SENSITIVITY AND UNCERTAINTY ANALYSIS OF COMBINED BUILDING ENERGY SIMULATION AND LIFE CYCLE ASSESSMENT

Implications for the Early Urban Design Process

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Abstract. Life Cycle Assessment (LCA) is a suitable approach for evaluating environmental impact (e.g. Global Warming Potential (GWP)) related to construction elements and building operation. Since both contribute significantly to the lifecycle based GWP of buildings, combined consideration is necessary. This applies especially for the early design stages when measures for climate change mitigation can be implemented in a cost-efficient manner. In this paper, we describe a sensitivity and uncertainty analysis (SA/UA) for energy simulation and LCA with a total of 8,000 parameter combinations. Thereby, we investigated valuable input for the setup of a collaborative design process with limited information. Standardised Regression Coefficients (SRCs) were used to obtain sensitivity and resulting uncertainties were investigated. The results indicate Primary Energy Source (PES), compactness and energy standard to be the most important information for the robustness of the combined LCA approach. Uncertainty can be reduced by e.g. defining the energy system in an early stage or by designing compact buildings. Related to the early design stages, the application of combined approaches for SA and UA is recommended, as the results differ for embodied and operational emissions.

Keywords. Early Design Stages; Sensitivity Analysis (SA); Uncertainty Analysis (UA); Life Cycle Assessment (LCA); Urban Scale; Synergy Potential; SDG 13.

1. Introduction and Use Case

For achieving a climate-neutral building sector, building energy simulations (BES) give valuable information on how to reduce buildings Global Warming Potential (GWP). While energy standards improve, it is also necessary to consider CO2-eq. emissions related to the materials used for construction, as their share over the lifecycle

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of buildings increases (Roeck et al., 2021), (Longo et al., 2019). LCA is an established method to calculate these so-called embodied emissions which result from production, use (replacement and exchange) and end-of-life stages. While operational and embodied emissions have been extensively investigated separately, research on combined approaches is still limited. Determination of sensitive inputs is necessary to improve the robustness of results. This knowledge is required to show which properties of buildings allow for high synergetic potential and point out possible deteriorations caused by their insufficient consideration. Especially in the early design stages, there is a high optimisation potential due to uncertainties in the design process. We investigate the main parameters for reducing building-related CO2-eq. emissions from a lifecycle perspective by combining energy and LCA simulation. We show to which extend input parameters affect these emissions separately, but also to which extent there is an interaction between construction and operation, leading to differing results. The findings shall be used to develop an LCA plugin for the Collaborative Design Platform (CDP) (Schubert, 2021), enforcing the consideration of the most important information in an early stage of urban design. Inside the framework, buildings are represented by simplified models, providing a minimum level of information. Within our research project 'Densification in the Context of Climate Change' we enrich the urban model with metadata for basic calculations concerning densification. Nevertheless, there is a vast amount of possible information that could be added by user interaction (energy standard, construction type, …). As the project is developed for an urban scale, users cannot define all buildings in detail, as this would decrease the intuitive handling. Instead of specifying exact values with numerous assumptions, we aim to provide a range of results for LCA, to show users the optimisation potential for the selected set of general inputs. To ensure focussing on the most important aspects of urban planning while not overloading the necessary inputs, we want to clarify which parameters should be examined in depth to obtain robust results for the CO2-eq. footprint of buildings.

2. Literature Review

LCA allows considering emissions resulting from operation as well as embodied emissions related to the materials used in buildings. Both parts have overlapping inputs, thereby causing interaction in the overall results (Heeren et al., 2015). SA has been applied for operational (Hemsath and Bandhosseini, 2015), (Singh and Geyer, 2019) or embodied CO2-eq. emissions (Schneider-Marin et al., 2020), (Basbagill et al., 2013). It is proven that SA can be utilised to show which parameters are most influential for the results of BES models and in which order their further consideration should be proceeded. The investigation of early design stages will thus improve results, as they offer great optimisation potential (Meex et al., 2018). While Harter et al. focus on reducing the uncertainty of results by adding information to building models, they consider operational and embodied primary energy usage (Harter et al., 2019). Other combined approaches, e.g. (Mukkavaara and Shadram, 2021) show how solutions can be selected and optimised on a multi-objective (embodied and operational) scale. They suggest an approach for post-optimisation SA to achieve the maximum outcome for the design progress. Nevertheless, SA is limited to the investigated context, as design parameters and observed outputs vary. We want to investigate the case of collaborative urban design in the early stages with the available information at that point.

