted B4m and B4t as was done in [5].

Operational energy efficiency is now a regulatory priority in most countries, and a stronger focus must be set on emissions from materials [6]. While national building codes enforce regulations on operational energy performance, there is no equivalent regulation for the embodied emissions. Some initial work for the inclusion in Norwegian building codes is ongoing [7], however, unsolved problems include lacking representative referential values and low transparency and comparability of the assessment methodology [8].

A construction project goes through several project phases from initial ideation, to the solidification of a plan, construction, and final operation. The information available about the building will increase along with these phases, but will vary from project to project. In the earliest project phases, statistical emission profiles of different building types can be used to get an idea of the variation between – and the range within – subparts of certain types of buildings that are being considered. Building types can be compared against each other to see the effect of choices made in the earliest project phases. The lack of information in early project phases, when little has been decided about the area plan and building composition, makes it difficult if not impossible to make informed decisions at this stage. Statistical results from building types can then serve as guidance. Building types are likely to have trends in the EE results giving each building type a unique emission profile. Statistical insights on the emission profiles and material use of building types can be derived from a sufficient dataset of representative buildings.

In addition to aid in improving the design of the building relative to itself, it would be useful to benchmark environmental performance against other building projects within the same building type. In the design phases, feedback on how the building and its subparts compare to other buildings of the same building type can point the analyst in possible directions for improving the design. In the evaluation phase, benchmarking can serve as documentation for building code requirements and certification schemes.

Many factors are affecting the embodied emissions of buildings, from climate to construction technologies, material production technologies, electricity generation and fuels used, transport distances and many more. When comparing the embodied emissions from one building to those of others, buildings should be categorized by these conditions. The term 'building types' is used here as a set of common characteristics that the buildings share, and that have an impact on the EE, such as location, typology (i.e. school, kindergarten, office building, etc.), and construction type (i.e. timber, concrete, steel, etc.). A building type can be general and include most buildings, i.e. have few restrictions on the descriptors, or can be specific and include only very similar buildings, i.e. have strict restrictions on the descriptors. By using data from similar building types, the generated statistics and thus the comparison is made representative for the case. Furthermore, each building consists of an inventory of building materials. Buildings can be broken down into subsets of their inventories, here referred to as subparts. This breakdown into subparts of building types makes comparisons more representative, by reducing the variability from both building characteristics and from building inventories [5, 8].

This paper presents a method for obtaining statistical emission profiles for greenhouse gas emissions related to the production, transport, and replacement of building materials for four different building types. The applications of the method include gaining statistical insights from emission profiles of building types and for benchmarking environmental performance against statistical reference values.

2. Methods

The statistics are based on 7 previously conducted LCAs of buildings, presented in Table 1, that were collected from various sources. All buildings have been designed to have low lifecycle emissions both from operational energy use and emissions embodied in building materials. Due to a limited dataset, the results will be strongly biased by the case-specific conditions and designs of these buildings.

Table 1. The building LCAs that are included in this study.

Name	Typology	Construction	Location	HFA [m^2]	Year, study
ZEB Living lab	Residential	Timber	Trondheim, Norway	102	2014
ZEB Multikomfort	Residential	Timber	Larvik, Norway	202	2014
ZEB SFH Concept	Residential	Timber	n/a, Norway	160	2013
Papirbredden II	Office	Concrete	Drammen, Norway	8536	2012
Østensjø skole	School	Concrete	Oslo, Norway	3629	2017
Flesberg skole	School	Concrete	Flesberg, Norway	6664	2018
Flesberg svømmehall	Swimming hall	Concrete	Flesberg, Norway	2344	2018

The results were made comparable by systematically organizing the original data used in the studies according to the method described by Resch and Andresen in [8]. Here, material inventory of the buildings and other relevant information is stored in a SQL database that categorizes the inventory according to hierarchical building elements from the Norwegian standard NS 3451 Table of Building Elements [9], and according to material categories by predefined material and product groups.

