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# Environmental Impact of Buildings—What Matters?

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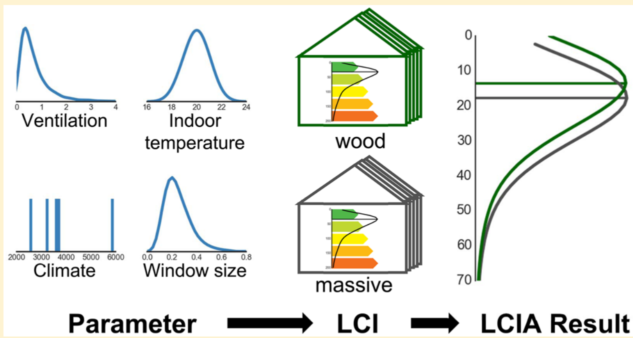
Supporting Information

**ABSTRACT:** The goal of this study was to identify drivers of environmental impact and quantify their influence on the environmental performance of wooden and massive residential and office buildings. We performed a life cycle assessment and used thermal simulation to quantify operational energy demand and to account for differences in thermal inertia of building mass. Twenty-eight input parameters, affecting operation, design, material, and exogenic building properties were sampled in a Monte Carlo analysis. To determine sensitivity, we calculated the correlation between each parameter and the resulting life cycle inventory and impact assessment scores. Parameters affecting operational energy demand and energy conversion are the most influential for the building's total environmental performance. For climate change, electricity mix, ventilation rate, heating system, and construction material rank the highest. Thermal inertia results in an average 2–6% difference in heat demand. Nonrenewable cumulative energy demand of wooden buildings is 18% lower, compared to a massive variant. Total cumulative energy demand is comparable. The median climate change impact is 25% lower, including end-of-life material credits and 22% lower, when credits are excluded. The findings are valid for small offices and residential buildings in Switzerland and regions with similar building culture, construction material production, and climate.




## ■ INTRODUCTION

The environmental impact of buildings is mostly dominated by the use phase, i.e. the energy demand for operation.[1−3] However, construction material impact (embodied impact) moves into focus due to the strict legislation and the efforts of governments and house owners to construct increasingly energy efficient buildings.[4−6] The choice of constructional material influences the operational energy demand of buildings. This is due to the differences in physical properties, such as thermal inertia or resistance. The capacity to store thermal energy over time differs greatly for different materials. For instance, wooden exterior walls may have one-third of the active thermal mass in comparison to brick or concrete walls, depending on the composition. This difference may result in an increased space heat and cooling demand.[7−10] The influence of thermal mass on the heat balance depends on several factors, such as the climatic conditions at the building location.[11] For example, Aste et al. found differences in space heat demand of about 10%, while Dodoo et al. reported only a minor increase of approximately 2%.[8,11] Despite the increased operational energy associated with wood as a construction material, it often displays a reduced environmental impact over its entire life cycle, depending on the end-of-life scenario.[12,13] Evidently, a tradeoff between material choice and building energy demand exists. Dodoo et al. investigated this issue by comparing a massive concrete and wooden variant of a single family home for Swedish climatic conditions and conclude that the lower material impact of the timber-frame variant outweighs the disadvantage of the reduced thermal mass.[11] In addition to conventional LCA studies, a number of studies have carried out sensitivity analyses for the energy performance of buildings.[1−3,14−18] However, none of these publications investigate the role and sensitivity of thermal inertia, nor do they quantify the influence of parameters on environmental impacts.

The goal of this paper is to (1) compare environmental performance of wooden and massive buildings for moderate central European climates, taking into account thermal inertia among others, (2) identify key drivers of environmental impact of buildings, and (3) perform a comprehensive sensitivity analysis.

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## METHODOLOGY

**LCA Modeling.** To investigate thermal inertia and parameter influence on the environmental impact of buildings, we performed a life cycle assessment (LCA) for total lifetime material and energy demand of parametric buildings.

The building's entire service life was considered, including material demand for construction, operation, renovation, and deconstruction as well as energy demand for building operation. Building inventories include the production of materials, transport, renewal, and disposal. Electricity demand for lighting and appliances was considered. User-specific equipment, such as furniture or technical installations, as well as construction work was omitted. Since the building model is parametric, it can either represent residential or office buildings. It uses varying inputs, such as building size, service life, and occupation, typically found in either occupation type. Functionality of wooden and massive variants is mostly identical; however some aspects, such as noise or fire protection, were not considered. The geographical system boundary was Switzerland. The functional unit was "1 square meter of conditioned floor area averaged for 1 year of service life."

The building model is parametric and based on recent single-family home constructions in Switzerland. The publication by Müller et al., describing a typical building floor plan, envelope composition, building size, and window ratio, was used as a basis.[19] The original building model has two stories, a rectangular shape, a flat roof and no basement floor. For the analysis, always two material variants of the building were generated, i.e. wood and massive. Therefore, thermal storage capacity and material inventories differed. All other characteristics, such as thermal transmission ($U$ value), surface area, volume, window size, etc., were always identical in both variants. Building foundations (concrete strip foundation), concrete reinforcement, and internal walls were included.[20,21] We used LCI data sets from the ecoinvent v3.1 database (allocation cutoff) for production and end-of-life processes.[22] Life-cycle inventories and material service life are documented in section 1 of the Supporting Information (SI).

Building operation included material renewal, space heating and cooling energy, electricity, lighting, as well as domestic hot water demand. Energy generation was included by means of the ecoinvent data sets for heat production. On-site energy distribution and storage were omitted. Energy and material use was accumulated over the buildings' service life, constituting the life cycle inventory (LCI).

Space heat and cooling demands were modeled by means of EnergyPlus v8.1 (CTF algorithm), a dynamic whole building energy simulation program.[23] The software is capable of accounting for the difference in thermal inertia of the two different wall types concrete and wood ($X_i$). By means of the Monte Carlo simulations, a 2 min simulation time step was determined to be a good tradeoff between calculation time and precision.