3. Concept and Methodology

Our approach is based on a parametrised BES model which was integrated into an LCA calculation for a broad range of combinations. From the results, sensitivity and uncertainty were calculated to show which parameters influence the variance of operational and embodied CO2-eq. emissions. The methodology is summarised in Figure 1 and further explained in the following sections.

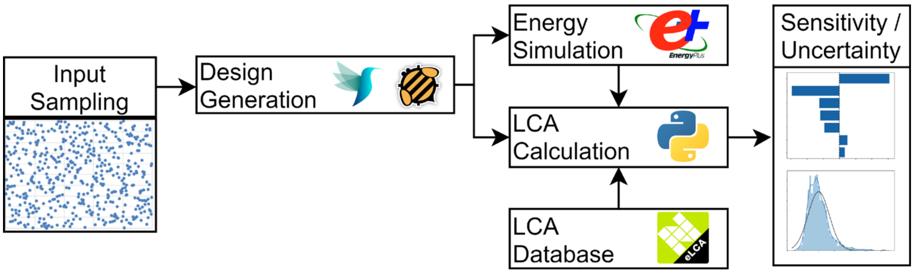

Figure 1: Summary of the proposed methodology

3.1. SAMPLING AND PARAMETRISATION

For creating a sufficiently large dataset of buildings, we used a parametrised, rectangular shape. The parametrisation was done in Rhino - Grasshopper with the Honeybee plugin (Roudsari and Pak, 2013) and Energy Plus simulation engine (Version 8.9.0). Latin Hypercube Sampling (LHS) is a common sampling method for building simulation inputs (Nguyen and Reiter, 2015) and was therefore utilised to create samples for the varied parameters (McKey et al., 1979). In addition to the continuous parameters shown in Table 1, we added a variation in energy standard and construction materials by assigning them based on ranges obtained from LHS as discontinuous variables (Table 2), which has been done before by e.g. (Mukkavaara and Shadram, 2021). Building geometry was limited to 28 meters, as the results should be used in the context of urban densification, which set our focus on geometries that can be added to the existing urban landscape. The parameters were selected based on shown influence on sensitivity and uncertainty in separated energy and LCA research (see section 3) as well as information available from CDP users. A number of 500 sets for the energy calculation was chosen, according to research where this was shown to be a sufficiently large number (Singh and Geyer, 2020), (Macdonald et al., 2009).

Parameter continuous	Unit	Min	Max
Building Width	Metre	10	28
Building Length	Metre	10	28
Building Height	Metre	10	28
Orientation	Degrees	0	90
Window-to-Wall Ratio (WWR)	%	0	90

Table 1: Parameters for the creation of the model

Parameter set	Subsets	Range LHS	U-value [W/m²K] [base, wall, roof, window]
Energy Standard	GEG (legal standard)	[0, 0.33),	[0.30, 0.24, 0.20, 1.1]
	KfW 55 (improved standard)	[0.33, 0.66),	[0.25, 0.20, 0.14, 0.90]
	KfW 40 (high standard)	[0.66, 1.0]	[0.19, 0.15, 0.11, 0.70]
Constr. Material	Timber	[0, 0.5),	-
	Mineral	[0.5, 1.0]	-

Table 2: Assignment of subsets for energy standard and construction material by sampling

3.2. ENERGY AND LCA CALCULATION

A multi-zone model was used for the energy simulation, as we also obtained construction masses from the honeybee model (e.g. ceiling area). Weather data was used for the city of Kempten (South Germany). After sampling the described inputs, the other necessary boundary conditions for energy simulation were set according to the German standard for the calculation of heating and cooling energy demand DIN V 18599-10:2018-09. The creation of simulation files and mass recording was done using the Colibri plugin for Grasshopper. The generated simulation files were run through Energy Plus group simulation afterwards and the results for heating and cooling energy demand were collected with the Eppy library for Python.

To assess a broad range of material combinations, we used the open-source tool eLCA (Federal Institute for Research on Building, U. A. and S. D., 2021) with the freely available LCA-Database Oekobaudat in version 2020-II (Federal Ministry of the Interior, B. and C., 2020). Typical components for timber and mineral structures (timber frame, solid timber, masonry, reinforced concrete) with two roof types (flat, pitched) were modelled and the results exported related to one square metre of a construction. We considered the building envelope as well as interior ceilings and walls. The system boundaries were set according to DIN EN 15978:2012-10 with LCA phases production (A1-A3), exchange (B4), operation (B6), end-of-life (C3-C4) and benefits beyond the system boundaries (D) under consideration. The buildings reference service life was set to 50 years and the functional unit was one square metre net floor area. Although the methodology could observe a broad range of impact categories, we focused on the GWP, as it is highly relevant in terms of climate change mitigation. Accordingly, it is contributing to Sustainable Development Goal (SDG) 13 - Climate Action.