The inventory data is then used to calculate aggregated metrics for each building by the method described by Resch et al. in [5]. Metrics that are relevant for the interpretation of the results, and furthermore, that are useful for generating statistical emission profiles, are calculated. These metrics are weighted average values of the inventory items, that describe the environmental performance of each building subpart, which in this way is treated as an isolated product. The metrics are the quantity Q [kg], the emission factors for production F [$kgCO_2e$] and for transport DT [$kgCO_2e$], as well as the lifetime factors for production L_F [-] and for transport L_{DT} [-], and the technological factors for production w_F [-] and transport w_{DT} [-] that are adjusting the replacement emissions according to an expected decrease in future emissions. The calculation of metrics for each building element and material category is enabling a detailed interpretation of emissions. The effect of technological improvements on future replacement emissions is implemented with technological vectors modeled as linear decreases from the year of construction until the final year of the study. Production emissions are assumed to be 50% lower and transport emissions to be 90% lower 60 years after the buildings are constructed. The metrics relations to embodied emissions are shown in Table 2.

Table 2. The metrics relations to embodied emissions [$kgCO_2e$]. Names of lifecycle phases shown in parentheses.

	Initial	Replacement
Production, cradle-to-gate	QF (A1-A3)	QFL_Fw_F (B4m)
Transport, factory to building site	QDT (A4)	$QDTL_{DT}w_{DT}$ (B4t)

These methods for systematically organizing and storing the results, and for calculating the metrics, together enable the use of previous LCA studies for establishing statistical reference values. First, buildings are categorized into building type categories according to their typology and main construction material. Then, each metric within each building type is averaged for each building element and each material category. All building elements, material categories, and lifecycle phases where data exist are used for the averaging, and conversely, excluded where data is not available. The number of data points used for each statistical value is therefore varying and restricted by the available data.

This results in a set of average metric values for the building types 'Timber residential', 'Concrete office', 'Concrete school', and 'Concrete swimming hall'. These average metric values are then used to calculate the embodied emissions for each building element and material category with the equations shown in Table 2. The results are then visualized in 'Metrics charts' as described in [5]. These charts display the embodied emissions for each lifecycle phase, and the breakdown of those emissions into the quantity, emission factors, and replacement emission factors. Moreover, these results are shown for each building subpart (building element or material category) to get a high-resolution overview of the emission profiles of the building types.

3. Results

Results are first presented as a comparison between the four building types, and then separately for each. The presented results include the embodied emission results from the lifecycle phases A1-A3, A4, B4m, and B4t, as well as the quantity, emission factors, and replacement emission factors. The plots show all building subparts and lifecycle phases that are available for the building types, which is varying because each building type has included different building subparts and lifecycle phases in the original studies.

3.1. Comparison between building types

The building elements that are included in the collected LCA studies vary and the building types can therefore not be compared directly on the aggregated level. The comparison is made for the building elements 21, 22, 23, 24, 25, 26, and 28, since they are available for the four building types (except for 28 for Concrete office) (see Figure 2 for building element names that correspond to these numbers). Figure 1 shows the average metrics from these building elements for the four building types, as well as the embodied emissions calculated from the average metrics.

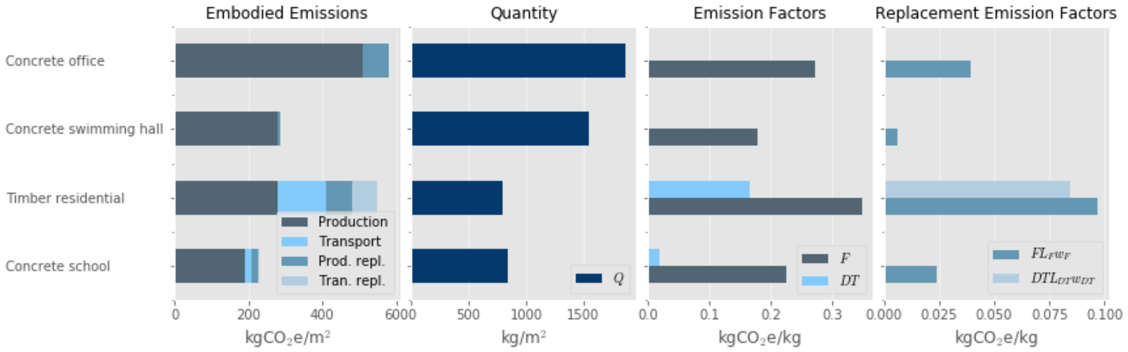

Figure 1. Comparing the emission profiles of the four building types. Building elements 21, 22, 23, 24, 25, 26, 28 are included in the comparison.

