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CO_2 emissions from building life-cycles

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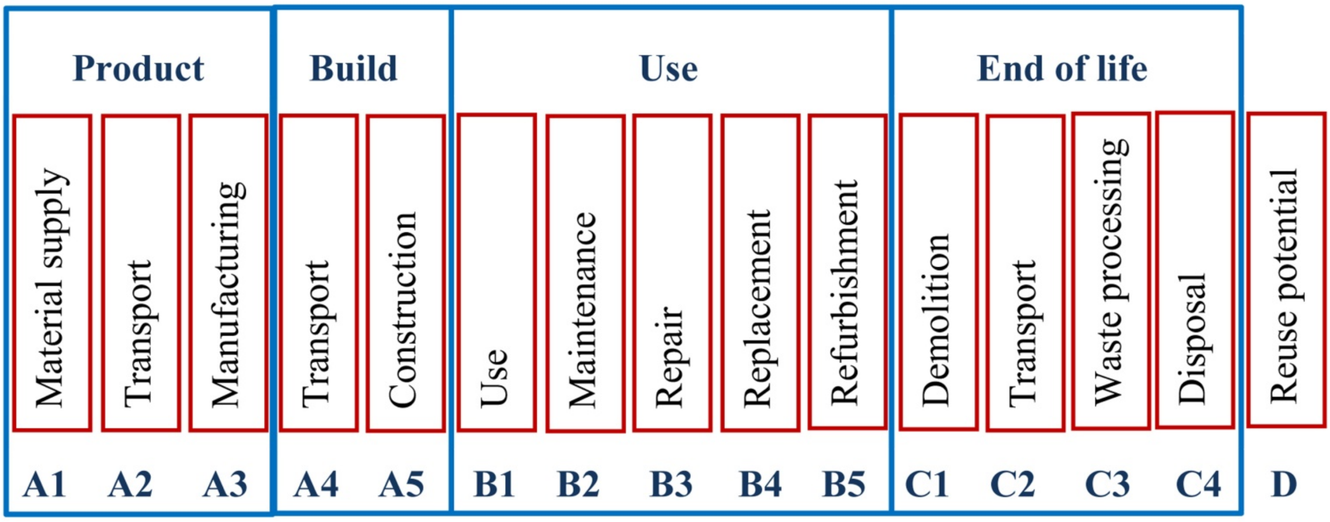


Life Cycle phases according to CEN [3]

CO_2 Emission from buildings and impact on the climate
The present edition of the notes replaces the first edition from 2010.
In the meantime, CO_2 emission from operation of buildings is reduced, where the contribution from construction of buildings and infrastructure is increased.

An early example of a study on these matters was a phd project by Sigurd Andersen [1] and [2], which was an answer to a question only a few have asked at the time. He found a level for energy consume of 500 -1000 kWh per m^2 for dwellings equal to 150 – 300 kg CO_2 per m^2, which corresponds well to modern calculations and to the results shown below.

Now, people and society pays much more attention to the impact on the climate and the conditions for the next generations. The CO_2 emission damaging the climate comprises that of production of materials and the building process plus the impact from the end of life stage. This stage includes demolition of the building and processing the materials as waste. The end of life stage is especially important, because without that you only obtain to store your old CO_2 to be released damaging the climate much more for the next generations.
References like CEN [3] and Hermann [4] therefore explains this in detail.

It is also obvious that you should relate the CO_2 emission of the life cycle to the lifetime of a structure or material, and that any comparison of climate impact of different building structures can only be made if the structures fulfill the same functional requirements.

You may add a potential for reuse prolonging the lifetime of a material or component.
CEN [3] suggests adding this as a phase D. However, you can only guess about how much will be reused in a far future. We therefore recommend implementing this as an initial phase of the life cycle, because you can be sure about how much reused materials and components you intend to apply in your own new construction, not what someone else will do in a different society many years ahead.

The first railway station of Copenhagen by J.D.Herholt 1863.
The timber structure is a bohlendach, which H. Wenck copied for the present Central Station from 1914.
Half of the old bohlendach structure is today reused as a sports hall in Aarhus. Herholt founded teaching and research in building design at DTU, which is now the Department of Civil Engineering.

