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Influence of construction material choice and design parameters on greenhouse gas emissions of buildings

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Abstract: *Wood has typically lower environmental impacts compared to other materials. However, it also has reduced capacity to store thermal energy, potentially causing increased operating energy demand. Here we investigate this trade-off between environmental impacts of the construction and operating phase and examine key factors determining the overall environmental performance. To do so we couple a sophisticated building simulation with a life cycle assessment tool. We investigate a massive and a wooden variant of a single-family home. Sensitivity is analysed by altering ten different input parameters, using upper and lower extreme values. We find that the influence of building thermal inertia on annual energy demand is relatively small, but may become significant when the building service life is taken into account. In general, impacts from building operation outweigh material-related ones. Accordingly, parameters affecting energy demand (e.g. ventilation rate) are most influential. Since massive and concrete buildings react differently to changes in different parameters, we recommend individual design strategies for each building variant.*

Keywords: building simulation, thermal inertia, embodied energy, life cycle assessment, wood construction, sensitivity analysis

Introduction

Swiss policy makers are looking for ways to stimulate increased wood use in the construction sector. Some cantons even require planners to consider a wooden alternative, when tendering out public buildings. However, wooden buildings may have a reduced capacity to store thermal energy, which may counteract the ecological advantages of the construction phase.

Figure 1 illustrates the effect of thermal inertia for massive walls (left) and different coverings for a massive wall (right graph). Massive walls of 15 cm thickness have about four times higher areal heat capacity, compared to wooden walls.[1] This may result in increased space heat demand of wooden buildings, offsetting environmental benefits due to construction material. This paper illustrates the life cycle greenhouse gas emissions (GHG) of a wooden construction, compared to an equivalent massive building. Furthermore, we vary ten different parameters between upper and lower extreme values in order to analyse the sensitivity of each building type.

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[1] Areal heat capacity X_i is calculated based on ISO 13786 (T=24h, $R_{si/se}$=0.0). Material properties are according to EN 12524.

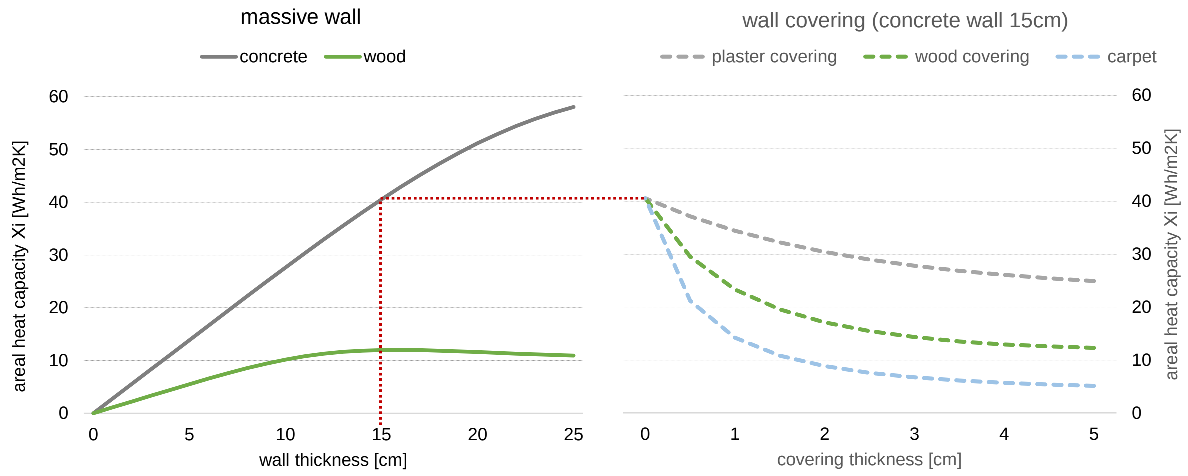

Figure 1 Thermal inertia of massive walls (left graph) for concrete (grey line) and wood (green line) and effect of wall covering (right graph). The red dotted line describes how thermal inertia of a 15 cm concrete element will change, when covered with different materials (dashed lines).