The initial production of building materials (A1-A3), available for all building types, is highest for the concrete office. This is due to a high quantity of materials per m^2 combined with a relatively high emission factor. It has 2.3 times more quantity than the timber residential, 2.2 times more than concrete school, and 1.2 times as much as concrete swimming hall. The high mass can be explained by the extensive works needed to stabilize the ground for this particular case. The emission factor for initial production, F, is smallest for swimming hall, and largest for timber residential. Their difference in emission factor is compensated for by a mass twice as large, and they end up having the same emissions from production of building materials. The smaller emission factors of the concrete buildings is partly because of concrete having high density, but is likely also affected by the residential buildings having more complete inventories. If one of the residential buildings were left out (ZEB Living Lab), then the building type based on the two remaining would have the lowest emissions of all building types and the production emission factor would be almost a third smaller. This highlights the limited usefulness small datasets.

The production of replacement materials (B4m), also available for all building types, is proportionally larger for the timber building type than for the concrete building types. Concrete is not replaced during the 60 year lifetime of the buildings, while timber is. This is reflected by the replacement emission factor $FL_F w_F$ which is 2.5-15.6 times larger for timber residential than for the concrete building types. Although timber parts are replaced more often than concrete, the timber buildings in these particular studies also have more complete inventories which contributes to the larger replacement emission factors.

The transport of building materials (A4 and B4t) have limited availability in the dataset, and thus, does not allow for a complete comparison. Nevertheless, data available on these lifecycle phases are important indications of the relevance of transport. Particularly, it is noteworthy that there is a big difference between timber residential, which has the most detailed inventory, and concrete school, with less detailed inventory.

The future replacement emissions are reduced by a technological factor corresponding to an expected development in emission reductions in production and transport, taking the years of replacement and replacement rates into account. The average reduction by building type is shown in Table 3. The reduction for the timber building type is much larger than the reductions for the concrete building types.

Table 3. The reduction of future replacement production emissions due to technological improvements.

Building type	w_F	Reduction, production	w_{DT}	Reduction, transport
Concrete school	0.970	3.0 %	0.980	2.0%
Timber residential	0.911	8.9 %	0.648	35%
Concrete office	0.969	3.1 %	-	-
Concrete swimming hall	0.978	2.2 %	-	-

3.2. Timber residential

Figure 2 and 3 show the average results from 3 timber residential buildings, where the subparts are divided into building elements and material categories, respectively. The emissions for '0: Whole building' are divided into subelements on the 1st hierarchy. The timber residential building type is the only building type where results are available for '3: Heating, ventilation, and sanitation', for '4: Electric power', and for '8: Other installations'. The system boundary is thus much more complete than for the other building types. However, '2: Envelope, foundations, and structure', which is available for all building types, is by far the most important part of the total emissions. The reason for this is apparent from the breakdown into the metrics: nearly all quantity goes into this building element. The emission factors are much higher for the other building elements, but in return, they have small quantities and therefore lower emissions. Notably, '4: Electric power' is responsible for a sizeable chunk of the overall emissions, which can be attributed further to '49: Other tech.: Photovoltaic' on the 2nd hierarchy. Looking further into '2: Envelope, foundations, and structure', the building elements on the 2nd hierarchy with digits 2x, and the building elements on the 3rd hierarchy with digits 2xx, show that '23: Outer walls', and in particular