CO_2 data

Anybody can find the data presented in this publication in reliable references like Hammond and Jones [5], Ruuska VTT [6], or in ÖkobauDat [7] or LCA Byg [8] that uses ÖkobauDat [7] data. An annex presents a concentrated list of CO_2 data as a single sheet.
The data represent the full life cycle including the end of life stage, which is important for the impact on the climate. The material data applied in these notes are in accordance with those of ÖkobauDat [7] and as applied in LCA Byg [8].

Timber

End of life is especially important for organic materials like wood that absorbs CO_2 when it grows, and releases it at the end of life. Sources like [5] and [6] do therefore not include the absorbed CO_2 in their numbers. However, using a source like ÖkobauDat [7] or LCA Byg [8], you have to add end of life manually as explained in [3] and [4].
For example, Cross Laminated Timber (CLT) gives a value about -632 kg CO_2/m^3 for production. With density 489 kg/m^3 it is -1.291 kg CO_2/kg. To that, [7] and [8] gives a value of 1.80 kg CO_2/kg for end of life, so that you get a total of 0.51 kg CO_2/kg for CLT. This is close to the values from the other sources.
Lifetime of timber structures is in general smaller than for stone structures due to rot, fire, and insects. However, reuse of unharmed timber is more common, and these two opposite effects makes it reasonable to compare CO_2 emissions for equal life times.


Firth of Forth Bridge by J. Fowler and B. Baker 1889 Photo KD Hertz

Steel

When you consider the CO_2 impact of steel, you find different values depending on whether the steel is new (virgin steel) or it is re-used. Virgin steel releases 2.80 kg CO_2/kg mainly because the steel is purified by removing oxygen from the iron ore by addition of carbon.

If you apply recycled steel, you only release 0.47 kg CO_2/kg by the melting process etc.
With an average amount of recycled material, you get 1.00 kg CO_2/kg for steel profiles and 1.85 kg CO_2/kg if they are galvanized.
You may say that you by application of these values, have considered a re-use potential as an initial phase as suggested above.

Even with this common recycling a considerable amount of virgin steel is produced, and in total the steel industry counts for approximately 7% of the global CO_2 emission.
In addition to steel structures, you also apply steel as reinforcement in concrete structures.
A certain part of the steel applied for reinforcement is recycled. According to Ökobaudat [7], the emission for reinforcement is therefore 0.75 kg CO_2/kg.
If you apply 100 kg steel per 2400 kg or per m^3 reinforced concrete structure, the emission from the reinforcement will be 0.03 kg per kg reinforced concrete.
Researchers try to reduce the CO_2 emission from production of virgin steel, and in the future, they may succeed reducing it considerably for example by application of hydrogen instead of carbon for binding the oxygen from the iron ore.

World Championship in Clean Technology won by the first author's start-up company Abeo in 2010.

Concrete

Concrete gives rise to CO_2 emission mainly from production of cement. A rather strong concrete of 55 MPa gives 0.14 kg CO_2/kg, where a not so strong concrete of 25 MPa gives 0.09 kg CO_2/kg. You can create a so-called green concrete replacing a part of the cement with reactive fly ash or pulverized ceramics reducing the emission.

The Romans built their Empire with concrete based on fly ash from volcanoes or pulverized glass or ceramics and burned limestone. All these ingredients can be produced in electric ovens, so that the only amount of CO_2 is chemical from the burned limestone. This can reduce the emission of a 55 MPa concrete from 0.14 to 0.05 kg CO_2/kg.
In addition, the concrete can reabsorb some of the CO_2 during its lifetime, especially if it is crushed after use. Then, the potential is a final emission of 0.02 kg CO_2/kg.
Although we have applied this technology before, reintroduction of it requires a change of the industry, and therefore we can only consider it as a future possibility.
It is therefore *not* included in the present text reflecting the present situation.

In 2008, the first author invented the super-light structures using a strong concrete, where the compression forces should be and fill out the rest with a light concrete, typically of

700 kg/m^3. This reduces mass and CO_2 emission. The invention won a world championship in clean technology - Clean Tech Open in San Francisco 2010.
Super-light deck-elements are today implemented and produced in several countries.

