Carbon budgets at the component scale and their impacts on design choices: the façade as a case study

N Rezaei Oghazi[1,2], T Jusselme[1] and M Andersen[2]

[1] Energy Institute, University of Applied Science of Western Switzerland (HEIA-FR, HES-SO), Fribourg, Switzerland
[2] Laboratory of Integrated Performance in Design (LIPID), Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland

nazanin.rezaeioghazi@epfl.ch

Abstract. In accordance with the Paris agreement, the Swiss Climate Strategy (SCS) defines the net-zero target to be reached before 2050, which demands for a thoughtful carbon budget allocation between the different contributors. Ongoing normalization tasks are currently defining life cycle carbon budgets at the building scale aligned with the SCS. While recent research has provided promising methodologies to break down a whole building's carbon budget, SCS-aligned budgets cannot be calculated at the component scale yet. Having the ability to define carbon budgets at the components' level could support a carbon-responsible design process by reducing the scope of the design problem: the idea is to ensure that the cumulative impact of all the building components (calculated per building energy reference area) remains below the allowed building carbon budget based on SCS targets. This would provide a straightforward link between SCS and carbon budgets at the component scale, a scale at which many decisions need to be taken during the design process. Moreover, based on the set SCS net-zero objectives to be reached by 2050, the carbon budget, whether for buildings or for their components, will have to decrease annually, thereby affecting design flexibility, i.e. the number of design solutions that can still comply with the building's carbon budget on any specific year. The research presented in this paper aims to provide a framework able to set carbon budgets at the components' scale and start discussing the consequences of such carbon budgets on façade design flexibility until 2050.

1. Introduction

As defined by the IPCC, the carbon budget refers to the maximum GHGs that can be released to the atmosphere to keep global warming below a given limit. Meeting the goals set out in Article 2 of the Paris Agreement, i.e. limiting global warming to below 2 ℃ and striving for a limit of 1.5 ℃ [1] requires unprecedented efforts and immediate action from all countries and from each of the involved sectors. To comply with the Paris agreement, the Swiss climate strategy (SCS) [2] has translated this limit into a net-zero carbon target, that is to be reached before 2050. In the construction sector, while previous research and norms in the Swiss context have been focusing on defining carbon budgets at the building scale [3–5], building stakeholders are faced with the need to define clear and coordinated targets at a much smaller scale, namely the *components* scale, for their project. This approach indeed allows informed choices to be made during the design process and options to be properly compared based on their respective carbon footprints, a resolution that is lost if the only target available is at the full building scale. In terms of end result, if all building components respect the carbon budgets calculated per building energy reference area (ERA) individually, the whole building will necessarily respect the carbon budget at the building scale, too.

Given that the SCS defines net-zero targets until 2050, the carbon budget available at the building's as well as at the components' scale will decrease year after year until 2050, and this gradual reduction will necessarily impact design flexibility, which can be referred to as the number of possible design solutions that would still respect the building's carbon budget on a given reference year. Moreover, evaluating the design flexibility evolution over time will help draw attention to the design limitations and constraints we are likely to face in the coming years. As SCS-aligned carbon budgets have not yet been investigated at the components scale, nor has their impact on design flexibility over time, more research addressing this gap is needed. To better define carbon budgets at the building's components level in line with the SCS and discuss how these budgets might impact design flexibility until 2050, we propose a methodology that combines a Target Cascading (TC) approach with a parametric LCA, which we then applied to a multi-family residential building archetype in Geneva, Switzerland as a preliminary case study.

2. Methodology

Previous research in the context of the built environment has highlighted the advantages of TC in streamlining the design process through the definition sub-targets for carbon emission [3,6,7]. The present study applies a parametric approach in combination with TC, which entails creating a knowledge database of design variants', and calculating the average relative weight of a building's components (TC approach), and adapting this relative weight to the building's whole carbon budget in compliance with SCS. These two steps are explained in the following sections.

2.1. Creating a knowledge database of design variants

To make a knowledge database populated by design variants and their corresponding whole life carbon emissions per kg CO_2-eq/ERA.year, a sample of 5000 design variants, based on various combinations of the study variables presented in Table 1, was created using the Sobol technique [8]. Note that the whole design space (i.e. the range of *all* possible design variants), would instead contain 4^9 alternatives since we study 9 variables and consider 4 options for each, i.e. over 260'000 alternatives (cf. Table 1). While such a design space would be complete, it would require to perform an enormous number of whole life CO_2 emissions calculations and thus, at least for the time being, be extremely time- and effort-consuming. Thus, we resorted to the Sobol sampling technique to ensure a manageable sample size that also has a uniform distribution of variants (representative sampling) over the full design space. The sampling approach we chose happens to disregard the actual proportion of construction techniques in the Swiss residential building stock and instead, gives each construction technique an equal chance: the idea is here to evaluate design *possibilities* and see how their compliance with the building carbon budgets will impact design flexibility.