Electricity (appliances, lighting) and hot water demand were considered on a per capita basis or per square meter basis. Reference values from the Swiss Standards SN 520 380/1 and SN 520 380/4 were used.[24,25] Lighting demand was coupled with the daylight illuminance calculation in energyplus and controlled by the lighting demand parameter. In order to compare the wooden and massive variant only the material composition and the resulting capacity to store thermal energy ($X_i$ [Wh/m$^2$ K]) differ. For both variants, the building envelope's thermal resistance (or heat flow $U$ [W/m$^2$ K]) was kept constant, by adjusting thermal insulation.

Material disposal was handled for each material individually (see SI Table S1). System expansion was applied for the recycling and thermal treatment of wood-based materials as well as for concrete and bricks. All other materials were either identical for both variants (e.g., windows), had no significant end-of-life (EOL) phase, or already included a recycled content in their inventory. Benefits from material substitution were applied with an expected material recovery rate and their marginal products. That means 1 kg of concrete substitutes 0.95 kg of primary gravel.[26] The thermal use of wood-based products considers the material's respective lower calorific value and recovery rate, as well as the combustion plant's efficiency. It was assumed that the final disposal of burnable construction waste is handled in municipal solid waste incineration plants, which in Switzerland have average annual conversion efficiencies of 13.2% and 24.6% for electricity and heat production, respectively.[27] As a substitution product for energy from waste incineration, Swiss national low-voltage electricity mix and heat from a natural gas boiler were assumed.

The resulting inventories were assessed for the life cycle impact assessment (LCIA) methods of total Cumulated Energy Demand (CED total), climate change IPCC 2013 100 year time horizon (GWP), and respiratory effects due to particle formation from ReCiPe midpoint H (particulate matter).[28−30] The SI additionally provides results for ReCiPe (H,A) midpoints and end point, nonrenewable Cumulated Energy Demand (CED nonren) and ecological scarcity 2013.[28,30,31] Brightway2 was used as the LCA software.[32]

**Sensitivity Analysis.** For the Monte Carlo analysis, building input parameters were randomly sampled. Each input parameter was assigned a realistic value range and probability density function (Table 1). Both are based on the literature, if available, or the authors' assumptions. The random parameters either relate to material (e.g., thermal resistance, window transmittance), design (e.g., window size, occupancy, shading), operation (e.g., ventilation, indoor temperature), or exogenic factors (e.g., climate, energy mix). The inputs were chosen so that they are representative for newly built Swiss constructions with different occupations. The bounds were based on recent Swiss residential buildings and standard values from the Swiss standard on thermal energy demand of buildings.[19,24,33] Other parameters (e.g., internal loads, occupation) were based on literature values (see "Source" in SI Table S1). For some parameters, no literature values were available. In these cases, we made conservative assumptions concerning the value range. Additional research was done for parameters that turned out to be influential in the sensitivity analysis. The location parameter $\mu$ (or mode $c$ for triangular) in Table 1 was chosen in a way that the median corresponded to the parameter's typical value. The scale parameter $\sigma$ (limits $a$, $b$ for triangular) was chosen, so that the 99.7th percentile ($3\sigma$) corresponded to the assumed extreme values. In the event of outliers (i.e., $>3\sigma$) which could result in erroneous simulation input files, the 99.7th percentiles also act as cutoff values.

From the parameters in Table 1, 4500 random samples were generated and translated into both a wooden and a massive building variant, which were subsequently evaluated for energy (thermal simulation) and material demand, as well as environmental impact. To compare the two building variants, we calculated the ratio of demand parameters and impact


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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Table 1. Overview of Boundary Values/Sensitivity Inputs (Parameters Are Varied Individually and Independently) for the Single-Family Home[a]