Method and model

To investigate the life-cycle implications of thermal inertia in building mass, a 200 m^2 single-family home (SFH) is modelled. The building is document in Müller et al. [1] along with four different construction variants (3 wood and 1 brick), typically found in recently built Swiss single family homes. For this analysis, the two extreme scenarios (in terms of thermal inertia) are used for the energy simulations. For the massive building, the exterior wall consists of 15 cm bricks, 18 cm thermal insulation, and interior plaster. The wooden exterior wall is more complex: interior plaster, vapour barrier, 22 cm thermal insulation (90%) / wood frame (10%) construction, medium density fibreboard, and a ventilated wooden façade. Furthermore, also roof, slab, and interior elements have different compositions in each variant. All other parameters, such as thermal transmittance (U-value), floor area, etc., are identical in the two variants. For both variants, input parameters are varied to investigate the respective sensitivities (see Table 1). The functional unit for the building variant comparison is “one single family home with 200 m^2 floor area and with a service life of 90 years”.

A newly developed program is used for the model calculations, using different software and Python modules, such as brightway2 [2]. Space energy demand is determined by an external dynamic simulation software (energyplus v8.1), using occupation and load profiles, as in the Swiss documentation SIA 2024 [3]. Loads from occupation, lighting and appliances are taken from the Swiss standard SN 520 380/1 (2009) [4]. The construction material accounted for is building envelope and interior walls for the entire building service life, including production, replacement, and disposal. Building foundation, roof covering, interior equipment, electrical and sanitary equipment are not included yet. Building service life and material replacement are based on SIA 2032 [2],[2] a documentation providing calculation guidelines on embodied energy in buildings. All life cycle inventories (LCI) either stem directly from the LCI-

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[2] Service life durations are not used directly, since they are described as “*payback periods*” and therefore assumed from an economical point of view.

database ecoinvent v2.2 [3] or are based on it. For material disposal the most adequate ecoinvent disposal process is selected for each material (i.e. normally "*...to sorting plant*"). In this study, results are provided in terms of greenhouse gas emissions [4][3] for energy demand and construction material, extrapolated to the building's entire life cycle.

Table 1 illustrates the scenarios and sensitivity parameters. The column with 'typical' values represents inputs of the two base cases. Each parameter is applied, for both extremes (lower and upper value), on both baseline scenarios, i.e. wooden and massive building variant. For each sensitivity parameter, only the parameter in question and the construction materials for each material variant are replaced. All other inputs remain as given in the column 'typical value' in Table 1.

Table 1 Overview of simulation input parameters, with lower, typical, and upper value for each sensitivity parameter

Parameter	**Indicator [unit]**	**Lower value**	**Typical value**	**Upper value**	**Impact on**	
					energy	**material**
Thermal inertia (baseline scenarios)	X_i [Wh/m^{2}K]	4.0 (wood frame)	none	12.3 (massive brick)	X	X
Climate data – Degree Days	$HDD_{20/12}$ CDD_{18} [Kd]	Lugano (2567 HDD, 281 CDD)	Zurich (3234 HDD, 148 CDD)	Davos (5864 HDD, 0 CDD)	X	-
Window ratio	% of façade area	10%	14 %	60%	X	X
Shading – window overhang	Length [m]	0.0	0.3	1.0	X	-
Ventilation rate	n [m^3/m^{3}h]	0.3	1.0	2.0	X	-
Internal load	[W/m^2] (mean)	6.8	2.9	14.6	X	-
Heat generation	energy carrier	Oil heating, non-condens.	Gas heating, condensing	Ground source heat pump	X	partly
Heating setpoint	T_h [°C]	17	20	23	X	-
Cooling setpoint	T_c [°C]	28	25	22	X	-
Thermal resistance	Insulation thickness [%]	50%	100%	200%	X	X
Window solar transmittance	g [-]	0.20	0.57	0.80	X	-

Results

Figure 2 illustrates the results of the sensitivity analysis as carried out using the parameters in Table 1. Results are presented here as total greenhouse gas emissions for material (production, replacement, disposal), space cooling and heating demand over the entire service life of the building. In the following section, results presented in Figure 2 are shortly described.