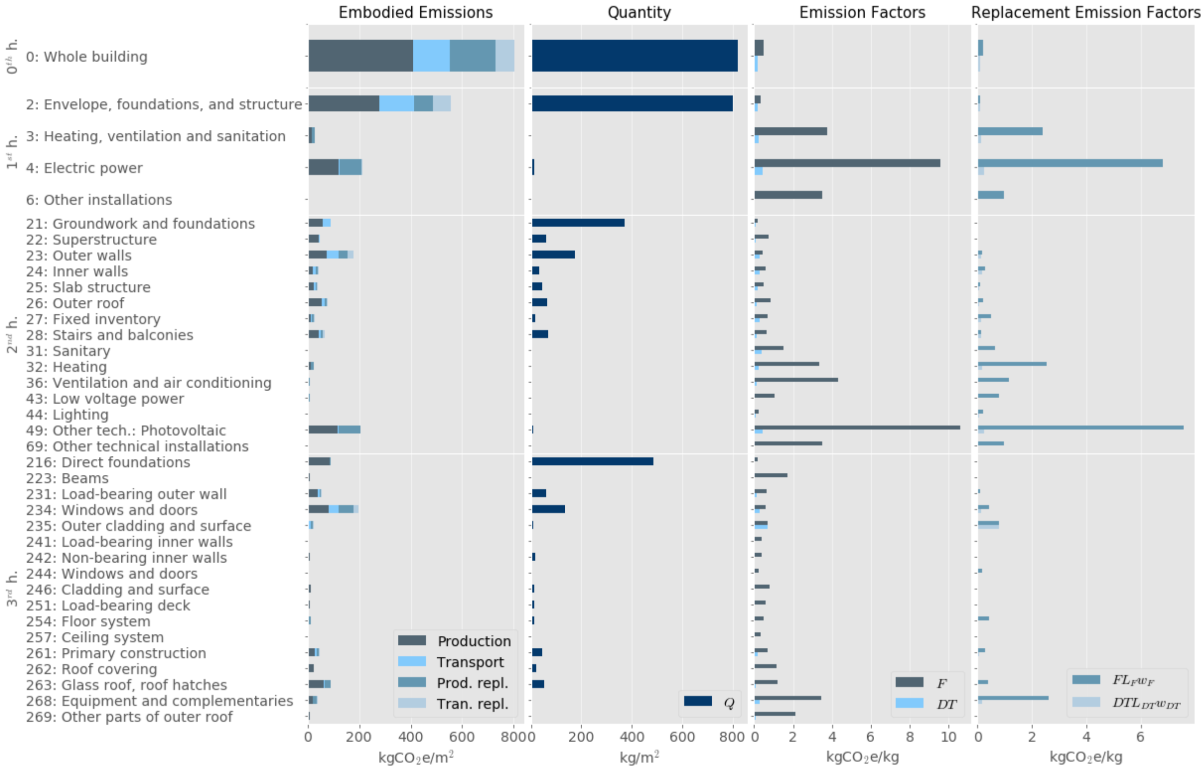

Figure 2. Timber residential (n=3).

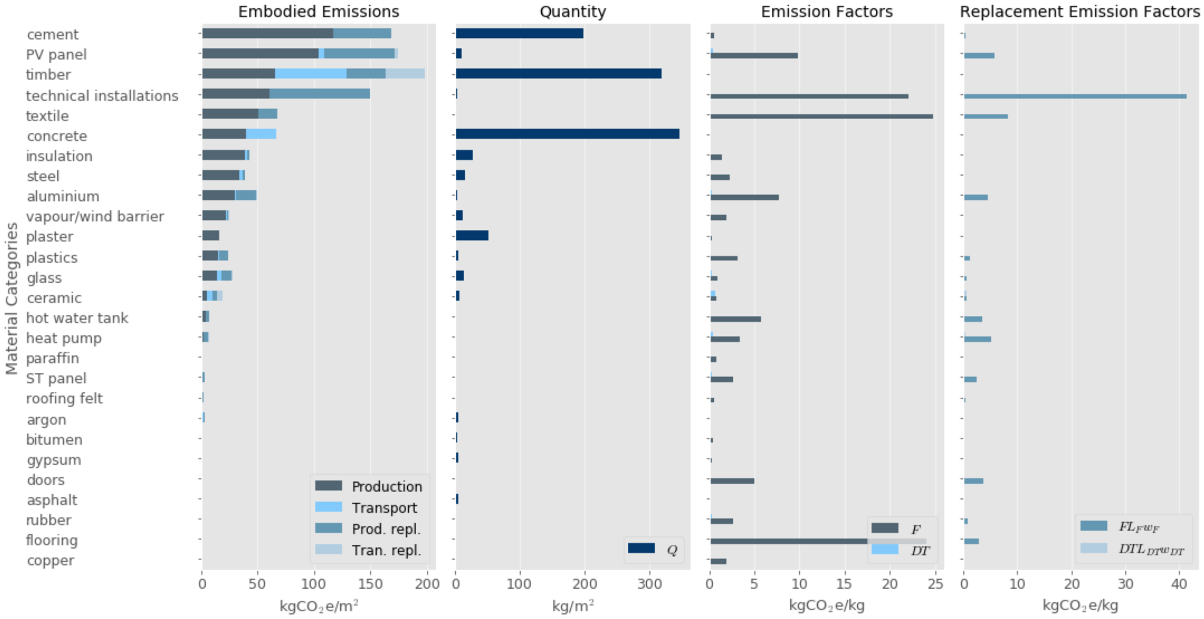

Figure 3. Timber residential (n=3).