| | parameter, indicator [unit] | distribution | scenario range | | description, source |
|---|---|---|---|---|---|
| **material** | construction material, areal heat capacity [Wh/m² K] | n/a | brick (12.3 Wh/m² K), wood (4.0 Wh/m² K) | | Müller et al., see SI 1.[19] No sampling since both variants are generated for each iteration. Areal heat capacity $X_i$ is calculated based on ISO 13786 ($T$ = 24h, *Rsi/se* = 0.0).[34] Material properties are according to ISO 10456.[35] |
| | thermal resistance of building envelope insulation, $\lambda$ value [W/mK] | lognormal* | $\mu = -3.219$<br>$\sigma = 0.280$ | Mdn: 0.04<br>95% CI (0.023, 0.069) | Lower value according to best available technology (e.g., aerogel) $\lambda$ = 0.02 W/mK, resulting in ca. $U$ = 0.17 W/m² K. Upper based on comfort criterion in, i.e. $U$ = 0.40 W/m² K.[36] Average heat demand results are below legal threshold.[24] The $U$ value cannot be influenced directly in the simulation software. Therefore, the thermal resistance ($\lambda$) of the insulation layer is varied. The resulting $U$ value is always identical for the wooden and massive variant. |
| | solar factor, $g$ value [−] | triangular | $a$ = 0.20<br>$b$ = 0.70<br>$c$ = 0.57 | Mdn: 0.50<br>95% CI (0.27, 0.67) | Ratio of light energy received/transmitted at a window. Assumption based on current glazing products. $c$ corresponds to typical 2-pane glazing. |
| | building service life [−] | lognormal | $\mu = 4.499$<br>$\sigma = 0.491$ | Mdn: 90<br>95% CI (34, 236) | Swiss recommendation uses 60 years as reference.[37] We assume 90 as base, 400 years as upper limit. |
| | material service life, multiplier [−] | lognormal | $\mu = 0.405$<br>$\sigma = 0.298$ | Mdn: 1.50<br>95% CI (0.84, 2.69) | Multiplier for the use-specific service life as in the Swiss recommendation.[37] Mdn value is increased by a factor of 1.5, since original values seem low, compared with other literature.[38,39] See also SI section 1.3. |
| | transport, distance [km] | lognormal* | $\mu = 3.912$<br>$\sigma = 0.768$ | Mdn: 50<br>95% CI (11, 225) | Transport distance for production and disposal of all materials. Assumption based on ref 40. Upper limit 500 km. Lower cutoff 10 km. |
| **design** | building size, building width [m] | discrete uniform | 5.6, 11.2, 16.8, ..., 67.2 | | Assumption. Multiples of reference building width.[19] |
| | window ratio, window/façade area [−] | lognormal* | $\mu = -1.478$<br>$\sigma = 0.438$ | Mdn: 0.228<br>95% CI (0.097, 0.538) | Ratio window/wall surface. Assumption based on literature.[19,33] Upper bound 0.80. |
| | shading − window overhang length [m] | lognormal | $\mu = -1.897$<br>$\sigma = 0.864$ | Mdn: 0.15<br>95% CI (0.02, 0.94) | Overhang above windows. Assumption. Base value: window frame/façade. Upper value: large balcony 2.5 m |
| | night setback temperature $\Delta T$ [K] | normal | $\mu = 2.00$<br>$\sigma = 0.33$ | Mdn: 2.00<br>95% CI (1.34, 2.65) | Reduction of indoor heating setpoint temperature between 23:00 h and 6:00 h. |
| | thermal energy generation, system [kg $CO_2$-eq./kWh] | discrete uniform | brine-water heat pump, air-air heat pump; oil boilercondensing;gasboilercondensing;pelletboiler | | Systems and data based on ecoinvent.[22] |
| **operation** | ventilation, air change rate [m³/m³h] | lognormal* | $\mu = -0.638$<br>$\sigma = 0.821$ | Mdn: 0.53<br>95% CI (0.11, 2.64) | Based on literature.[41,42] No heat recovery applied. |
| | Heating setpoint, temperature, [°C] | normal* | $\mu = 20.0$<br>$\sigma = 1.0$ | Mdn: 20.0<br>95% CI (18.0, 22.0) | Indoor temperature lower threshold. Assumption based on literature.[43,44] Upper cutoff at 23.0 °C. Cut-off values in place to avoid overlapping heating and cooling setpoint temperatures. |
| | cooling setpoint, temperature [°C] | normal* | $\mu = 24.5$<br>$\sigma = 1.0$ | Mdn: 25.0<br>95% CI (23.0, 27.0) | Indoor temperature upper threshold. Assumption based on EN 15251.[43] Lower cutoff at 23.0 °C |
| | occupation density, thermal load [m²/P] | normal* | $\mu = 60.0$<br>$\sigma = 13.3$ | Mdn: 60.0<br>95% CI (33.9, 86.10) | Building occupation (surface per capita). Based on Swiss standard.[24] |
| | lighting load, heat gains [W/m²] | normal* | $\mu = 9.40$<br>$\sigma = 2.17$ | Mdn: 9.4<br>95% CI (5.2, 13.6) | Electrical power of lighting installation. Based on SIA 2024.[45] |
| | internal load, heat gains [W/m²] | lognormal | $\mu = 0.693$<br>$\sigma = 0.418$ | Mdn: 2.0<br>95% CI (0.9, 4.5) | Electrical power of electrical appliances. Based on SIA 2024.[45] |
| | daylight illuminance setpoint [lx] | lognormal | $\mu = 5.298$<br>$\sigma = 0.337$ | Mdn: 200<br>95% CI (103, 387) | Lighting demand in lux during daylight availability (switching rule). Based on Swiss standards.[25,45] *M*: residential case, upper 99.7 percentile: office case + 10% (i.e., 550 lx). |
| | building occupation, schedule [P/$h_i$] | discrete uniform | residential, office | | Schedule specifying occupants presence and electricity demand. Official Swiss residential and office occupation schedules as in SIA 2024.[45] Schedules are normalized to give equal (diurnal) energy demand. |
| | hot water demand [kWh/P] | triangular | $a$ = 250<br>$b$ = 4000<br>$c$ = 3000 | *Mdn*: 2521 *95% CI* (758, 3694) | Based on standard values.[24] |

Table 1. continued

| | parameter, indicator [unit] | distribution | scenario range | description, source |
|---|---|---|---|---|
| | shading control | discrete uniform | always off, on if outdoor temperature ≥ 22 °C | Operation of exterior window shading device. Assumption |
| exogenic | climate, climate station [heating, cooling degree days] | discrete choice | Bern (3600, 75), Glarus (3708, 64), Lugano (2567, 281), Zurich (3234, 148), Davos (5864, 0) | Climate data (solar irradiation, outdoor temperature, etc.) for energyplus simulation. Using extreme climate stations throughout Switzerland. Data: Meteonorm.[46] Heating and cooling degree days are calculated according to SN 565 381−3:1982.[47] |
| | electricity mix, data set [g $CO_2$-eq./kWh] | *discrete choice* | CH mix (114), CH mix label-certified (14), ENTSO-E 2009 (459), gas power plant (747) | Assumption. data: ecoinvent.[22] ENTSO-E mix based on data from European Network of Transmission System Operators for Electricity 2009. |

[a] $\mu$ and $\sigma$ are the location and scale parameters. Mdn is the median and 95% CI the 2.5th and 97.5th percentile (enclosing the 95% confidence interval). The asterisk * denotes that a cut-off applies.

scores. This procedure ensured that uncertainty applying to both alternatives canceled out and that, accordingly, the difference between both variants was quantified under comparable conditions. For example, there was considerable variation in user behavior (e.g., heating setpoint), but the same user would probably make the same choice independent of whether they lived in a wooden or massive building.

To ensure that results converge, the number of iterations was determined in a preliminary screening phase. During the screening, other parameters, such as temporal resolution or shading material, were also tested. However, they showed negligible influence on the results and were therefore not included in the study.

Monte Carlo results were analyzed for the rank order correlation between each input parameter and the respective result vector (heating, cooling, electricity, and mass demand as well as LCIA scores). Since data were often not normally distributed, the Kendall Tau-b ($\tau$) was chosen as coefficient.[48] Results are illustrated as correlations (Table 3). Greater numbers indicate a stronger relationship between the parameter and the result. Positive coefficients indicate that an increase of a parameter will cause an increase in the respective demand or result score. Vice versa, negative coefficients will have a beneficial effect. Furthermore, results are ranked by their absolute correlation value. Results with low statistical significance ($p$ value below 0.01) were omitted.