As can be seen in Table 1, the two **baseline scenarios** (low and high inertia), differ by a factor of three in their total areal heat capacity, i.e. X_i = 4.0 Wh/m^{2}K and X_i = 12.3 Wh/m^{2}K

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[3] IPCC 2007 100a [4]

respectively.[4] This difference in thermal inertia slightly influences the results in space heat demand. The lightweight variant has an increased annual space heat demand of 55 kWh/m^{2}a, compared to the heavyweight variant with 53 kWh/m^{2}a. Space cooling demand is in the wooden variant 13 kWh/m^{2}a, thus 28% higher than the massive variant with 10 kWh/m^{2}a. Analysis shows that it is in particular during the intermediate seasons (i.e. spring and autumn) that the high inertia variant has more autonomy, therefore requiring less thermal energy input to maintain the desired indoor temperature. However, the amount of embodied energy differs by a factor of two: 36 t CO_2-eq.and 72 t CO_2-eq. for the wooden and massive base scenario respectively (two left-hand bars in Figure 2). The total lifetime greenhouse gas emissions of the massive building is composed of the following: 72 tons (21%) materials, 11 tons (3%) cooling, and 265 tons (76%) heating. For the wooden scenario, the relationships change: 36 tons (11%) material, 15 tons (4%) cooling, and 275 tons (84%) heating. Thus, the wooden scenario yields an overall slight advantage of 7%, due to advantages in construction material. Total material mass of the wooden variant is approximately one third that of the massive building.