'234: Windows and doors' are responsible for a large part of total emissions. The reason for this is a high quantity, but also significant emission factors and replacement emission factors both for production and for transportation. Further, it can be observed that '21: Groundwork and foundations' has a large quantity but small emission factors and zero replacement emission factors, while '22: Superstructure', '26: Outer roof', and '28: Stairs and balconies' all have similar emission profiles with both quantities and emission factors being relevant.

The material categories that are dominating the timber residential building type are cement and concrete (used mainly in foundation), PV panel, timber, and technical installations. Furthermore, textile, insulation, steel, aluminium, vapor/wind barrier, plaster, plastics, glass, and ceramic are also important material categories. The remaining material categories are small and should therefore not be an important focus in terms of emission reductions. Among the categories that do matter, the PV panel, technical installations, and textile have high emission factors for production and replacement production, while timber, concrete, and cement have large quantities.

3.3. Concrete office

Figure 4 and 5 show the results from 1 concrete office building, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure', and resolution restricted to the 2nd hierarchy. Transport emissions are not available. Most of the quantity is divided equally between '21: Groundwork and foundations' and '25: Slab structure', but the former has higher emission factor and therefore much higher emissions. These building elements' emissions can be attributed to large quantities of concrete and cement. '23: Outer walls' is the only building element where replacement emissions are large. Although the quantity is small, both the emission factor and replacement emission factor are the highest for the building type. In Figure 5 it can further be seen that this to a large degree is caused by the material category windows and its high emission factor and replacement emission factor.

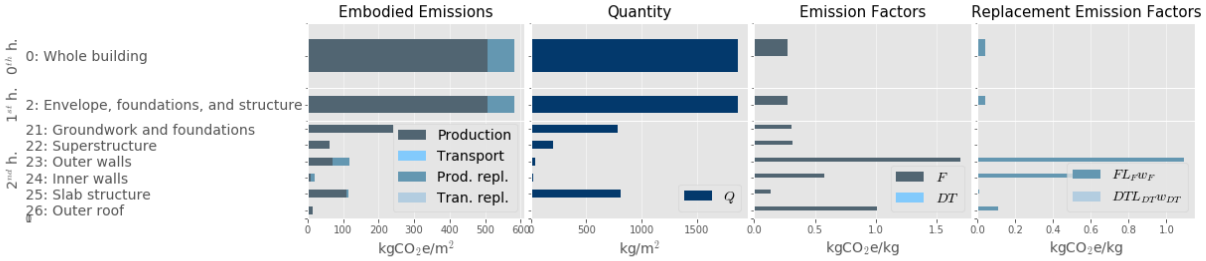

Figure 4. Concrete office (n=1).

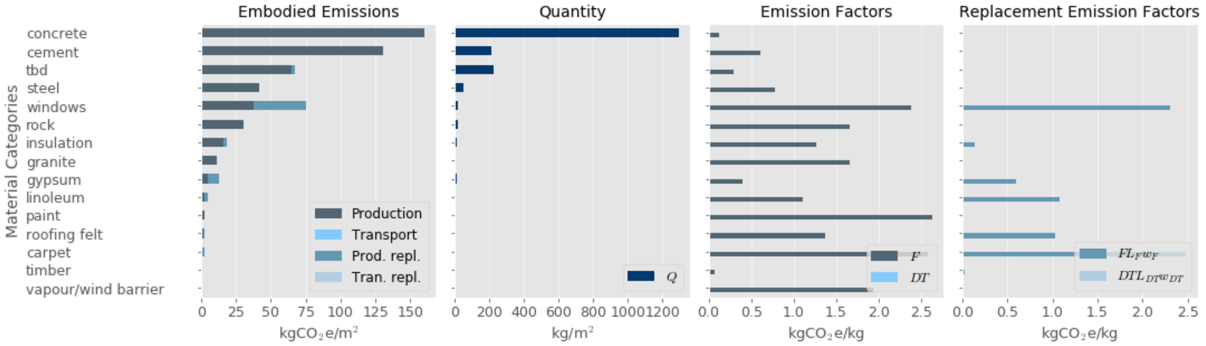

Figure 5. Concrete office (n=1). Uncategorized materials are grouped in *tbd*.