## ■ RESULTS

**Model Results.** For CED nonren and climate change impacts, the wooden variant performs better in more than 95% of the simulations (Figure 1), while the results for the other environmental impacts are less significant. Results for energy and material demand (Figure 1) are within the ranges of typical Swiss new buildings and mostly compliant with legal requirements.[24,45] Space heat represents the largest energy demand fraction (Table 2). The effect of material choice is visible for thermal energy demand (thermal inertia), as well as material mass demand. SI section 2.2 provides further detail on the effect of thermal inertia, including hourly simulation results (Figure S2). Electricity and hot water demand are not affected. Space heat demand of the massive variant is lower (Figure 1 and ratios in Table 2, last two columns). Space cooling demand results have a large range with Mdn = 0.39 and 95% CI [0.00, 1.00]. This is mostly because the massive variant often has little to zero cooling demand. Material mass is approximately half for the wooden variant.

LCIA results are mostly in favor of the wooden variant. CED nonren score is lower (*Mdn* = 1.30), while CED total is practically identical. Global Warming results are around one-fourth lower (*Mdn* = 1.26). Particulate matter emissions are approximately 6% lower. Compared to the concrete credits, those for the wooden variant are significantly higher (Table 2), due to the higher use of the waste wood (thermal use).

Figure 1 (bottom) illustrates total results for the case of climate change scores in more detail. Typically, energy demand dominates the climate change results for the wooden variant. In the massive variant, greenhouse gas emissions due to material are often more important than emissions caused by heating demand.

**Sensitivity Analysis.** Correlations between input parameters and demand, as well as input parameters and impact score, are shown in Table 3. The results are subdivided into wooden and massive building variants, in order to identify differences in



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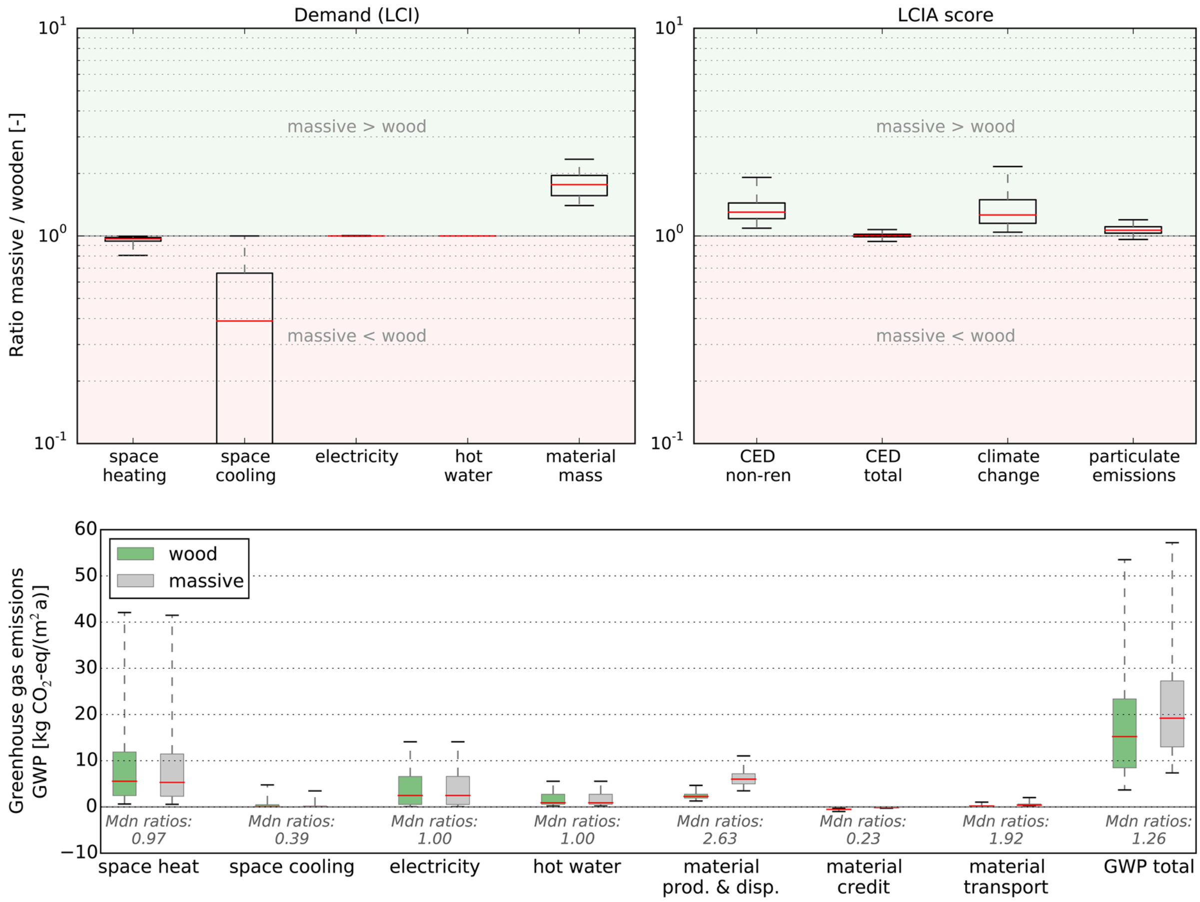


**Figure 1.** Top: Ratio between wooden and massive variant (i.e., massive results divided by wooden result). Demand (LCI scores) is to the left and LCIA scores to the right. Zero/zero divisions are evaluated with 1 as a result. Bottom: climate change results per demand category. Material EOL credits are included, and outliers are excluded. Red dash, median; box, 1st and 3rd quartile. Whiskers correspond to the 95% confidence interval. Additional results are provided in SI 3.

