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Closing the gap to sufficiency-based absolute climate targets for wood buildings

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Closing the gap to sufficiency-based absolute climate targets for wood buildings

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Abstract. This research investigated the distribution of the global climate planetary boundary (PB) on a national scale. Then it was distributed to a sector-specific carrying capacity by the principles of acquired rights (grandfathering) and sufficientarianism. Then, four wood dwellings were compared against these carrying capacities using the life cycle assessment methodology. The climate safe operating space for new dwellings is about three times larger when using the principle of sufficiency compared to acquired rights. The rationale for the sufficiency perspective is that it considers the fundamentals of a society leading to a fulfilling life. The concept disregards the current surplus elements in society, which gives more space for emissions for the remaining elements in a fulfilling society. The acquired rights reflect the current society as optimal but require systemic changes in the different sectors to reduce their total impacts to remain within climate PB while keeping the sector's current share of impacts. However, building with wood cannot alone contribute to society staying within the climate target. The end of life contributes most to the impact due to biogenic carbon release, and energy consumption follows next. Reduction of the average yearly built area shows considerable potential to close the target gap. In addition, improving and implementing circularity, carbon capture, and material efficiency would reduce biogenic carbon's end of life impacts. Combined with energy-positive buildings and low-carbon materials, this could be a viable mitigation pathway to explore further.

Keywords: Absolute sustainability assessment, Carrying capacity, Carbon budget, Science-based target, Life cycle assessment, Planetary boundaries.

1. Introduction

Evidence suggests that the Holocene state of the past 11,000 years has been a period of stable Earth conditions supporting human societies to thrive [1]. The Holocene state had an upper CO_2 limit of 350 parts per million (PPM) for a stable climate. In 2019 this boundary was transgressed to an estimated 410 PPM, equal to a temperature rise of 1.1 °C above the reference year 1900 [2]. The Planetary Boundaries (PB) concept was, therefore, introduced as a framework of a safe operating space (SOS) for different Earth systems. Climate change is one of these systems and is already beyond its PB [1]. However, it is still possible for humankind to reverse the transgression of the climate PB [3].

Currently, buildings are a key global driver of greenhouse gas (GHG) emissions [4], which resulted in the introduction of wood as a material with the potential to decarbonise the built environment [5], [6]. One of the most significant challenges is ensuring that future buildings contribute to humanity to stay within the PBs. It involves the vital challenge of distributing the global climate PB to national and sector-level SOS by so-called normative sharing or distributing principles.

Recent research explored various combinations of downscaling the PBs to the building or dwelling level [7]–[11]. Recently, a dynamic method of the SOS of up-front construction emissions (A1-A5) was developed in line with a maximum of 1.5 °C temperature increase by combining four different distribution principles [12]. Another study suggests an absolute sustainability assessment for the consumption of metal products in the building sector [13].

The studies above do not cover the principle of sufficiency, a principle previously identified to need a proper distribution method [14]. In addition, only a few of the studies involve wood dwellings, limiting the current empirical sample. This study, therefore, seeks to assess the dwelling sectorial climate SOS by the sufficientarianism principle and compare it to the more used and industry-adopted acquired rights principle. Second, the study presents four wood dwellings to assess if the relative climate impact improvement of using wood is adequate regarding the Earth's capacity to assimilate GHG emissions.

2. Methodology

2.1. Planetary Boundary and national safe operating space

A cross-disciplinary project in the Danish building industry named Reduction Roadmap [15] has emerged to establish scenarios for a climate SOS for Danish dwellings. First, they identified the absolute global SOS of GHG emissions using the planetary boundary framework, which Petersen et al. [3] translated into CO_2-equivalents. The climate SOS is in accordance with the Paris Agreement of limiting climate-induced temperature increase of the preindustrial era to 1.5 °C towards 2050. It is also the time frame used in this study. Scaling the PB for climate change to the national level of Denmark, the egalitarian distribution principle was chosen, meaning an equal per capita SOS every year [14]. This study presumes the population of Denmark to be 5.8 million people and the global population to be 7.9 billion people, as adopted in the Reduction Roadmap [15].