Some factories are still producing light ceramic aggregate in coal fired ovens. This gives an emission of approximately 0.27 kg CO_2 per kg concrete of density about 6-900 kg/m^3.
Usually 20% of the cement is replaced by fly ash, reducing this number to 0.24.
In Denmark, light aggregates are today produced in ovens fired approximately 85 % by fossil free waste, 5% coal plus 10% coal embedded in the clay. This reduces the emission to 0.14 kg CO_2 per kg light aggregate concrete.

Super-light deck element at Krøyers Plads. Architect Cobe

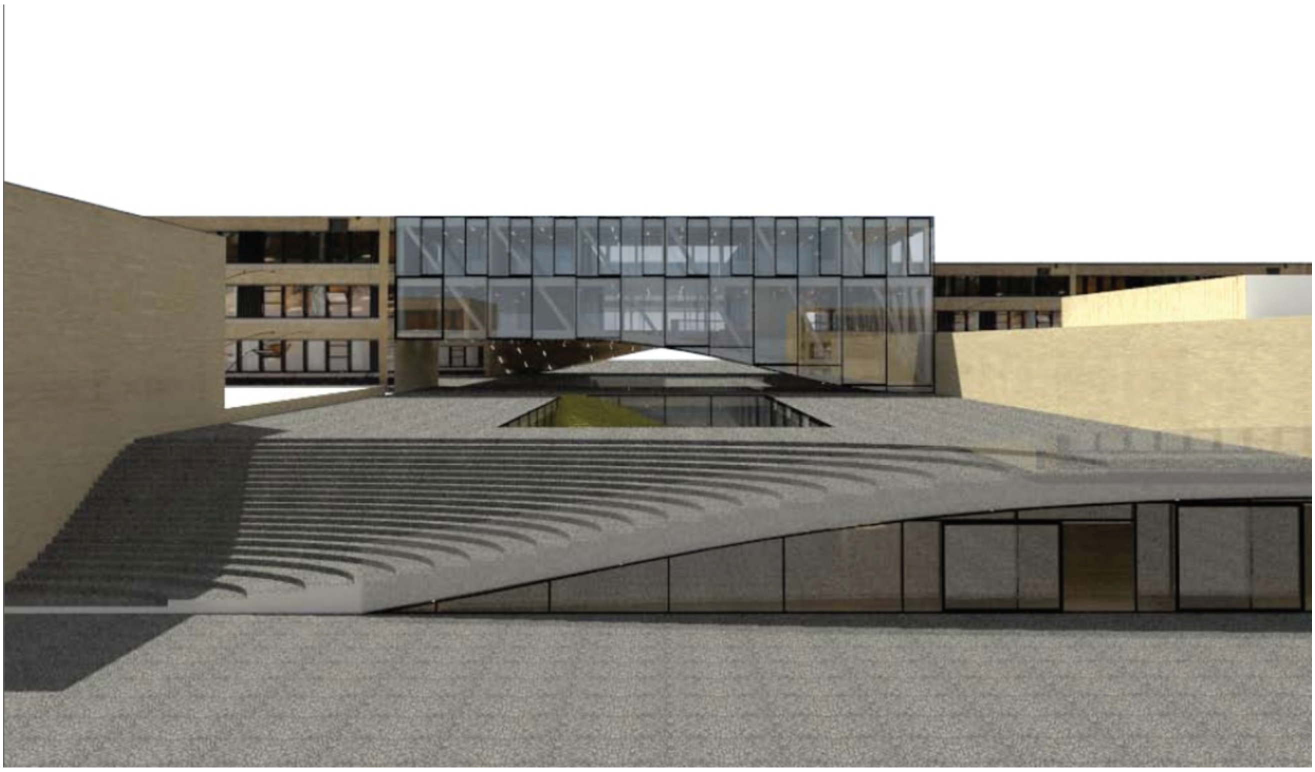
Building components

The main hindrance for reducing CO_2 emission producing domestic building components is the consideration of sound insulation. Danish authorities require a minimum insulation of 55 decibel (dB), for which you need a mass of 440 kg per m^2 separating deck or wall made of the same material. You can e.g. obtain that by:

- **A 190 mm massive concrete deck** of 55 MPa concrete giving **63.8 kg CO_2/m^2.**
- **A 220 mm hollow core slab** 55 MPa **with 55 mm top concrete** of 25 MPa concrete with and five pretensioned 12.5 mm wires per m giving **58.1 kg CO_2/m^2**.
- A **190 mm massive concrete wall** of 25 MPa concrete with two nets of 6 mm steel per 250 mm giving an emission of **42.0 kg CO_2/m^2**.
- A **900 mm massive wall of CLT** (Cross Laminated Timber): **224.4 kg CO_2/m^2**.

If you combine materials of different density and stiffness in a composite structure, you can reduce the total mass needed to 340 kg per m^2 for obtaining the 55 dB sound insulation. Here are some examples of that:

- A **180 mm super-light SL-dec**k **with 20 mm top concrete** uses the five pretensioned wires per m, 233 kg/m^2 strong concrete of 55 MPa, 58 kg/m^2 light concrete (700 kg/m^3), and 45 kg/m^2 **top concrete** of 25 MPa. It can obtain the 55 dB sound insulation with a total weight of 340 kg/m^2 giving an emission of **53.3 kg CO_2/m^2** or **47.5 kg CO_2/m^2** for the Danish 85% fossil free light aggregate.



Super-light proposal for DTU Building 324. Architect BIG, Engineer Werner Zobek

- A **180 mm sandwich wall** with 299 kg/m^2 strong concrete of 25 MPa and 35 kg/m^2 light concrete and two reinforcing nets gives **38.0 kg CO_2/m^2**.or **34.5 kg CO_2/m^2** for the Danish 85% fossil free light aggregate.

- A **CLT wall** as described by Ljunggren [9] is calculated and tested for 55 dB sound insulation with two slabs of 120 mm and 95 mm air or mineral wool between.
It has a minimal total weight of only 171 kg/m^2 and gives **87.4 kg CO_2/m^2**.

- **A 175 mm CLT deck with 110 mm top concrete.** One 5-layer CLT slab of 85.6 kg/m^2 and **254 kg/m^2 concrete** of 25 MPa gives **66.6 kg CO_2/m^2**.

Sand as sound insulator
340 kg per m^2 needed for composite sound insulation has been obtained by adding sand for example to a CLT deck. However, it gave practical problems with sand moving and even penetrating the structure, when the deck was subjected to oscillations.
Therefore, the contractors known to have applied it, now use a concrete topping instead.

Nevertheless, if you calculate this solution for a **5-layer CLT slab** of 86 kg per m^2 and **254 kg sand** per m^2, you find an impact of **43.7 kg CO_2/m^2**.
If you compare this with a **90 mm pre-tensioned slab of 55 MPa concrete** of 210 kg per m^2 and **130 kg sand** per m^2 the impact becomes **31.2 kg CO_2/m^2**.

District heating
Some calculations include a benefit when combustible materials are burned at the end of life stage and replaces fossil fuels like coal in the power plants producing district heating. Likewise, oven heat from production of cement or light aggregates contributes to district heating. This is only relevant, if the power plants are based on fossil fuels like coal and if you can foresee that they still will be that in at least 50 years' time from now. In most countries in the western world, this is not the case, and such contributions are not included in the numbers of these notes.

Waste fuel
It might be relevant to apply CO_2 numbers based on fossil free ovens for material production, if waste is applied as fuel or the ovens are heated electrically. In Denmark, waste at present replaces about 20% of the fuel for cement production and 85% of the fuel for light aggregate production. This is considered in separate CO_2 numbers in these notes in order to make them applicable elsewhere and to make them in accordance with databases like ÖkobauDat [7] and in order to avoid misinterpretations of the calculations.

References

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CO_2 Data

Materials
CO_2 emissions per 2020 from materials including a full life cycle with production, transport, building, application, demolition and removal.