**Table 2. Demand (Energy and Material) and LCIA Score Median Results for Each Building Variant ($n$ = 4500) per Square Meter and Year[a]**

| | | wood variant | | massive variant | | massive/wood | |
|---|---|---|---|---|---|---|---|
| output | unit | result | credit | result | credit | Mdn | 95% CI |
| space heat demand | kWh/m$^2$a | 48.1 | n/a | 46.1 | n/a | 0.969 | [0.805, 0.997] |
| space cooling demand | kWh/m$^2$a | 1.9 | n/a | 0.6 | n/a | 0.389 | [0.000, 1.000] |
| electricity | kWh/m$^2$a | 11.6 | n/a | 11.6 | n/a | 1.000 | [1.000, 1.000] |
| hot water demand | kWh/m$^2$a | 11.4 | n/a | 11.4 | n/a | 1.000 | [1.000, 1.000] |
| material demand | t/m$^2$a | 3.8 | −6.2 | 6.8 | −12.9 | 1.767 | [1.401, 2.341] |
| | | | | | | | |
| CED nonrenewable | kWh-eq./m$^2$a | 119.5 | −14.7 | 158.5 | −2.3 | 1.302 | [1.090, 1.915] |
| CED total | kWh-eq./m$^2$a | 187.5 | −16.0 | 191.1 | −2.3 | 1.004 | [0.941, 1.073] |
| climate change | kg $CO_2$-eq./m$^2$a | 15.2 | −0.5 | 19.3 | −0.1 | 1.262 | [1.043, 2.159] |
| particulate matter | g PM10-eq./m$^2$a | 25.9 | −0.5 | 27.7 | −0.4 | 1.066 | [0.962, 1.196] |

[a]Results include all life phases (construction, renewal, and disposal). End of life credits are included and declared separately in the "credit" column. The last column gives the median and 95% CI of massive and wood ratios (EOL credits included). Additional results in SI 3.2.

the parameter influence. SI 4 provides additional LCIA scores for CED nonren, ecological scarcity, and ReCiPe, as well as correlations for the wood/massive result ratio.

The parameters with the largest influence on space cooling demand are window ratio, climate, and ventilation rate. All of these factors have a strong influence on the solar gains received in the building. Climate and ventilation rate also determine the heat accumulation in the building. As seen in Figure 1, construction material greatly determines cooling demand. Most parameters have a similar influence on space cooling demand of the two material variants. However, the massive building is more susceptible to extended periods of high exterior temperature, which will continuously charge the building's thermal mass, which, in turn, is why the correlation score is higher for climate (Table 3 and SI 2.2).

Space heat demand has by far the highest correlation with ventilation rate ($\tau \approx 0.71$), since air exchange is an important means of thermal energy transport. Further relevant parameters


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are climate data ($\tau \approx 0.15$), thermal resistance ($\tau \approx 0.12$), heating setpoint ($\tau \approx 0.10$), and night setback ($\tau \approx -0.10$). Comparing the two variants, the parameter correlations are very similar for both. However, they cannot be compared directly. Section 4.1 of the SI provides correlations with result ratios massive/wood, where it is evident that variations in ventilation rate and internal load cause the largest differences in space heat demand.

Electricity demand correlates the most with occupation schedule ($\tau = 0.65$). This is due to the daylight lighting control algorithm. The office-building schedule has highest occupation during daytime and therefore highest benefits. In second and third rank are internal and lighting load, both being a direct consequence of the parameter sample. In fourth rank is window ratio, which strongly affects daylight availability.

Material demand is mostly determined by building service life and type of construction material. The wooden building variant has on average 50% lower material mass (see Figure 1) but more material renewal during its life phase. This is why building service life is more important for the wooden variant ($\tau = -0.73$ as opposed to $\tau = -0.48$ for the massive variant). Material service life is ranked third for both variants, while the correlation is twice as high for the massive variant. The parameter building size is ranked fourth in both cases, illustrating the saving potential of building compactness.

As expected, transport distance, thermal generation, hot water demand, electricity mix, material, and building service life show no correlation with energy demand, since they have no influence on its calculation. Likewise, material demand is not influenced by building operation parameters, such as occupation or ventilation rate.

**Life Cycle Impact Assessment, LCIA.** CED nonren (SI Table S9) shows the strongest correlation with space heat demand ($\tau \approx 0.34$). Therefore, the same parameters influencing space heat demand will have high impact on this LCIA score. Consequently, ventilation rate is the dominant factor for CED nonren. Construction material plays the second biggest role, due to the different amounts of embodied energy. The heat generation technology scores similarly and is mostly due to the large difference in CED nonren content between pellet and fossil-based systems. CED total shows quite a different picture, compared to the nonrenewable fraction. Both correlations and ranks differ greatly, because renewable and nonrenewable CED fractions mostly show opposing correlations, canceling each other out (SI 4). Only for ventilation rate and service life do the two subindicators coincide, giving a more pronounced result. This also explains why no correlation with the parameter construction material exists in Table 3 and why the CED total scores in Figure 1 are almost identical. Moreover, the correlation with electricity mix is relatively weak.

The climate change scores have a similar trend as the CED nonren results. However, the ranks differ. The most important parameter here is the electricity mix with $\tau \approx 0.3$, caused by significant differences in $CO_2$ intensity (see Table 1). The following ranks essentially follow the trend of CED nonren: ventilation rate, heat generation, and construction material.

Particulate matter formation is mostly influenced by the heat generation system, with the pellet heating system having the highest impact. In the second rank is ventilation rate. The third and fourth ranks are occupied respectively by electricity mix and building and material service life.

The other fully aggregating methods, documented in SI 4.2, show similar trends as CED nonren and climate change.

A number of parameters are significant for the demand results but have little to no correlation with the LCIA result. This mostly occurs when two or more demands show opposing signs, i.e. impact. For instance, adding thermal insulation will increase material demand and at the same time reduce space heat demand. Energy saving comes with the "cost" of increased material impact. The two demand categories will partly compensate for one another, and consequently, impact score correlations are low. Further examples are window ratio, shading, and solar factor, for all of which cooling is opposed to heating demand.