To calculate the results for each of the 500 samples, we used Python programming language and Pandas library. First, each of the 500 samples was expanded using the LCA values generated in eLCA for construction. Second, we used heating and cooling demand in combination with Oekobaudat datasets for PES (gas, district heating, heat pump with 2020 electricity mix for Germany, pellet) to obtain the operational impact (LCA phase B6). Finally, the results of operational LCA and construction LCA were merged. The approach resulted in a total number of 8,000 combinations.

3.3. SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivity analysis is commonly used to identify input parameters whose uncertainty contributes highly to uncertainty in the outputs (Saltelli et al., 2008). In the field of building simulations, the Standardised Regression Coefficient (SRC) has been applied before and was shown to give an indication of parameter importance (Loeffler et al., 2021), (Sing and Geyer, 2020). Higher absolute SRCs mean more impact on the model outputs, where positive SRCs cause an increase and negative SRCs a decrease of the model outputs. For a second proof of the parameter order, Standardised Rank Regression Coefficients (SRRC) were also calculated. The use of these coefficients brings up the need to check inputs for significance. A calculation of probability-values (p-values) was therefore utilised and inputs above the significance level of 0.05 were excluded. For the following calculation of SRC, Scipy and Statsmodel libraries were used, plotting was done with Seaborn. We conducted the analysis first for operational and embodied emissions in isolation. These results were then compared to the ranking of input sensitivity after the combination.

UA allows observing the possible variation in model outputs, caused by the uncertainty present in the inputs (Saltelli et al., 2004). It has been applied to energy simulations (Kotek et al., 2007) and is gaining importance in LCA (Röck et al., 2021). From our results, we investigated uncertainty in the outputs by analysing their distribution via boxplots.

4. Results

4.1. SENSITIVITY ANALYSIS

The regression model was built with significant inputs resulting in R2 values of 0.771, 0.932 and 0.922 for embodied, operational and combined assessment. These values are above the usability threshold of 0.7 given by (Saltelli et al., 2008). Residual differences for combined results came close to a normal distribution (see Figure 2 (d)), thus the information is sufficiently represented by the models. From the regression models, SRC was calculated for the remaining inputs, resulting in the order shown in Figure 2 for embodied (a), operational (b) and combined (c) GWP. Calculation of SRRC resulted in values close to the SRC, where only construction material (CM) and energy standard (ES, represented by the global U-value calculated for the thermal envelope) changed position in the ranking but with a little deviation (SRC CM = 0.1348, SRC ES = 0.1447, SRRC CM = 0.1283, SRRC ES = 0.1221).

For embodied GWP, results showed the highest sensitivities to geometric values (surface area to volume ratio, A/V), WWR and construction types. Operational GWP was highly influenced by the chosen energy system, WWR, geometrical parameters and the energy standard. When operation and embodied emissions were regarded in combination, energy system, compactness, WWR and energy standard were the most sensitive inputs. Negative SRCs as e.g. in Figure 2 (a) for global U-value can be interpreted in such a way that an increase in the global U-value (which means lower energy standard and thus less material use for insulation) results in a decrease of embodied emissions.

To confirm our approach for energy simulation gives reliable results, we also calculated SRC for heating demand (R2 = 0.858), resulting in the order geometry, quality of thermal envelope and WWR. The energy system resulted in an SRC of zero, as final heating demand and not primary energy demand for heating was observed. For the regarded parameters of our research, this agrees with current research (Singh and Geyer, 2020), (Loeffler et al., 2021).

