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The Absolute Environmental Performance of Buildings

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Abstract

Our paper presents a novel approach for absolute sustainability assessment of a building's environmental performance. It is demonstrated how the absolute sustainable share of the earth carrying capacity of a specific building type can be estimated using carrying capacity based normalization factors. A building is considered absolute sustainable if its annual environmental burden is less than its share of the earth environmental carrying capacity. Two case buildings – a standard house and an upcycled single-family house located in Denmark – were assessed according to this approach and both were found to exceed the target values of three (almost four) of the eleven impact categories included in the study. The worst-case excess was for the case building, representing prevalent Danish building practices, which utilized 1563 % of the Climate Change carrying capacity. Four paths to reach absolute sustainability for the standard house were proposed focusing on three measures: minimizing environmental impacts from building construction, minimizing impacts from energy consumption during use phase, and reducing the living area per person. In

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an intermediate path, absolute sustainability can be obtained by reducing the impacts from construction by 89%, use phase energy consumption by 80%, and the living area by 60%.

Keywords: Sustainability assessment; Life-cycle assessment; Carrying capacity; Absolute sustainability; Environmental performance of buildings; Planetary boundaries

1. Introduction

Traditionally, housing was made from simple local materials with low environmental impacts, but today materials with larger environmental impacts such as concrete, aluminum, and PVC take on a dominant role in the building sector and are used in ever increasing amounts globally [1]. Today, the construction sector is thus responsible for 40% of the global energy use and around 30% of the global greenhouse gas emissions (considering the building sector's share of the global environmental burden) and reducing the environmental impacts of this sector appears to a play key role in mitigating the global climate changes [2].

Reducing the environmental impacts of buildings is not a new topic. The energy crisis in the 1970s made energy savings a "hot" topic, and energy related building regulations became an important tool in restricting the energy loss from buildings [3]. An increasing public awareness of the anthropogenic climate changes led, in the 1990s, the building sector to recognize the need for changes in the way buildings were designed, built, and operated [4]. This recognition was manifested by the first environmental building rating systems, allowing for assessment of the environmental impacts/performance of the whole building.

Reduction of the environmental impacts from buildings, was in the beginning primarily focused on reducing the operational energy which also is reflected by building legislation such as the Energy Performance of Buildings Directive in the European Union[5]. However, the focus, in recent years, on the whole life cycle perspective of buildings has become more prevalent [3] and studies have identified the embedded energy in building materials as an important indicator in the environmental performance assessment process of buildings [6]. The application of the Life Cycle Assessment (LCA) methodology has been increasing in the building sector only within recent years, even though the methodology has been known in the sector for many years; for example the Building Environmental Assessment Tool (BEAT) [7] has been available in Denmark since the 1990s but has been used mainly for research purposes and is not widely used in the building sector. Life cycle thinking was introduced, in 2013, in the assessment scheme LEED in the form of LCA as an optional analysis that could improve the overall energy and environmental rating of a building [8]. Another example is the assessment scheme DGNB where a full LCA of the building is mandatory [9].

The general approach to building sustainability performance assessment in schemes, like the ones mentioned above, is to rate buildings through relative comparisons, i.e. building "A" compared to building "B" which form the basis of a sustainability benchmarking [9].

LCA of buildings is a widely studied topic in research [1]**.** One of the first LCA studies was carried out by Peuportier and was based on a comprehensive building inventory where different buildings using concrete and wooden blocks were assessed [10]. Asif et al. carried out LCA of a dwelling in Scotland and reported that the embodied energy in the construction materials was one of the most important contributors to the environmental impact of the building [11]. LCA of six common single-family house construction typologies in Jordan highlighted that energy impacts and water depletion were good proxy indicators in Jordan [12]. Marjaba and Chidiac conducted a critical review of building LCAs and other approaches for assessment of a building's sustainability performance and concluded that LCA is the most suitable methodology for this purpose [13].

LCA in its present form facilitates comparative assessments; i.e. it is possible to assess whether building "A" has a better/worse environmental performance than building "B". However, the methodology as such does not provide answers to how the building performs relative to indicator specific target levels such as carrying capacity of the local, regional, as well as global environment. The need for an "absolute" evaluation criteria, based on a scientific understanding of the capacity of the environment to cope with anthropogenic perturbations/emissions instead of the current practice in the form of traditional comparative environmental impact assessment, was identified in a study by Olgyay and Herdt [14]. Identification of carrying capacity based environmental sustainability assessment has been attempted in the past [15], but these attempts were not aligned with the fundamental principle of life cycle thinking in ISO 14040 [16].