The lower part of Table 3 shows the correlation between demand (LCI) and LCIA score. For all impact indicators, space heat demand has the strongest correlation with the LCIA scores. In the second rank is material demand, with the exception of climate change impacts in the wooden variant. There, cooling demand comes in second, since the correlation with material demand is very low ($\tau = 0.06$ as opposed to $\tau = 0.14$ in the massive variant). Cooling demand usually ranks third, with a negative correlation. The difference between ranks one and two for climate change and CED nonren is more pronounced in the wooden variant.

The parameters are grouped into material, design, operation, and exogenic (Table 1). The material related properties play an important role. From this group, the choice of construction material is generally the most important (except CED total). Both material service life (the parameter determining material renewal intervals) and building service life (operation phase duration), have a large effect on material demand. This is especially the case for the wooden variant and building service life, since (according to SIA 2032) the material renewal intervals are short (SI 1.4).[37] The massive building has higher overall material impact and therefore profits more from longer building and material service life. Material transport distance usually has a relatively small influence on the LCIA result, affecting the massive building substantially more, due to its high mass.

The building design parameter group appears to be relatively influential for all results. Considering climate change and CED nonren for the wooden and massive variant respectively, the second and third most important parameter overall is heat generation with similar correlation as ventilation rate. However, for particulate matter the sign is reversed, since pellet heating systems have low carbon, but extensive particle emissions. Moreover, building density (size) is among the higher ranking parameters and will affect all demand and result vectors positively, except for electricity, due to increased lighting demand. In particular, cooling demand is reduced, due to the lower solar gains per floor area. Heat demand is reduced due to lower thermal transmission losses per floor area.

Most parameters categorized as "occupation" have a relatively low impact on energy demand and negligible impact on the LCIA scores. However, ventilation rate ranks first or second for most impact scores. Since it is by far the main driver for space heat energy demand and the third most important parameter for cooling demand (see Table 3), ventilation rate can be considered a proxy for energy demand. Other parameters in this category have much lower influence. Occupation schedule has a strong influence on electricity demand and therefore ranks relatively high. The choice of heating setpoint ranks fourth for space heat demand. However, it plays a rather subordinate role for LCIA scores, as all other occupation parameters do.


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Table 3. Kendall $\tau$ Correlation for Each Input Parameter (row) and LCI and LCIA Scores (column)[a]

| | Result / Parameter | Demand (LCI) | | | | | | | | Impact (LCIA) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Space cooling | | Space heat demand | | Electricity demand | | Material demand (mass) | | CED total | | GWP | | Particulate matter | |
| | | wood | massive | wood | massive | wood | massive | wood | massive | wood | massive | wood | massive | wood | massive |
| material | Construction material | -0.183 (7) | 0.183 (5) | -0.023 (10) | 0.023 (12) | | | 0.560 (2) | -0.560 (1) | | | 0.167 (4) | -0.167 (4) | 0.063 (8) | -0.063 (7) |
| | Thermal resistance | 0.028 (13) | 0.036 (13) | -0.124 (3) | -0.118 (3) | | | 0.093 (5) | 0.073 (5) | -0.036 (16) | -0.026 (17) | | | | |
| | Solar factor | 0.194 (4) | 0.179 (6) | -0.076 (7) | -0.084 (7) | | | | | -0.036 (14) | -0.049 (13) | -0.036 (10) | -0.044 (9) | | -0.029 (13) |
| | Building service life | | | | | | | -0.731 (1) | -0.487 (3) | -0.145 (3) | -0.151 (3) | -0.041 (9) | -0.075 (6) | -0.120 (4) | -0.157 (4) |
| | Material service life | | | | | | | -0.215 (3) | -0.488 (2) | -0.151 (2) | -0.165 (2) | | -0.088 (5) | -0.116 (5) | -0.133 (5) |
| | Transport distance | | | | | | | | | 0.044 (13) | 0.083 (7) | | | | 0.036 (11) |
| design | Building size | -0.186 (6) | -0.162 (8) | -0.038 (8) | -0.032 (10) | | | -0.108 (4) | -0.080 (4) | -0.125 (4) | -0.099 (6) | -0.046 (5) | -0.053 (7) | -0.084 (7) | -0.051 (8) |
| | Window ratio | 0.324 (1) | 0.274 (1) | | -0.038 (8) | -0.096 (4) | -0.096 (4) | | | | | | | | |
| | Window overhang | -0.109 (9) | -0.094 (10) | | 0.029 (11) | 0.036 (7) | 0.036 (7) | | | | 0.027 (16) | | | | |
| | Night setback temp | | | -0.097 (5) | -0.094 (5) | | | | | -0.077 (8) | -0.074 (10) | -0.036 (11) | -0.035 (12) | -0.048 (10) | -0.044 (10) |
| | Thermal generator | | | | | | | | | -0.026 (17) | | -0.198 (3) | -0.192 (3) | 0.349 (1) | 0.342 (1) |
| operation | Ventilation rate | -0.204 (3) | -0.220 (3) | 0.714 (1) | 0.712 (1) | | | | | 0.483 (1) | 0.481 (1) | 0.256 (2) | 0.252 (2) | 0.276 (2) | 0.277 (2) |
| | Heating setpoint | | | 0.101 (4) | 0.098 (4) | | | | | 0.079 (7) | 0.075 (8) | 0.034 (12) | 0.033 (14) | 0.049 (9) | 0.045 (9) |
| | Cooling setpoint | -0.164 (8) | -0.167 (7) | | | | | | | | | | | | |
| | Occupation density | | | | | | | | | -0.055 (11) | -0.055 (12) | -0.032 (13) | -0.034 (13) | | |
| | Lighting load | 0.036 (12) | 0.039 (12) | -0.032 (9) | -0.032 (9) | 0.213 (3) | 0.213 (3) | | | 0.036 (15) | 0.034 (15) | | | | |
| | Internal load | 0.045 (11) | 0.046 (11) | | | 0.278 (2) | 0.278 (2) | | | 0.044 (12) | 0.042 (14) | 0.029 (14) | 0.027 (15) | | |
| | Daylight illuminance | | | | | 0.074 (5) | 0.074 (5) | | | | | | | | |
| | Occupation schedule | 0.082 (10) | 0.104 (9) | -0.092 (6) | -0.090 (6) | 0.647 (1) | 0.647 (1) | | | 0.104 (6) | 0.105 (5) | 0.044 (7) | 0.048 (8) | 0.086 (6) | 0.087 (6) |
| | Hot water demand | | | | | | | | | 0.063 (10) | 0.062 (11) | 0.043 (8) | 0.041 (11) | 0.029 (12) | 0.028 (14) |
| | Shading system | 0.188 (5) | 0.191 (4) | | | | | | | | | | | | |
| exog. | Climate | 0.205 (2) | 0.246 (2) | -0.148 (2) | -0.146 (2) | 0.049 (6) | 0.049 (6) | | | -0.077 (9) | -0.075 (9) | -0.045 (6) | -0.041 (10) | -0.037 (11) | -0.036 (12) |
| | Electricity mix | | | | | | | | | 0.122 (5) | 0.115 (4) | 0.335 (1) | 0.324 (1) | 0.263 (3) | 0.250 (3) |
| Demand (LCI) | Cooling demand | 1.000 (1) | 1.000 (1) | -0.311 (2) | -0.358 (2) | 0.039 (3) | 0.068 (3) | | | -0.132 (3) | -0.173 (3) | -0.083 (2) | -0.103 (3) | -0.078 (3) | -0.109 (3) |
| | Heating demand | -0.311 (2) | -0.358 (2) | 1.000 (1) | 1.000 (1) | -0.088 (2) | -0.084 (2) | | | 0.520 (1) | 0.515 (1) | 0.273 (1) | 0.272 (1) | 0.290 (1) | 0.287 (1) |
| | Electricity demand | 0.039 (3) | 0.068 (3) | -0.088 (3) | -0.084 (3) | 1.000 (1) | 1.000 (1) | | | 0.098 (4) | 0.102 (4) | 0.052 (5) | 0.058 (4) | 0.074 (4) | 0.076 (4) |
| | Hot water demand | | | | | | | | | 0.083 (5) | 0.082 (5) | 0.055 (4) | 0.054 (5) | 0.035 (5) | 0.035 (5) |
| | Material demand | | | | | | | 1.000 (1) | 1.000 (1) | 0.229 (2) | 0.271 (2) | 0.058 (3) | 0.137 (2) | 0.181 (2) | 0.240 (2) |