To define the most relevant variables to keep, a design workshop was organized with professionals from the architecture and civil engineering fields, from which the variables' performance levels representative of new-built multi-family residential buildings in the Swiss French part were extracted. The resulting list is provided in Table 1. Note that some parameters were considered as fixed since there was either no known alternative or the difference between the known alternatives' impacts per ERA was too low. These include: excavation and shielding, underground building envelope, installations, roof covering, floor slabs covering, load bearing and non-loadbearing internal walls. The composition of all components, whether variable or fixed, are based on the SIA 2032 [9]. The whole life carbon emissions of building elements were calculated using equation (1), in which I_{Wi} (kg CO_2-eq/ERA.y) is the whole life global warming potential (GWP) of variant i amortised over 60 years of building life span, I_{Ei} (kg CO_2-eq/ERA.y) is the embodied carbon emissions of variant i, M_j represents the material quantity of component j in variant i (extracted thanks to a parametric model previously developed by the authors [10]), IF_j ($kgCO_2$-eq) is the carbon impact factor of the component j based on the KBOB [11], RSP_B (year) is the building reference study period, LM_j (year) is the component j's lifetime, ERA (m^2) is the energy reference area and I_{Oi} (kg CO_2-eq/ERA.y) indicates the operational impacts of variant i, which is calculated thanks to the dynamic energy simulations and KBOB impact conversion factors [11].

$$I_{Wi} = I_{Ei} + I_{Oi} = \sum_j [(M_j . IF_j . \frac{RSP_B}{LM_j}) * (\frac{1}{RSP_B * ERA})] + I_{Oi} \quad (1)$$

The whole life carbon emissions calculations in this study actually include the same phases as those considered in SCS-aligned budget calculations at the building scale, performed by Prior et al. in [5] and include production and construction, use phase and end of life. Once the knowledge-base is populated, the value of I_W can be defined for each building element according to the eCCC-Bât building elements classification [12], which is widely adopted in Switzerland.

2.2. Target cascading calculations

Each component's embodied carbon budget (CB_C) is calculated according to equation (2), in which RW_C is the relative weight of each component. I_{Ci} is the embodied GWP of the component in variant i, I_{Bi} is the building embodied GWP of the variant i, and CB_B is the carbon budget at building scale at a reference year.

$$CB_C = RW_C * CB_B = \frac{\sum_{i=1}^{n} I_{Ci}}{\sum_{i=1}^{n} I_{Bi}} * CB_B \quad (2)$$

Almost half of the database's I_{Bi} is aligned with CB_B at 2030 and the other half is not. Therefore, this question raises: how carbon budgets at *components* scale (CB_C) are influenced by the variants' embodied GWP at *building* scale (I_{Bi})? To answer this question, the proposed methodology suggests performing a TC on two datasets: the whole database (d_w) and a sub-population of variants (d_{2030}) whose I_{Bi} is aligned with building carbon budget set for 2030, itself adapted from [5]. The comparison between the TC results considering the d_{2030} and the d_w will be discussed in section 3.3.

Table 1. Study variables and their performance levels

Variables	**Performance levels**			
Wall structure	Massive wood	Wood framed	Brick	Concrete
Façade cladding	Mineral plaster	Cement plaster	Wood	Fibrocement
Glazing	Double, 24 mm, U=1 W/m^2K	Double, 18 mm, U=1 W/m^2K	Triple 40 mm, U=0.5 W/m^2K	Triple 36 mm, U=0.7 W/m^2K
Frame	Wood, U=1.4 W/m^2K	Wood-Aluminium, U=1.2 W/m^2K	Aluminium, U=1.3 W/m^2K	PVC, U=1.1 W/m^2K
Venetian blinds position	No shading	Open (horizontal)	Open (45 degree)	Close
Envelope insulation	Straw	Cellulose fibre	Glass wool	EPS
Slab/Roof structure	Massive wood	Wood framed	Concrete	Metal deck
Window-to-Wall ratio	30%	40%	50%	60%
Loggia depth (m)	-2.4	-1.2	0 (no loggia)	+1.2 (balcony)