2.1.1. Distributive justice principles

This research implements two absolute sustainability approaches to distribute the national SOS to an SOS for new dwellings (see Table 1). First, an acquired rights (grandfathering) distribution principle was developed to apply to the Danish housing sector by a consortium comprising industry representatives, research institutes, and NGOs, the previously mentioned Reduction Roadmap project [15]. The attractive feature of this method is its development by and for the industry practice that could ensure a wider adoption in the building sector while at the same time being scientifically rooted. It does not consider the impacts of mobility, energy and water infrastructure that come with new buildings, which puts the SOS at the lower end. Three scenarios are considered: a base scenario of the expected annual average area for new dwellings (RR_{base}), a 50% area reduction of the base scenario ($RR_{50\%}$), and a 75% area reduction of the base scenario ($RR_{75\%}$), see Reduction Roadmap [15] for details.

Table 1. Safe operating space at global, national, industry and area levels. Adapted from [15]. Pop_{DK}=Denmark's population, Pop_{World}=World population, $GWP_{dwelling,hist}$=historical dwelling emissions, $GWP_{DK,hist}$=historical Denmark emissions, $DLS_{shelter}$=decent living energy for shelter and water heating in Denmark, $DLS_{DK,total}$=decent living energy for Denmark.

AESA approach	Global SOS	National distributive justice principle	Industry distributive justice principle	Scenarios for new dwellings
Reduction Roadmap	Scenario M1 - AR6+ from [3] where this scenario has a 95% confidence interval of being the certain climate boundary for the entire Earth	Egalitarianism $\frac{Pop_{DK}}{Pop_{World}} = 0.075\%$	Acquired rights (grandfathering) $\frac{GWP_{dwelling,hist}}{GWP_{DK,hist}} = 3.3\%$	RR_{base}: 3 mill. m^2/year $RR_{50\%}$: 1.5 mill. m^2/year $RR_{75\%}$: 770,000 m^2/year
DLS			Sufficentarianism $\frac{DLS_{shelter}}{DLS_{DK,total}} = 18.6\%$	DLS: $\frac{A_{dwelling,new,DK}}{A_{dwelling,total,DK}} = 1.03\%$

Second, this study employs the recent concept of the decent living scenario (DLS) [16]. The DLS considers a certain energy consumption per capita of basic needs such as nutrition, shelter, and living conditions. The geographical context influences the energy consumption per capita. The DLS focuses on the sufficientarianism distribution principle[14], which requires comprehensive examination among absolute sustainability studies. It offers another advantage by providing a decent standard of living at a materiality level that is less extreme than often anticipated when using the idea of sufficiency [16].

The findings of the DLS related to Denmark, in the Supplementary Information of [16], reveal a total necessary energy consumption of 15.6 GJ/capita. The considered DLS categories for dwellings are house construction, thermal comfort, illumination, and water heating. It includes the water (heating) supply infrastructure but not mobility because the latter is an individual dimension in the DLS study; hence, the SOS is more accurate than the RR. Dwellings necessitate 2.9 GJ/capita (18.6%) of the total energy consumption per capita. The 18.6% is also the considered share of the SOS for new dwellings in Denmark in this study. The average yearly area of new dwellings is 3.072 million m^2 [15]. Statistics Denmark table BOL106 and BOL203 were used to calculate the total dwelling area.

2.2. *Case studies and LCA*

The case study comprised a sample of four wood buildings collected from industry partners and designed between 2010 and 2021. A further description can be seen in Table 2. In case M01, the energy production from photovoltaics is subtracted from the energy consumption in the building.

Table 2. Overview of cases and description.