3.4. Concrete school

Figure 6 and 7 show the average results from 2 concrete school buildings, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure', and resolution restricted to the 2nd hierarchy. '25: Slab structure' is dominating quantity, and as a consequence it is the building element with the largest embodied emissions. '21: Groundwork and foundations' and '23: Outer walls also have substantial quantities, while '24: Inner walls' and '26: Outer roof' mainly have their high emission factors and replacement emission factors causing their contribution to emissions.

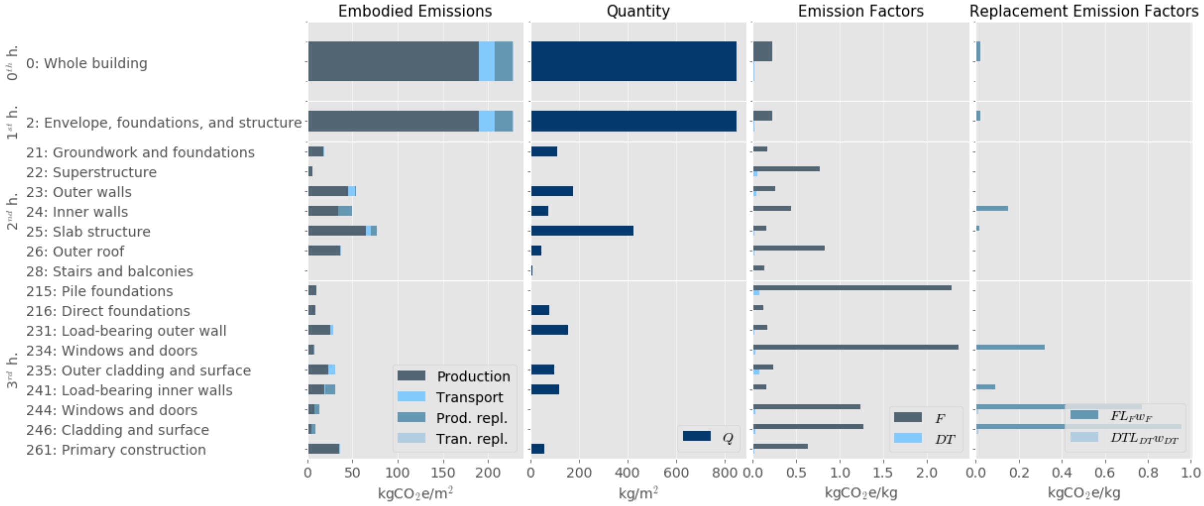

Figure 6. Concrete school (n=2).

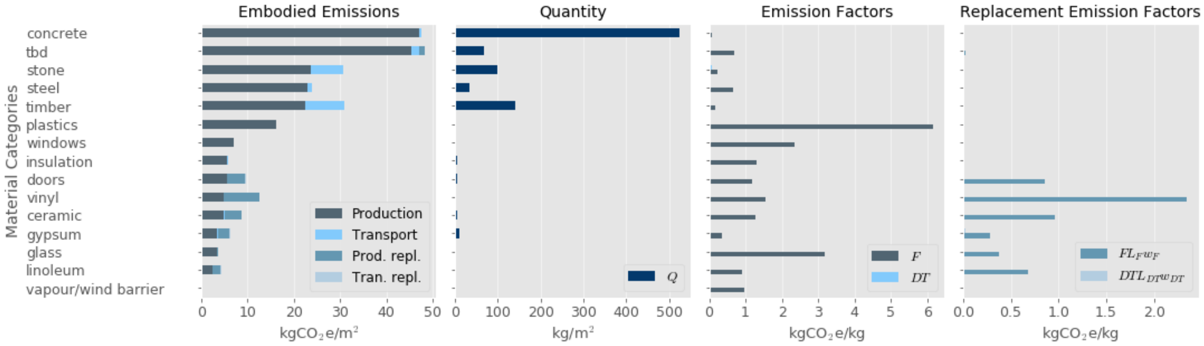

Figure 7. Concrete school (n=2). Uncategorized materials are grouped in *tbd*.