[a]Positive coefficients indicate that an increase of the parameter also causes an increase in demand (vice versa for negative coefficients). The cell's background color intensity corresponds to the rank correlation coefficient $\tau$ (red/orange for positive/increasing and blue/green for negative/decreasing effect) and demand category (yellow and grey background color) per LCIA category. Grey numbers have a $p$ value between 0.005 and 0.01; blank cells have $p$ values greater than 0.01. The number in parentheses denotes the parameter's ranking of absolute importance for the respective demand. The parameter construction material is based on all results (not only material subset).

The exogenic parameters climate and electricity mix are both important. Although the climate region is important for energy demand (rank two for cooling and heating), it has a less pronounced impact on the LCIA scores. Electricity mix is by far the most important parameter for climate change impact.

## ■ DISCUSSION

**Applicability.** The results are primarily valid for the Swiss and Central European context. Some of the assumptions, e.g. on transport distances or construction, may have to be reconsidered for studies outside of Switzerland. For most other regions different conditions in terms of climate, construction technique, and architecture exist, making an update of the thermal inertia simulations necessary. The same is true for buildings with poor thermal insulation. However, the Swiss climates used here cover a wide range of climates. They range from 2567 K·day (*Kd*) heating degree days in Lugano to 5864 *Kd* in Davos. This corresponds to practically Mediterranean (Milano, Italy: 2706 *Kd*) to rigid Nordic (Trondheim, Norway: 5211 *Kd*) climates, in terms of temperature. Furthermore, the LCI data sets are only partly applicable to a context outside of Europe.

**The Role of the Construction Material.** Table 3 shows that thermal inertia has an influence on energy demand of buildings. However, the impact is inferior to that of most parameters, such as ventilation rate, climate, or thermal insulation. Most parameter correlations differ slightly between the two material variants. In the wooden variant, cooling demand is affected more by solar factor, window ratio, and window overhang. That means that the wooden variant is more susceptible to solar and internal gains. Moreover, the parameter building size hints toward this finding. In addition, cooling demand of the wooden building decreases slightly for a residential occupation schedule. On the one hand, it has a lower peak load at noon, when cooling is typically required and, on the other hand, more heat gains during night hours, when thermal transmission losses are typically largest. For space heat demand, there is little difference in the parameter correlations when comparing the wooden and massive variant. The most obvious differences are again the ones related to solar gains. This hints toward the fact that the massive building is more capable of exploiting additional solar gains but may also suffer from prolonged hot periods (see Table 3: correlation between climate and space cooling demand and SI 2.2). It appears that the categories building design, material selection, and exogenic factors play a similar role to that of the building occupant.

Overall, including further LCIA indicators from the SI, the wooden variant shows a varying but consistent advantage for most LCIA scores. Since the advantage is sometimes marginal, caution should be exercised when drawing general conclusions. Project-specific decisions may easily overturn the advantage of wooden construction. For instance, on the grounds of aesthetics, long transport distances (exotic materials), large window surfaces, or excessive reinforcement may be the case, all of which would degrade its environmental performance.

**Limitations.** The parameter assignment to the different categories was a subjective decision by the authors and is debatable. For instance, in modern buildings, especially in offices, ventilation may be controlled by an automated system and could therefore be considered a design parameter instead of an occupation parameter.