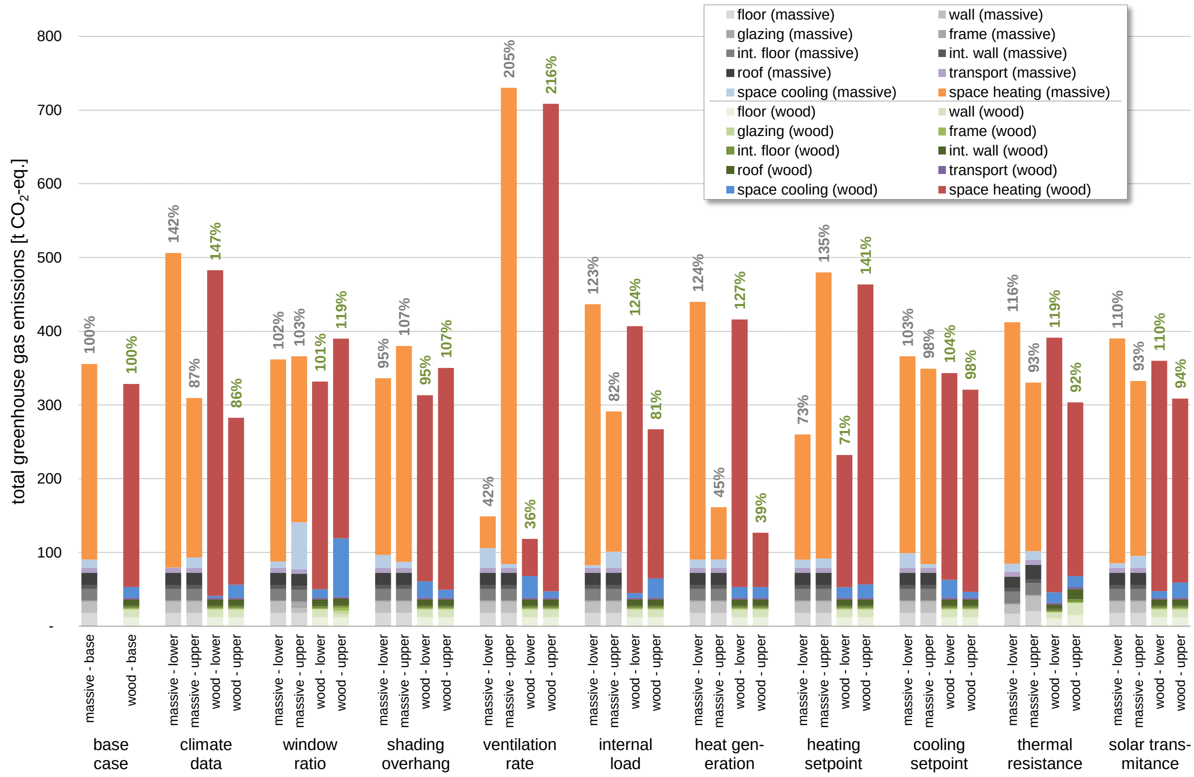

Figure 2 Total greenhouse gas emissions in tons CO_2-equivalents. Each bar represents one sensitivity run for material variant (massive and wood) and lower, upper value assumption as given in Table 1. Percentages above the bars relate to the respective base scenarios on the left-hand side (grey: massive, green: wooden).

The **climate data** has an important impact on the lifetime performance of both building types. The colder climate increases space heat demand to 86 kWh/m^{2}a (massive) and 89 kWh/m^{2}a

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[4] Areal heat capacity X_i is calculated based on ISO 13786 (T=24h, $R_{si/se}$=0.0). Material properties are according to EN 12524.

(wooden), respectively. In the colder climate of Davos, the massive building variant has practically no more space cooling demand. The warmer climate (Lugano) reduces space heat demand to 43 kWh/m^{2}a (massive) and 45 kWh/m^{2}a (wooden). Space cooling demand increases slightly for both the massive (25%) and wooden (19%) variant. Overall greenhouse gas emissions may increase by as much as 47%, this effect being more pronounced for the wooden building. In fact, this ‘upper’ scenario is the only parameter where total greenhouse gas emissions of the wooden scenario will surpass the ones of the corresponding massive scenario.

A change in **window ratio** has several effects, which partially cancel each other out. Therefore, only moderate changes in total greenhouse gas emissions are observed. Smaller window areas result in increased space heat demand (less solar gains), as well as in reduced cooling demand. Larger window surface actually reduces the material impact of the massive building by 2%, because of the relatively lower embodied energy in windows, compared to bricks. For the wooden building the opposite effect is observed – larger window surfaces result in increased overall material impact of 3%. These effects mostly compensate one another. Only the wooden building has significantly higher greenhouse gas emissions for the ‘upper’ scenario, due to increased space heat demand.

Window overhang (shading) has a similar effect. The more overhang depth (‘upper’ scenarios) a building has, the lower the solar gains, and accordingly the higher space heat demand will be. This is contrary to changes in cooling demand, i.e. the more overhang, the less cooling demand. Overall, smaller overhangs will have a slightly beneficial effect for both scenarios – at least for the (relatively moderate) climate of Zurich. Results would certainly be different in warmer climates. The material fraction of overhangs was neglected here.

Typically, the **ventilation / design flow rate** has an important effect on a building’s space heat demand, therefore also affecting greenhouse gas emissions (building life 90 years). It should be noted, that the ‘lower’ scenarios represent extremely energy-efficient buildings (ca. 10 kWh/m^{2}a, comparable to passive houses), since the base scenario already has very good thermal insulation. Relatively moderate changes in air change will result in an increase in total greenhouse gas emissions by a factor of two. The result is more pronounced for the wooden building, underlining the effect of thermal inertia. The more thermal mass a building has, the better it will be able to maintain the temperature during ventilation periods (e.g. window opening). In the case of cooling, however, this can be a disadvantage.

Internal load / gains also have an important effect on space heat and cooling demand. Low occupation and gains from appliances and lighting, will strongly affect space heat demand, resulting in approximately 20% increased greenhouse gas emissions. Highly occupied scenarios have very low space heat demand, but significantly higher cooling energy demand. The overall effect on greenhouse gas emissions was found to be in the range of ±20%, being slightly higher for the wooden variant.