Case	Building Typology	Structural typology	Cladding	Area [m2]	Foundation	Remarks
M01	3-4 storey apartment building	Wood frame (prefab)	Wood + slate	17,530	Concrete raft	PV panels
R01	1-2 storey terraced house	Cross-laminated timber	Fibre cement	3,720	Concrete raft	
R02	1-2 storey terraced house	Wood frame (prefab)	Wood	4,196	Concrete footing	
R03	2-storey terraced house	Wood frame (prefab)	Steel sheets + wood	13,010	Concrete raft	

The LCA of the dwellings follows the EN 15978:2011 standard. The data collection process and included life cycle stages for the life cycle inventory (LCI) are presented in Figure 1. A projected mix of technologies constitutes the energy production. The functional unit is *1 m^2 of average gross dwelling area of two to four storeys for a 50-year reference period complying with the Danish building code*. After, the LCI was entered into the tool LCAbyg, developed for the Danish construction industry [18]. The impact assessment uses the global warming potential (GWP) with a 100 years' time horizon.

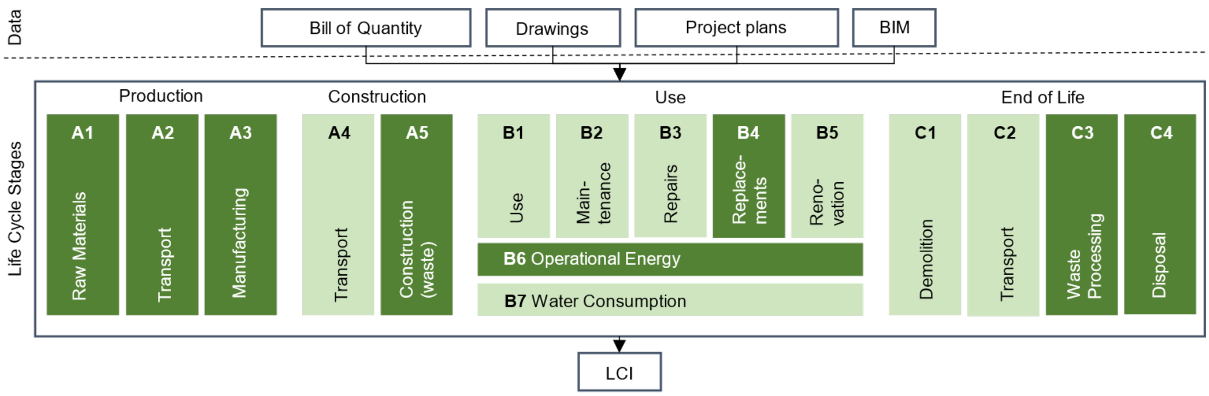

Figure 1. Building data sources and the considered life cycle stages (highlighted dark green) leading to the final life cycle inventory.

3. Results

The first set of results presents the climate change PB as a global SOS. Then, the global SOS is scaled down to the national and dwelling sector levels. Finally, the GWP impact from the four dwellings is presented relative to the four scenarios of SOS at the sector level.

3.1. Distribution of the safe operating space per m²
Table 3 shows the global climate change SOS distributed at the national and sector levels. The analysis reveals a spectrum between 0.4 to 1.61 kg CO_2-eq/m²/year for new dwellings. The decent living scenario leads to a higher allocated climate impact per area than the base and 50% area reduction scenarios. The $RR_{75\%}$ scenario has an SOS for dwellings by about factor 4 compared to the RR_{base} scenario, and it is also greater than the DLS.

Table 3. Distribution of the safe operating space (SOS) from the global level to dwelling per m².