The term *Ecological Footprint* was introduced in 1992 as a concept for comparison of human impact on the Earth, or a specific area, to the bio-capacity of the same area, and the ecological footprint is a popular indicator of humanity's level of sustainability [17]. These attempts to quantify carrying capacity have continued for the last decades, and recent studies have enabled a more nuanced approach to sustainability assessment based on environmental carrying capacity. The concept of planetary boundaries was introduced, in 2009, as "the safe operating space for humanity with respect to the earth's system and in association with the planet's biophysical subsystems and processes" [18]. This was followed by a framework for *Absolute Sustainability* introduced by Bjørn [19]. This particular part of the LCA method development led to a set of carrying capacity based normalisation references for LCA presented by Bjørn and Hauschild [20]. This is in contrast to traditional normalisation references which allow for an absolute sustainability assessment.

Our study seeks to operationalize the absolute sustainability assessment framework for assessing a building's sustainability performance in an absolute context. We demonstrate, in our paper, with a case study how carrying capacity based normalization factors can be applied. Also, we have developed a facet of the LCA methodology which facilitates an estimation of a building's carrying capacity – more precisely the carrying capacity allocated to the service of accommodation. Finally, strategies, to improve the construction industry's performance in the context of absolute sustainability assessment, are presented and elaborated on.

2. Method

The study, presented in this paper, takes into consideration absolute sustainability assessment measures which enable quantification and evaluation of the absolute sustainability performance of a building. Bjørn and Hauschild [20] presented a framework for absolute sustainability assessment based on the application of carrying capacity based normalization factors in LCA. There are two ways to operationalize absolute sustainability assessment in LCA; one is to develop characterization factors for impact assessment based on carrying capacity, the other is simply to use carrying capacity based normalization factors. In an absolute environmental sustainability assessment, based on normalization factors, these factors are expressed as the carrying capacity of a region divided by its population. Such normalized measures provide a representation of a person's annual share/occupation of the carrying capacity.

We use carrying capacity based normalization factors to quantify buildings' sustainability performance in our study. A building is, according to this approach, sustainable if its annual environmental burden is less than the share of the environmental carrying capacity of the earth available to the building type to which the building, under assessment, belongs.

Two case buildings were evaluated in our study, one representing prevalent Danish building practices and one representing low environmental impact practices. Initially, an LCA was conducted assessing both case buildings, and the results of these assessments were subsequently compared to those of similar LCA studies to get an overview of the assessment validity. The absolute normalisation factors proposed by Bjørn and Hauschild [20] were then applied along with an allocation-key facilitating estimation - the (acceptable impact space) share available to a building yielding target values - to assess the absolute sustainability of the building. The absolute sustainability performance of the dwelling, across a multitude of impact categories, was quantified based upon the impact potentials obtained from the LCA combined with the target values for the dwelling.