3. Results and discussion

3.1. SCS-aligned carbon budgets at the component scale

A Swiss building's embodied carbon budget (CB_B) can be anticipated to be equal to 9.9 CO_2-eq/ERA.y in 2030 based on [5]. The TC calculations were thus performed based on d_w and the results are shown in Figure 1. Applying the methodology described in section 2, we find that in average, the slabs, including slab structure and finishing, represent the most carbon-intensive element of the building as it accounts for 29% of the CB_B. This is followed by the façade (21%) to which a budget of 2.1 kg CO_2-eq/ERA.y, i.e. 21% of CB_B, was thus allocated (Figure 1.c). Installations (17%), interior walls structure and finishing (15%), underground building envelope (7%), roofs structure, insulation and covering (6%) and preparatory work including excavation and shielding (5%) complete the building carbon budget. Investigating the façade in more depth, we see that, when WWR stays between 30% and 60%, the walls and windows' CB_C respectively represent 66% and 34% of the façade's carbon budget (CB_F). Among the various façade's components, we also see that the wall's structure shows the highest carbon budget: it is equal to 6% of the whole building's embodied budget, and is followed by wall insulation (4%), façade cladding (4%), glazing (3%), shading (3%) and window frame (<1%).

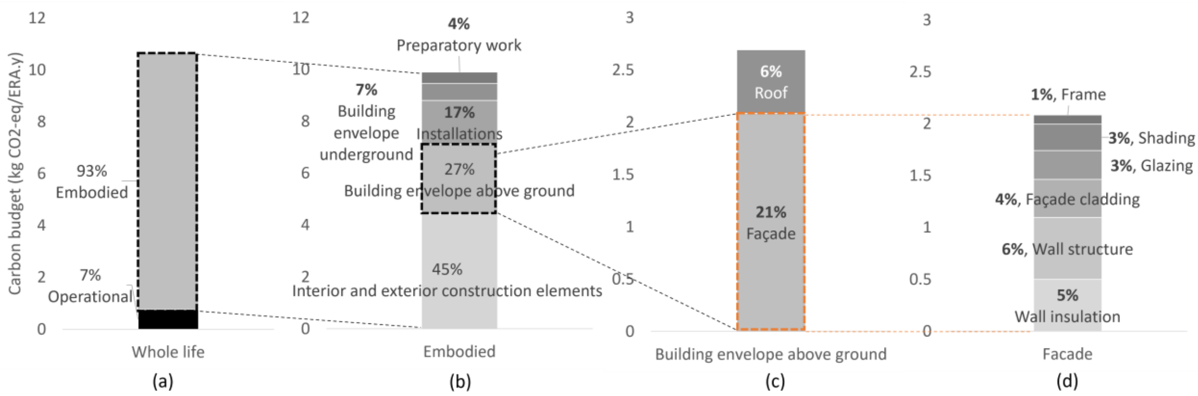

Figure 1. The building carbon budget breakdown at building scale (a), eCCC-Bât sub-categories (b), building envelope (c) and façade components (d).

3.2. Carbon budgets until 2050 and their impact on design flexibility

Figure 2.a shows that while the studied glazing options are compliant with the glazing's CB_C set for 2030, none of them would meet the glazing's CB_C set for 2050. This finding emphasizes the urgency of mitigating the glazing material's impact in the next 20 years so as to keep a chance of staying compliant with SCS targets. On the positive side, we should highlight that while the studied glazing options do not respect their corresponding CB_C set for 2050, the choice of a low-carbon wall structure, wall insulation, façade cladding, frame and shading do still make it possible to keep the total façade embodied impacts below the CB_F set for 2050. To respect the 2050 carbon budget at façade level, this finding thus brings the following design strategies as most likely to be compliant: avoidance of aluminium venetian blinds, use of wooden window frames, keeping a WWR≤40%, opting for massive wood and wood-framed wall structures, and using mineral plaster as the exterior cladding.