Steel virgin from factory and wrought iron	2.80 kg CO_2/kg
Steel recycled	0.47 kg CO_2/kg
Steel profiles with average recycled content in Germany	1.00 kg CO_2/kg
Steel profile hot galvanized	1.85 kg CO_2/kg
Reinforcement with average recycled content	0.75 kg CO_2/kg
100 kg reinforcement in 2400 kg/m^3 concrete gives an addition of	0.03 kg CO_2/kg
Cement	0.90 kg CO_2/kg
Concrete 55 MPa	0.14 kg CO_2/kg
Concrete 25 MPa	0.09 kg CO_2/kg
Light concrete (600-900 kg/m^3)	0.27 kg CO_2/kg
Light concrete with 20% fly ash	0.24 kg CO_2/kg
Light concrete with 20% fly ash and 85% fossil free aggregates	0.14 kg CO_2/kg
Aerated concrete 480 kg/m^3 on aluminium powder	0.34 kg CO_2/kg
Timber	0.35 kg CO_2/kg
CLT Cross-Laminated Timber 489 kg/m^3	0.51 kg CO_2/kg
Laminated wood, plywood, chipboard 507 kg/m^3	0.52 kg CO_2/kg
Gypsum plaster board 630 kg/m^3	0.23 kg CO_2/kg
Brick 1800 kg/m^3	0.23 kg CO_2/kg
Glass 3 mm 2500 kg/m^3	1.37 kg CO_2/kg
Aluminium profile	10.93 kg CO2/kg
Mineral wool	1.60 kg CO_2/kg
Foam Plastic PE	6.13 kg CO_2/kg

Transport
0.008 kg CO_2 per kg for 1000 km ship deep sea container
0.016 kg CO_2 per kg for 1000 km ship short sea
0.031 kg CO_2 per kg for 1000 km barge
0.022 kg CO_2 per kg for 1000 km km rail
0.062 kg CO_2 per kg for 1000 km road
0.602 kg CO_2 per kg for 1000 km air

Energy
Diesel oil or Gas 0.24 kg CO_2/kWh = 0.067 kg CO_2/MJ.
Coal or Wood 16 *(MJ/kg) * 0.108 kg CO_2/MJ = 1.73 kg CO_2/kg

Building structures with **55 dB** sound insulation:

190 mm Massive concrete deck 55 MPa 440 kg/m^2.	**63.8 kg CO_2/m^2.**
220 mm Hollow-core + 126 kg 55 mm top concrete 440 kg/m^2.	**58.1 kg CO_2/m^2.**
180 mm SL-deck + **45 kg 20 mm top concrete**	**53.3 kg CO_2/m^2.**
180 mm SL-deck with 85% fossil free aggr + **20 mm top concrete**	**47.5 kg CO_2/m^2.**
220 mm SL-deck 360 kg/m^2. (makes 58 dB)	**59.7 kg CO_2/m^2.**
220 mm SL-deck with 85% fossil free aggregate	**52.6 kg CO_2/m^2.**
900 mm Massive CLT deck or wall 440 kg/m^2.	**224.4 kg CO_2/m^2.**
175 mm CLT deck 5-ply 86 kg/m^2 with **110 mm top concrete** ^{2}.	**66.6 kg CO_2/m^2.**
Steel deck 150 kg/m^2 with **290 kg top concrete** per m^2.	**303.6 kg CO_2/m^2.**
190 mm massive concrete wall 440 kg/m^2.	**42.0 kg CO_2/m^2.**
180 mm sandwich concrete wall 340 kg/m^2.	**38.0 kg CO_2/m^2.**
180 mm sandwich concrete wall with 85% fossil free aggr	**34.5 kg CO_2/m^2.**
CLT wall as tested 2x120 mm CLT+ 95 mm air 171 kg/m^2.	**87.4 kg CO_2/m^2.**

Orign of data
Anybody can look the presented data up in references like ÖkobauDat [7] or LCA Byg [8] and you would get almost the same data from other references like Hammond and Jones [5] or Ruuska VTT [6],

The data represent the full life cycle including the end of life stage, which is important for the impact on the climate. End of life is especially important for organic materials like wood that absorbs CO_2 when it grows, and releases it at the end of life.
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