The building consists mainly of the material categories concrete, timber, stone, and steel, as well as uncategorized materials in tbd (most because they are modular elements consisting of many materials). These categories are the most important in terms of embodied emissions, caused directly by their large quantities. On the other hand, plastics, windows, glass, etc. have high emission factors. Quite surprisingly, and in opposition to the timber residential and concrete office building types, the windows have no replacements. This is a methodological choice difference, where the analysts of the different studies have assumed different lifetimes for the windows. Accordingly, this may perhaps not be a realistic assumption, and it complicates comparison and the trustworthiness of the individual studies. Vinyl is the material category with the highest replacement production emissions (B4m) due to its high replacement emission factor. Timber and stone are responsible for most of the transport emissions.

3.5. Concrete swimming hall

Figure 8 and 9 show the results from 1 concrete swimming hall building, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure'. Transport emissions are not available. There are similarities between the emission profile of this building type and the concrete school building type, since one of the school buildings are part of the same construction project as the swimming hall, and the LCA was performed by the same analysts. '25: Slab structure' is dominating both in terms of quantity and emissions, followed by '22: Superstructure' and '23: Outer walls'. If windows were replaced at the same rate as in the timber residential building type, '23: Outer walls' would have had even higher emissions. Steel is an important material category, but concrete is dominating both quantity and emissions.

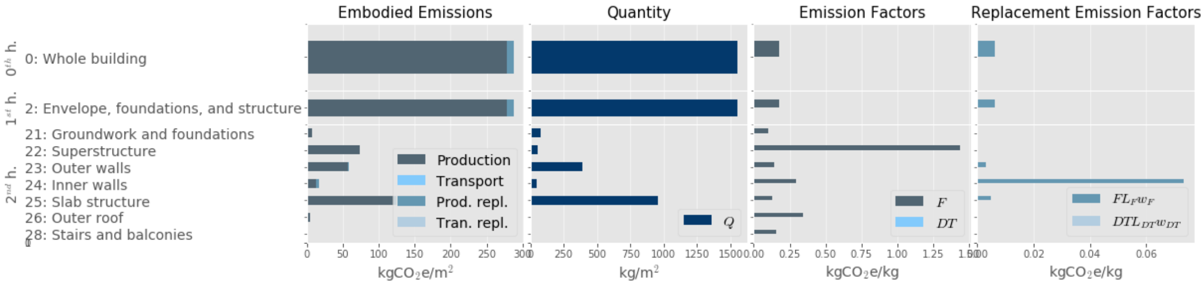

Figure 8. Concrete swimming hall (n=1).

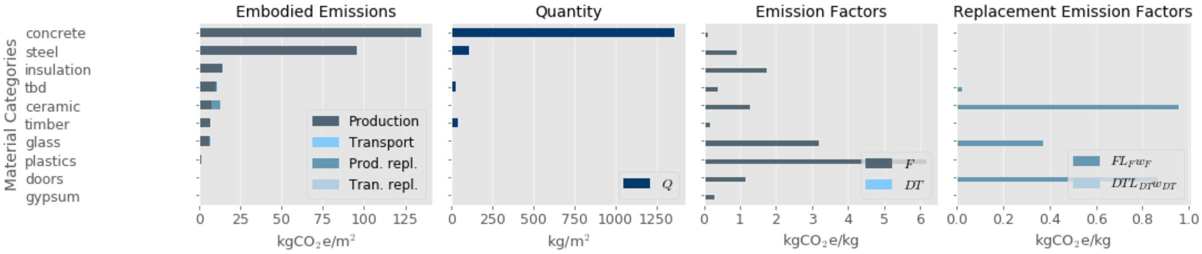

Figure 9. Concrete swimming hall (n=1). Uncategorized materials are grouped in *tbd*.