According to Figure 2.b, and starting from 2039 onwards, we can see that if the materials' impact remains the same in the following years, the average I_E of the considered design variants will not respect the CB_B. Also, we can see clearly that design flexibility will decrease, with a quite steep slope (notably from 2029) and that eventually, the design space will contain no more variants compliant with CB_B after 2039. In other words, and based on these preliminary results, we have only 6 years left (until 2029) to change the construction techniques, otherwise design flexibility will decreases significantly. Given that the knowledge database contains *variations* of a reference building, it is worth noting that even if all we can do is to vary the quantity or type of common components for facade, slabs, and roof, we still have 16 years left (i.e. until 2039) until we will have to switch entirely to different construction techniques such as earth walls, grass insulation, buildings without underground, etc. In fact, we already know how to build with such construction techniques and know they make it likelier to stay compliant with 2050 carbon budgets; what the present study provides is a time frame, namely the (limited) period left during which different design possibilities remain available with commonly used construction techniques while still staying compliant with the CB_B. Unlike building scale, the design space contains façade variants whose average embodied GWP is compliant with façade carbon budget (CB_F) until 2050. This finding highlights the carbon mitigation potential of the façade, while at the building scale this potential is much less due to the limited construction choices for underground building envelope (which is built entirely in concrete), excavation, shielding walls, slabs finishing, interior walls and installations, which are in total responsible for 60 % of building embodied GWP.

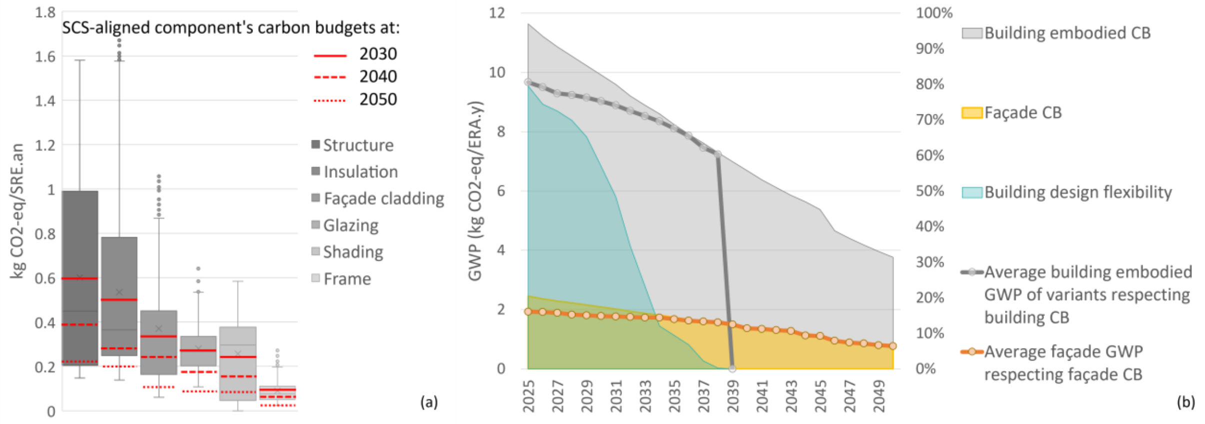

Figure 2. Discrepancy of façade components GWP and the CB_C for the years 2030, 2040 and 2050 (a) The building and façade embodied carbon budget until 2050 (b)

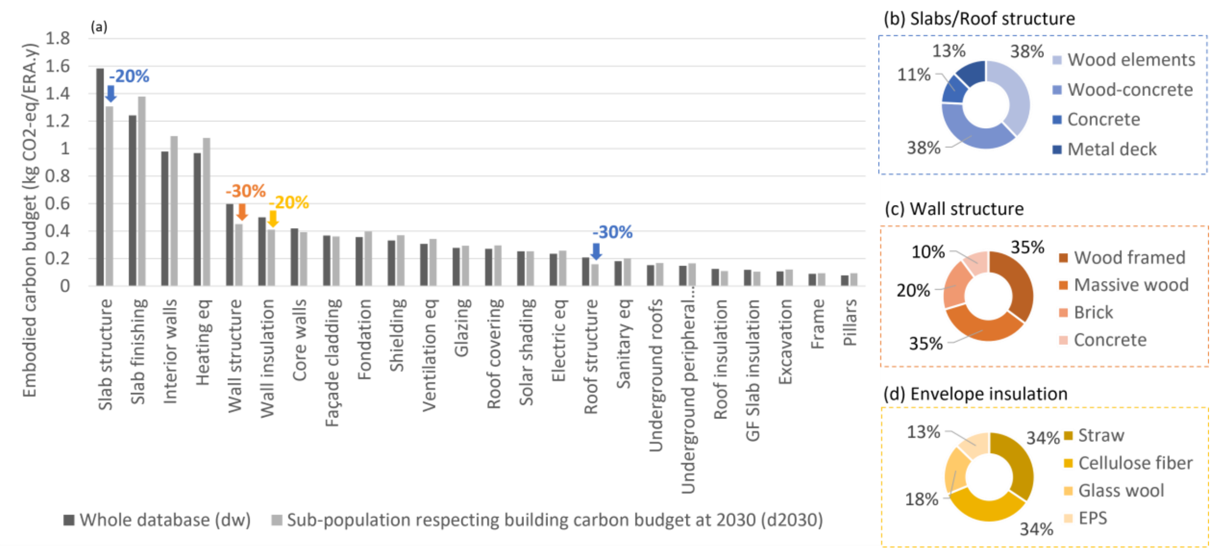

Figure 3. Carbon budgets at components level based on d_w and d_{2030} (a), the percentage of each construction technique within d_{2030} (b,c,d)