The choice of (space) **heat generation** has an important effect on the overall greenhouse gas performance of buildings. Dated non-condensing oil-based burners have approx. 30% higher greenhouse gas emissions than the condensing gas boiler in the base scenario. The result in the 'upper' sensitivity parameter is also a result of the clean Swiss electricity mix, used to drive the heat pump. Lifetime greenhouse gas emissions are affected quite considerably (minus 60%), especially for the less CO_2-intense scenario of the heat pump. It is important to note that, at least in the case of the massive building, greenhouse gas emissions of materials become almost equally important as operating energy demand.

Heating setpoints, respectively indoor temperatures, influence space heat demand considerably. A reduced temperature of 17 °C (compared to 20 °C in the base scenario), will cut overall greenhouse gas emissions by approximately one fourth. 3 °C higher temperature leads to 35% (massive) and 41% (wooden) increased total emissions. The wooden building seems to react more to changes in this parameter, since often larger temperature swings occur. The 'upper' scenario also causes a considerable increase in cooling demand for the wooden building, since the wooden building generally has a higher tendency to overheat.

Analogously, the **cooling setpoint** affects space cooling demand by 2 to 4 percent, depending on the scenario. Accordingly, total emissions will be affected by 2-4%. Again, here the wooden building's tendency to overheat will make this effect more pronounced for the 'upper' wood sensitivity parameter.

Varying the **thermal resistance**, and consequently the amount of thermal insulation, will affect both scenarios similarly. Since the base scenario is already very well insulated, the effect on the 'upper' case is relatively small (8%). As seen for the parameter of ventilation rate above, energy efficiency measures usually have a slightly larger effect on the wooden case. These results indicate that savings in GHG emissions from space heating usually compensate impacts due to the additional insulation material – even in very efficient buildings.

The **solar transmittance** or heat gain coefficient (also g-value) shows similar effects, as observed for the window ratio or shading overhang, above. In addition, here the amount of solar gains increases with an increasing coefficient. At 6-10%, the overall effect is relatively small. However, it should be kept in mind that the base scenarios have a relatively low window ratio of 14%. Again, the wooden building exhibits significantly increased cooling demand. The material aspect of this parameter has been neglected here, although a change in g-value may be a result of the number of window panes.

Comparing the results for the different sensitivity parameters yields that impacts from energy demand are usually substantially more important during the building's lifecycle than from material. This is especially true for the wooden variant, which will therefore profit comparatively more from any reduction in energy demand. The material-energy relationship has been shown by several authors in recent years (e.g. [5], [6]). However, this trend is reversed and material impact becomes practically as important as operational energy consumption, when looking at extraordinarily energy-efficient buildings or buildings with clean energy production.

Discussion

We were able to investigate some important drivers for greenhouse gas emissions of wooden and massive buildings. As illustrated above, wooden / low inertia buildings have some particular properties, in terms of thermal behaviour and lifetime environmental impact. Therefore, it is important to pay special attention to those aspects when designing wooden buildings. In particular, aspects, such as, ventilation (airtightness) or overall energy demand should be considered more carefully when choosing low thermal inertia constructions. Since cooling demand tends to be high in wooden buildings, also good shading systems are important. Large window surfaces should be avoided for the same reason and due to the additional material impact. For massive buildings, special attention should be paid to the selection of the construction material, respectively its environmental impact. The results are mostly in line with the findings in similar studies. For example, Doodoo et al. [7] also find that the impact of difference in thermal inertia is relatively small and that, in contrast, the advantage due to the material component in wooden buildings is far more important. Here we show results only for one environmental impact indicator (i.e. greenhouse gas emissions). However, for other indicators the findings may differ considerably. For instance, when considering total cumulated primary energy (not presented here), the massive base variant performs slightly better than the wooden equivalent. We intend to consider further indicators in a future publication.

Outlook

The results, presented in this paper, represent the first findings of a parametric study. A journal publication will be submitted in the course of 2014 and include further parameters, as well as a numerical sensitivity analysis. Further aspects of building life cycle demand (such as service life, transport, hot water demand, electricity demand and mix, material disposal) will most likely have similar impact on the building's lifetime performance.

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