4. Discussion

The purpose of this paper is to demonstrate a methodology for establishing emission profiles of building types. Such emission profiles can be useful in the early planning phases of construction projects when little information is available about the building, and few decisions have been made regarding the design, material use, and other factors affecting embodied emissions. Furthermore, emission profiles can be useful for policy and strategic planning decisions that influence the future building stock. Finally, emissions profiles is an efficient benchmarking strategy, whereby finalized construction projects can be compared and the emission performance evaluated. A rich dataset is needed to make full use of the method.

Building types can be narrowly or broadly defined, depending on the use case. A building type including a large variety of buildings in a country is useful for establishing a national average. The building types in this paper are specified by main construction material and typology because these two descriptors are expected to influence the final embodied emissions substantially. These building types will then be more useful than a national average for practitioners designing these building types and for decisions made regarding typologies and construction materials. Additional descriptors that affect embodied emissions can be specified to further narrow down the area of application and make the building types representative for specific building cases. These might be dimensional and morphological descriptors such as the number of stories or the floor area, or contextual parameters such as year of construction or a narrowly defined geographical area, or thermal conductivities, ground conditions, or any other descriptor that can be expected to have an influence on embodied emissions. A narrowly defined building type will be better suited for benchmarking a specific building and improvements made towards emission reductions during its design, while a national average building type will be suited to compare and place the building in a broader context. Narrowly defined building types will, however, need large amounts of sufficiently high-quality data with related descriptors. The building LCA database tool described in [8] is tailored for storing and handling this kind of data, and the applications presented in this paper scale seamlessly with additional data added. The limiting factor is the availability of the building LCA data.

In this paper, the emissions from future replacements of materials are reduced by a technological factor for production and another for transport. Taking these reductions into account reduces the importance of future emissions, and underlines the importance of keeping the focus on current and near-future emissions. Besides, future emissions are dependent on many uncertain conditions that are outside of present-day scope of influence. Furthermore, the technological factors show the future emissions from timber buildings to be more affected by technological improvements than for the concrete building types. This is largely due to the more rapid replacement of timber parts than concrete. Future emissions due to replacements are thus much less important than near-future emissions, for timber buildings as well as for concrete.

We have demonstrated how case-specific conditions can have large effects on the emission profiles when the underlying dataset is limited. These initial results are a demonstration of the methodology, which needs to be updated with a larger dataset of building LCAs. The sample sizes are too small to draw conclusions about building types from the results. The differences between the building types are likely to a considerable degree explained by differences in system boundaries and inventory completeness within building elements, as well as case-specific conditions such as ground conditions. One such case-specific condition is the unstable ground conditions for the concrete office, leading to higher emissions in Groundwork and foundations, and explaining much of the difference. Nonetheless, the results give an indication of the emission profiles of the four building types in the Norwegian low-carbon building context.

The data quality presented here depends on the data quality of each of the collected studies. When the number of data points is small, low data quality and incomplete or incorrect system boundaries and inventory will have a big impact on the results. As the dataset grows, these limitations will gradually be mitigated by smoothing out individual study limitations. The current dataset has too much variation in system boundaries and inventory completeness to be valid for general conclusions. Although the methods applied in this paper, e.g. separating inventories into building subparts and applying the statistics on the metrics instead of the final aggregated results, is to a large extent mitigating the uncertainties related to these issues, a larger dataset is needed for generalizable and accurate results.

The results in this paper are missing uncertainty which is a major limitation; this should be included in future work for results to be reliable enough to be used for policy measures. When this is in place, emission profiles can be used for setting maximum allowance levels in building code regulations, and carbon taxes or incentives can be based on such benchmarks.

5. Conclusions

This paper presented a method for establishing emission profiles and material use profiles for material production, transport, and replacements, which will be representative for building types when a sufficient dataset is available. This is useful for gaining insights into how emissions are distributed, and to understand the effect of choices made in the early phases of construction projects. Furthermore, emission profiles can be used to establish benchmark values by which the emission performance of buildings can be measured, and to set regulatory limits on the allowed embodied emission levels of building materials, analogous to existing regulations on operational energy performance. The dataset is not sufficiently large to get reliable emission profiles that are representative for these building types, rather, the results are initial indications and a demonstration of the method. Future work includes an expansion of the dataset and the quantification of uncertainties.

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