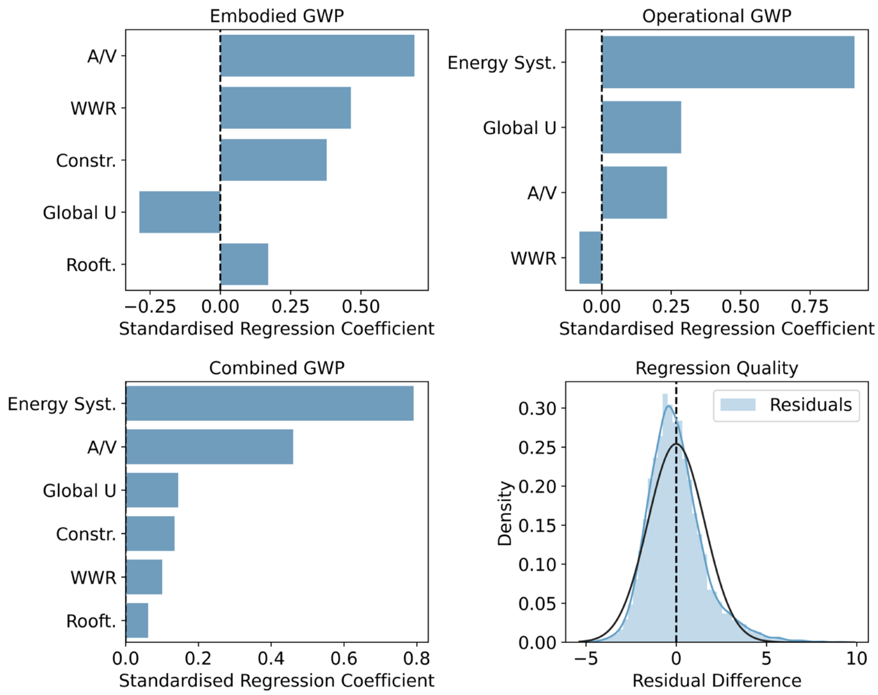

Figure 2: (a - top left) SRC Embodied GWP, (b - top right) SRC Operational GWP, (c - bottom left) SRC Combined GWP, (d - bottom right) Residual Error of Combined Regression

4.2. UNCERTAINTY ANALYSIS

To gain a deeper understanding of the optimisation potential for the identified variables, UA was conducted. For uncertainty especially the categorical variables were used for differentiating (energy standard, primary energy source, construction type). Regarding the PES, we observed a high contribution to uncertainty in the combined results, see Figure 2 (c). Figure 3 (a) shows the results for energy systems, where (I) a high difference between the energy systems is observable and (II) the comparison with the uncertainty induced by energy standards (Figure 3 (b)) confirms the calculated order of sensitivity ranking. Improved energy standards contributed to a reduction in uncertainties (Figure 3 (b)). An improved thermal envelope resulted in slightly reduced emissions over the building's lifecycle. In general, timber constructions performed better than mineral ones in terms of combined GWP, due to the lower embodied emissions associated with wooden materials.

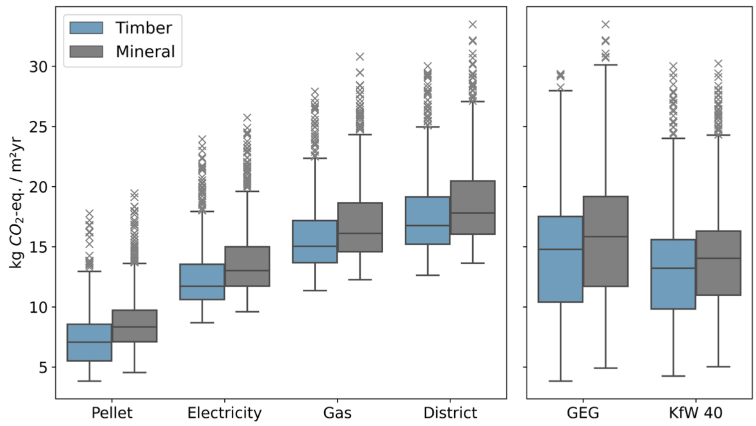

Figure 3: Boxplots for combined results (a - left) split for construction type and energy standard (b - right) split for energy source and construction type

As WWR showed high sensitivity in terms of embodied emissions and is also relevant for combined consideration, we categorised it into groups of 0.1 ranges to print boxplots for it. The results are shown in Figure 4 (a), indicating a slight rise in combined GWP with higher WWRs. Categorisation was also done for A/V ratios (fig. 4 (b)), showing a rise in GWP for increased values, meaning more compact geometries have a lower environmental impact than less compact forms. Furthermore, a reduction of uncertainty for more compact shapes is observable, as 1.5 quartile ranges get closer to the interquartile, resulting in a 33% decrease of standard deviation from 0.55 to 0.25 A/V-ratio.