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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

As described in the Results, numerous parameters have opposing effects on the demand vectors (Table 3), therefore having low or no impact score. Furthermore, some variables are indirectly interdependent. For instance, occupation density implies larger internal gains, thus increasing cooling demand and decreasing heating demand. However, at the same time hot water demand increases, because it is calculated on a per capita basis. Therefore, the parameter interactions are not directly visible from the results or may influence the correlation with dependent parameters. Nevertheless, the statistical method was deliberately chosen, so that the cumulated effect of parameters can be illustrated. In general, we tried to counter possible weaknesses of the method by choosing a rather large number of iterations ($n$ = 4500) and a conservative cutoff ($p$ value of 0.01). This corresponds to 160 iterations per input parameter and is thus well beyond the figure of 100 iterations per parameter that was described by Mutel et al. to reach model convergence.[49]

The assumed parameter ranges (Table 1) predetermine the results. For instance, thermal resistance has arguably a comparable effect on space heat demand as air exchange does. However, here it has only a relatively small bandwidth, with the legal and the technical limits being the restricting factors. Consequently, insulation does not appear as significant. We consider the chosen parameter ranges as realistic bounds for current buildings (with a likelihood of "faulty" operation) and that they represent the largest range of scenarios (office, residential occupation, etc.) possible. Some of the assumptions used for the model can be considered somewhat extreme or pessimistic. For instance, the wooden construction is extremely lightweight, and constructions with higher thermal inertia will often be chosen instead. Furthermore, accounting for the thermal inertia of the building interior would also slightly reduce space heat demand results for the wooden variant. As defined by Müller et al, the primary material for the massive exterior walls was assumed to be brick (SI Table S4).[19] Along with concrete, this is a common construction material for massive buildings in Switzerland. We estimated the difference if concrete exterior walls were to be used instead. The LCIA results would be increased by ca. 8.2% for GWP and 1.0% for ReCiPe. Only the results for CED nonren would decrease by approximately 1.4% and 1.3% for CED total, respectively.

Moisture sorption was not fully accounted for in the thermal simulations, since an approximate algorithm was used for energy demand calculation. However, studies show that the hygrothermal effect may have a similar impact to that of thermal inertia.[50−52] The difference in moisture sorption capacity between the two building variants is also likely to have an impact on indoor air quality, which was not considered here. Indoor air quality may again indirectly affect a building's ventilation rate and therefore its energy demand.

The functional unit chosen for the study does not account for all use cases. However, some aspects may limit the comparability of the two building variants. Some examples are indoor air quality, acoustic properties, fire safety, and indoor comfort.[53]

Concrete has two effects at the end of life, which were not accounted for in this study. On the one hand, it will carbonize, taking up carbon dioxide. Dodoo et al. conclude that the effect is significant, but will not overturn most LCA results.[13] On the other hand, some authors argue that, in order to use concrete as a recycling material, increased amounts of cement are necessary to achieve the same properties as primary concrete, which should be accounted for.[54] We avoided this issue by substituting the precursor material, gravel.

The EOL credits of wooden products substitute only Swiss electricity mix and gas heating. It could also be argued that other electricity mixes and oil heating should be substituted. This would give an additional benefit to the wooden constructions (Swiss electricity has a large share of hydropower with low impacts according to most LCIA methods used here).

**Comparison with the Literature.** Previous studies find comparable results. Aste et al. find the influence of thermal mass on space heat demand to be 2−10% and 5−20% for space cooling.[8] Dodoo et al. find a lower increase in space heat demand of 1−2% for Nordic climates.[11] Our simulations show a relative standard deviation of 11% and 76% for space heating and cooling, respectively.

**Implications.** The presented model allows a combined analysis of building energy demand and material use. This way combined effects and tradeoffs can be investigated. Furthermore, results are provided for different environmental methods. Such a holistic view is important, in order to avoid hidden rebounds. For instance, thermal insulation seems important when looking at space heat demand. However, the LCIA scores suggest that this factor is actually less important than others are.

Given the results discussed above, the choice to use a wooden construction is often environmentally beneficial. Depending on the indicator, the benefit differs. While for the nonrenewable fraction, wooden buildings have an 18% advantage, their total cumulative energy demand is identical. Median climate change impacts are 25% lower with EOL material credits and 22% lower, when excluding EOL credits. Overall, other parameters, such as ventilation rate and heat generation, play a more important role than material choice, given a good thermal insulation standard.

The lower energy performance of wooden buildings (due to the reduced thermal inertia) is overcompensated by the lower environmental impact of the material. As illustrated in Figure 1 (bottom), material impact has a low deviation for each construction type. Therefore, short service life, low energy demand, clean energy production, or long transport distances will make the environmental benefit of wooden construction even more pronounced. Since legislation aims at a further reduction of space heat demand of buildings, the relative importance of the construction material will increase in the future.

**Design Recommendations.** Since energy demand is the main driver for environmental impact, planers may want to focus on its reduction, with ventilation strategy (e.g., heat recovery) being a main leverage. An equally important aspect is the choice of energy source for thermal and electric energy. The decision to use wood or bricks as a construction material has an important influence (especially for energy-efficient buildings). Other planning decisions, such as planning larger, compact buildings, also have notable potential to reduce a building's impact. Table 3 can be considered a reference guide to identify the leverage of individual measures.

Since the main disadvantage of wooden buildings is its low thermal inertia, it should be a priority in wooden building design to plan for supplementary thermal inertia. This could be in the form of phase change materials (PCM) or the design of hybrid wood/concrete buildings etc.[55−57] The environmental impact of any supplementary material should be evaluated, however. The results for parameters affecting solar gains play an important role. Since wooden buildings have a tendency to


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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

overheat and are more susceptible to large solar gains, a sound shading strategy should be designed and large window surfaces, as well as high internal gains avoided.

For massive buildings, the impacts from material input are particularly important. Therefore, massive construction should be avoided when short material life or building service life (e.g., commercial or temporary buildings) is expected. Furthermore, they should be designed in a way that transport distances are kept short, for example by using local materials.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information accompanying this article provides additional information on the model inputs, thermal simulation results (thermal inertia effect), LCIA results, and sensitivity analysis. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01735.

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### Notes

The authors declare no competing financial interest.

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*Environ. Sci. Technol.* XXXX, XXX, XXX–XXX