AESA approach	Global SOS	Denmark SOS	Sector SOS	Scenarios SOS
Reduction Roadmap	2.51 Gt CO_2-eq/year	1.88 Mt CO_2-eq/year	61,440 t CO_2-eq/year (only new dwellings)	RR_{base}: 0.4 kg CO_2-eq/m²/year
				$RR_{50\%}$: 0.82 kg CO_2-eq/m²/year
				$RR_{75\%}$: 1.61 kg CO_2-eq/m²/year
DLS			350,000 t CO_2-eq/year	DLS: 1.16 kg CO_2-eq/m²/year

3.2. *Wood dwellings in relation to the absolute climate target scenarios*
The climate impact of the four wooden dwellings was compared to the four scenarios of climate SOS. Figure 2 reveals that the wood dwellings did not reduce enough GHG emissions to meet the climate targets in any of the four scenarios. In the RR_{base} scenario, the dwellings' impacts transgress the SOS by a factor of 12.7 to 20.4, whereas reducing the annual area of new dwellings by 75% leads to a transgression factor of 3.2 to 5.1. The sufficiency scenario shows that the buildings exceed the climate SOS by a factor of 4.4 to 7.

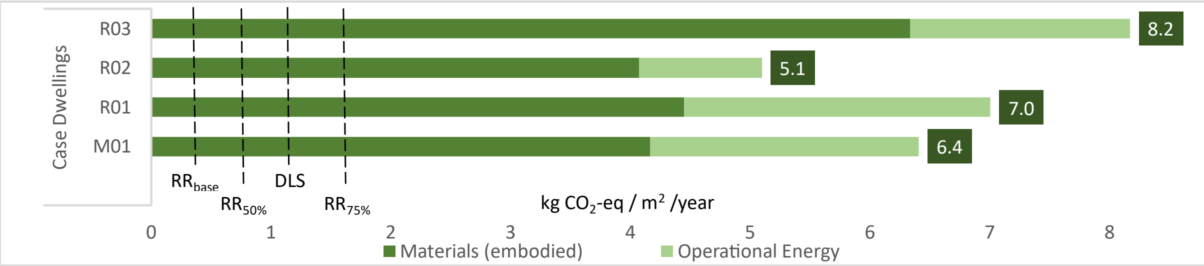

Figure 2. The four case studies' impact relative to the four scenarios of the climate SOS per m2.

Interestingly, the embodied impacts are not within the SOS in any scenario and have a more considerable impact than the operational energy impacts, with a factor of 1.7 to 4 among the dwellings. Figure 3 highlights that embodied impacts mainly occur at the end of life due to the release of biogenic carbon. In contrast, the negative or lower impacts at the production stages are due to the temporary storing of biogenic carbon in the wooden building products. In addition, the energy consumption in the use phase also contributes to considerable emissions.

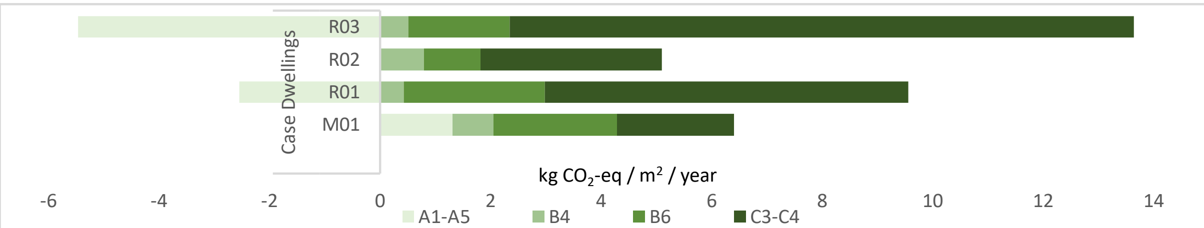

Figure 3. The four case studies' impact contribution from the different life cycle stages.

4. Discussion
This study's use of the distribution principles of acquired rights and sufficiency for absolute sustainability assessment taps into the debate about the architecture of a (national) society in ecological harmony. The first principle presumes that the existing societal activities should still compose the future. It involves systemic sector changes that affect the societies in which they are entangled. The second considers what is fundamentally essential to a society with a decent life, which then influences the sectors. So, is society currently reflecting the desires of its people or has it evolved into an undesirable state that neglects the

essential components of a fulfilling life? It is the crucial question arising from this study's applied distribution principles. For an in-depth discussion on distributing the PBs to the building level, see [19].