3.3. The impact of variants embodied GWP at a 'building' scale on the carbon budgets at 'components' scale

As mentioned in the methodology, TC calculations were performed on two datasets, i.e. d_w and d_{2030} and CB_C of each dataset is presented in Figure 3. The respective budgets of the slab structure, roof structure, wall structure and wall insulation in d_{2030} are 20%, 30%, 30% and 20% less than that of d_w. This reduced budget in d_{2030} is distributed to the rest of building components proportionally to their GWP relative weight and, as a result the grey bar in Figure 3.a is higher than the black bar (except for slab/roof/wall structure and envelope insulation). This budget reduction is due to the impact of the number of each construction technique within each database on the CB_C. As shown in Figure 3.c, only 11% of variants in d_{2030} have concrete walls, while in d_w, generated using a Sobol sampling technique, design variants are evenly distributed: as a result, the frequency of each of the four types of wall structures, for instance, will be equal to 25% in d_w.

4. Conclusion

This study aims to provide insights on SCS-aligned carbon budgets at the components level and on the gap between these budgets and the current practices, as well as to highlight the impact of respecting carbon budgets on façade design choices. Towards this end, a target cascading approach was adopted to allocate the carbon budget at the components level in line with SCS, based on a database of a representative selection of 5000 design variants generated using the Sobol sampling technique for a multi-family residential building in Geneva, Switzerland. The whole life GWP was calculated for those design variants by following a two-step methodology consisting of first creating the knowledge database then performing target cascading calculations. The relative weight of each building component was then calculated and finally, adapted to the building's carbon budget compliant with the SCS. Results show that the façade is responsible for 21% of the total building embodied carbon budget, coming second in terms of relative impact after the slabs (structure and finishing), which account for 29%. Results also show that if the carbon emissions related to material production and the adopted construction techniques both remain the same, design flexibility will decrease and from 2039 on, no design option will remain available to comply with the building's targeted carbon budget. At components scale, a gap was identified between the glazing's carbon budget in 2050 and the lowest glazing GWP within the database. It should be noted that the generalizability potential of these results, notably the calculated budgets, remains limited and should be used carefully as they are highly project-specific and were calculated according to the specific form factor of the building. Further investigations on a broader range of construction techniques, for diverse residential building archetypes and in different climate zones should hopefully improve the generalizability of the results.

References

[1] Intergovernmental Panel on Climate Change 2018 Global warming of 1.5° C: An IPCC special report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways

[2] Federal Council 2021 Switzerland's Long-Term Climate Strategy

[3] SIA 2040 2017 La voie SIA vers l'efficacité énergétique.

[4] Habert G, Röck M, Steininger K, Lupísek A, Birgisdottir H, Desing H, Chandrakumar C, Pittau F, Passer A and Rovers R 2020 Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions Build. Cities **1** 429–52

[5] Priore Y D, Habert G and Jusselme T 2023 Exploring the gap between carbon-budget-compatible buildings and existing solutions–A Swiss case study Energy Build. **278** 112598

[6] Jusselme T, Rey E and Andersen M 2018 An integrative approach for embodied energy: Towards an LCA-based data-driven design method Renew. Sustain. Energy Rev. **88** 123–32

[7] Jochem E and Rudolf von Rohr P 2004 Steps towards a sustainable development: A white book for R&D of energy-efficient technologies (Novatlantis)

[8] Sobol I M 2001 Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates Math. Comput. Simul. **55** 271–80

[9] SIA 2032 2010 L'énergie grise des bâtiments

[10] Rezaei Oghazi N, Jusselme T and Andersen M 2021 Evaluation of daylighting strategies based on their embodied carbon emissions: a first methodological framework and case study Proceedings of the 17th IBPSA Conference

[11] KBOB 2022 Ökobilanzdaten im Baubereich (Bern)

[12] SN 506511:2020 eCCC-Bât SN 506 511 Code des coûts de construction par éléments Bâtiment