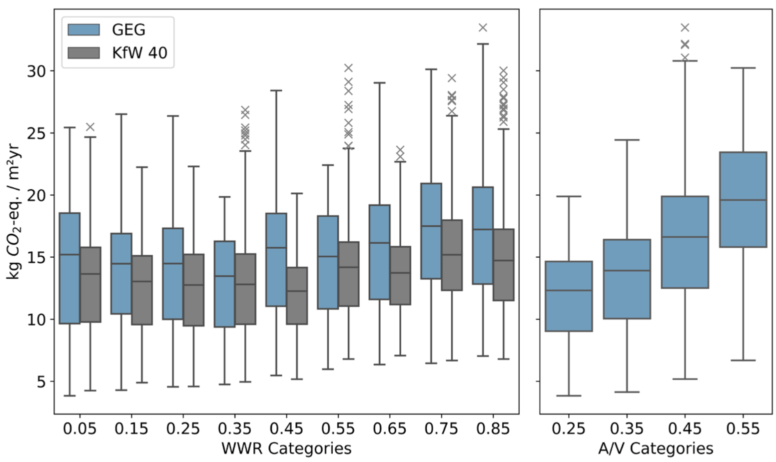

Figure 4: Observation of uncertainty contribution to combined GWP through (a - left) categorised WWRs and (b - right) categorised A/V ratios

5. Discussion

Due to the rising importance of climate change mitigation, lifecycle-based approaches gain attention, as they allow a holistic consideration of buildings CO2-eq. emissions. To assist planners in early stages of design, we set up a SA and UA on a combined approach of embodied and operational emissions. Due to the overlapping inputs for the two parts, an interaction was expectable. From the results we observe, that a combined consideration shows a change in the order of sensitivity. PES remains the most sensitive parameter for operation and combined consideration, thus its fixing will contribute most to narrowing the range of results. For operational GWP this is to be expected, as research has shown that despite the rising share of embodied CO2-eq. emissions, building operation is still the main source of energy and resource consumption (UBA, 2019). The impact of PES has also been shown and discussed in the context of building refurbishment, where e.g. (Panagiotidou, 2021) concluded that net zero energy buildings cannot be achieved without decarbonisation of the electricity grid. While the construction type is of importance for the embodied impact, its sensitivity decreases for the combined assessment. By conducting a further UA, we observe reduced optimisation potential for higher energy efficiency standards in terms of GWP, due to the increase in embodied emissions caused by adding insulation. This is in line with the conclusions drawn by (Mukkavaara and Shadram, 2021), who investigated primary energy use over a building's lifecycle. Also this trade-off in energy standards contradicts efforts to achieve CO2-eq. neutral buildings, an improvement of energy standard decreases uncertainty of results. This study was conducted for a specific use case, thus it is limited to that context. To provide conclusions for other locations, the methodology should be expanded to different climatic zones with a more extensive consideration of inputs. Further validation against case study buildings is also valuable, as this research was limited to synthetic data from the parametric model.

6. Conclusion

Emissions from building production, operation and end-of-life stages are highly interdependent. In order to set up a collaborative urban design plugin, we determined the most sensitive inputs which users need to give. We conducted parametric energy simulations and combined the results with typical building constructions and primary energy sources. Regression analysis was used to calculate sensitivity for embodied, operational and combined GWP.

In general, the need for a combined consideration of lifecycle emissions can be derived. Our analysis shows a change in the sensitivity ranking compared to considering embodied and operational emissions in isolation. As PES is of high sensitivity, it should be fixed in an early stage of design. By that, the possible range of results can be reduced most and further optimisation is most effective. This study was conducted with the German electricity mix 2020. As energy systems showed high sensitivity it can be concluded, that future changes in emission factors of energy carriers will affect the outcome of LCA noticeably. Thus, an improvement in e.g. electricity or district heat generation will also improve GWP from a combined perspective and is recommended. From the results, we also derive the need for high compactness of buildings, as this reduces uncertainty while synergistically optimising the overall outcome. By applying the described methodology to other climates or building shapes, influential parameters for lifecycle based GWP in early design stages can be identified and planners are enabled to focus on their optimisation first.

The findings described in this paper serve as a basis for the development of a CDP simulation plugin in the next step. Regarding our initial intention to provide robust ranges of LCA results during collaboration it is concluded, that beyond the geometrical information, especially information regarding the PES and energy standard should be basic input parameters. By that, users are enabled to observe the high variability of results due to their interactions with the CDP. Finally, providing the identified parameters during the urban design process will entail a reduction of uncertainty, setting the stage for further optimisation.

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