The significance of sufficiency on climate targets for wood dwellings
On the question of whether wood enables dwellings to remain within the absolute sustainability targets, this study revealed that wood is still not providing the necessary decarbonisation of Danish dwellings. Several studies have previously shown similar results for buildings in general and of wood [8], [10], [11]. However, these studies apply mainly the distributive justice principles of acquired rights (grandfathering), egalitarianism, and utilitarianism to distribute the national SOS to the sector level.

In contrast to earlier absolute sustainability assessments, this analysis considers one scenario that uses the distribution principle of sufficientarianism. What is curious about this approach is that the SOS is almost three times larger for dwellings than in the RR_{base} scenario. This difference arises because dwellings have a certain prioritisation in the DLS concept [16] as a primary need classification. The priority will, meanwhile, be different from other building categories.

Another factor explaining the target discrepancy relates to the impacts of excessive lifestyle behaviours that are not considered necessary, thus omitted, in a decent living society. It leaves more space for climate impacts for the remaining elements of the DLS. This study simplifies the sufficiency approach by distributing the SOS by the dwellings' energy consumption share of the total energy consumption in the DLS, which assumes an equal emission factor per GJ. It could be nuanced by relating the current climate impact of dwellings to the area per person and GJ per capita explored in [16].

Reduction pathways
The dwellings' climate SOS per m^2 could be even higher in the DLS derived in this study because we divide the housing sector-specific SOS by the expected annual average area of dwellings. Instead, the proposed annual average area of 15 m^2 per person in the DLS study could be implemented. Hence, the SOS per m^2 could be about 3 to 4 times larger if each person lives on these designated 15 m^2 on average.

As indicated by the RR scenarios, reducing the number of annual built areas is a significant pathway to get closer to staying within the SOS for dwellings. Other ways of mitigating the climate impact include (i) enabling material efficiency and circularity that reduces and avoids, respectively, the release of biogenic carbon at the end of life, (ii) using carbon capture and storage at the end of life, (iii) designing energy positive buildings to reduce use stage impacts. Improving products and using low-carbon materials can supplement the previous strategies where steel and cement, still used in wood buildings, can provide up to 54% and 24% reductions if following sustainable development pathways [20], [21].

5. Conclusions

This research downscaled the climate planetary boundary (PB) to a national level by the egalitarianism principle, then to new dwellings in Denmark by the principles of acquired rights (grandfathering) and sufficientarianism. The sufficiency principle allocates a climate safe operating space (SOS) of 1.16 kg CO_2-eq/m^2/year to new dwellings, and it is 0.4 for the principle of acquired rights in the base scenario. This study analysed four wood dwellings in four scenarios of a climate SOS. The buildings are not staying within the target in any scenario. In addition to the acquired rights base scenario, two scenarios shed light on reducing new dwelling areas by 50% and 75% as a viable strategy to close the gap to the climate SOS. Then, a cross-strategy analysis of area reduction, circularity, net-energy-positive buildings, and the efficiency and low-carbon production of materials is needed. This study omits some life cycle stages leading to a performance gap where the buildings will have greater real impacts. In this case, the annual area per dwelling might be even less than in this study if they are to stay within the SOS. It accounts particularly for the sufficiency-based SOS since it covers some side effects of infrastructure, while the analysed buildings do not. It is less apparent for the acquired rights SOS because it is based on current building emissions considering the same life cycle stages as the analysed buildings, so the impact of the SOS and buildings will both be greater, but the proportionality will be very similar. This study is useful in understanding the sufficiency principle for distributing the climate planetary boundary within a nation. Applying the sufficiency principle suggests that new dwellings get about three times larger SOS than by the principle of acquired rights. However, it implies that other building types, considered less necessary to a decent fulfilling life, will have a smaller SOS. Therefore, the study is a contribution to the literature and democratic debate about the roles of different building categories in society that as well can be elevated to the political discussion.

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