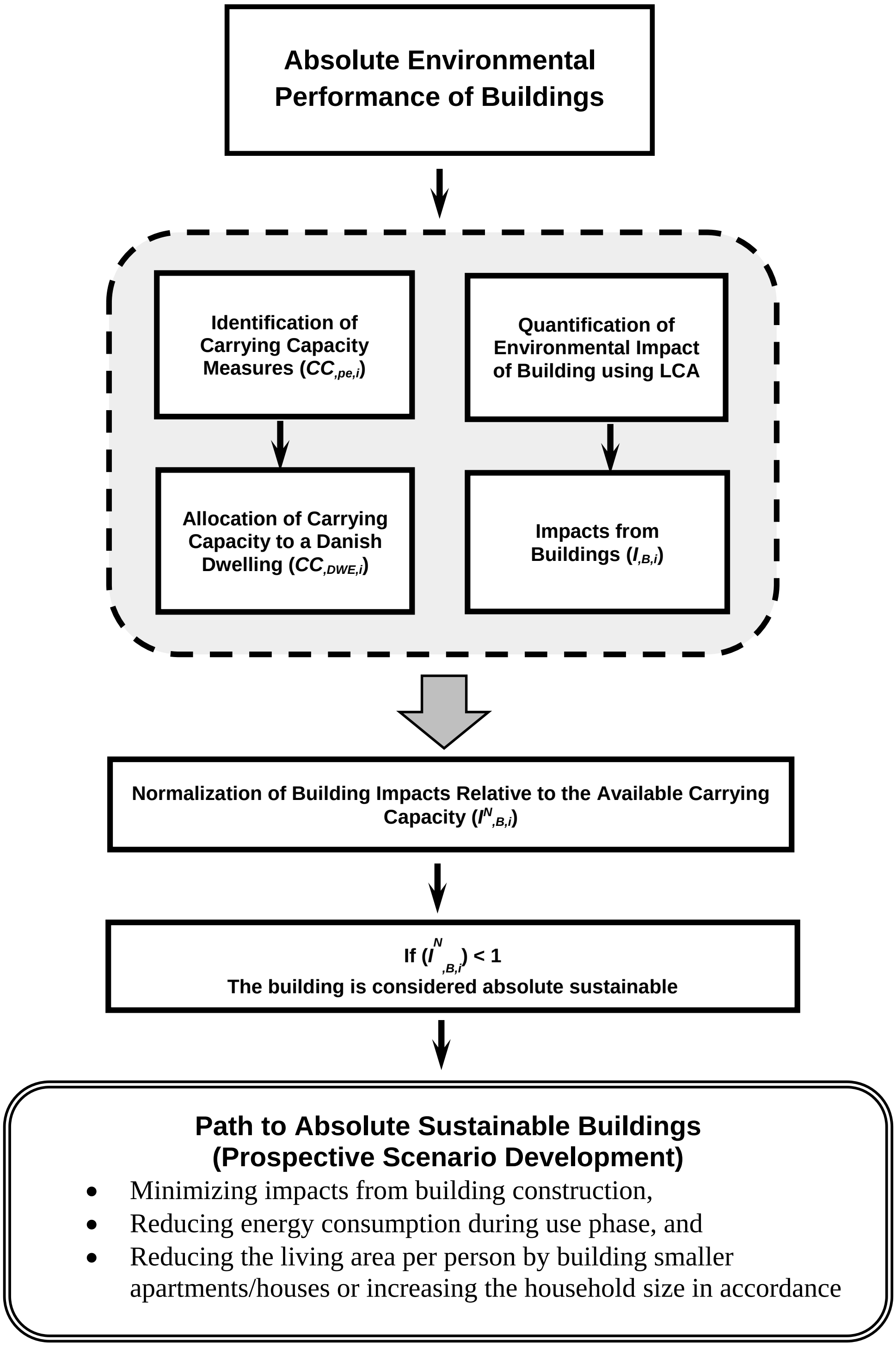


Figure 1 Method for Assessing Absolute Sustainbility of Buildings.

2.1 Absolute Sustainability Assessment

The framework proposed by Bjørn and Hauschild [20] was followed to assess a building's absolute sustainability, and some operational challenges were faced to implement this framework. Initially, it was essential to obtain the absolute characterization factor (absolute normalization factor) sets representative for the 11 impact categories used to assess the carrying capacity estimates presented by Bjørn and Hauschild [20]. First, we implemented the characterization and absolute normalization factors for the five impact categories suggested by Bjørn and Hauschild [20] in GaBi 6.0 [21]: Terrestrial Acidification (TA), Terrestrial Eutrophication (TE), Water Depletion (WD), Land Use – Soil Erosion (LUS) and Land Use – Biodiversity (LUB). We applied the ILCD recommended LCIA methods [22] for the remaining six impact categories; Climate Change (CC), Ozone Depletion (OD), Freshwater Eutrophication (FE), Marine Eutrophication (EP), Photochemical Oxidant Formation (POF) and Freshwater Ecotoxicity (FET). Table 1 summarizes the adopted impact categories for our study which are aligned with those used by Bjørn and Hauschild [20] as well as the global carrying capacity based normalization factors for each impact, also in accordance with Bjørn and Hauschild [20]. The normalization factors are here annual person equivalent based carrying capacities ($CC_{PE,i}$) as presented in Table 1.

Estimation of carrying capacities, as presented by Bjørn and Hauschild [20], involve various uncertainties. Table 1 includes two normalization factors estimates for absolute sustainability assessment in the impact category CC. One is based on the IPCC suggested global climate change target of maximum 2 °C increase, intended to limit the global warming to 2 °C above pre-industrial levels [23]. The other is a more precautionary target of reducing radiative forcing from greenhouse gasses to 1 W/m^2 [20]. Our study includes both of these carrying capacity based normalization factor estimates, and leaves it open which of the two options is most relevant as basis for the absolute normalisation.

Table 1 Global Person Equvivalent Carrying Capacity Based Normalization Factors.

Impact Category	**Global Normalisation Factor (Annual Person Equivalents) ($CC_{PE,i}$)** [20]	**Implementation Approach**
Terrestrial Acidification (TA)	$2.3 \cdot 10^3$ mole H^+ eq./yr	Implemented characterization and normalisation factors in Gabi 6.0 from Bjørn and Hauschild [20]
Terrestrial Eutrophication (TE)	$2.8 \cdot 10^3$ mole N eq./yr	
Water Depletion (WD)	306 m^3/yr	
Land Use Soil Erosion (LUS)	1.8 ton eroded soil/yr	
Land Use Biodiversity (LUB)	$1.5 \cdot 10^4$ $m^2 \cdot$year/yr	
Climate Change (CC, temp.*)	985 kg CO_2 eq. /yr	As mentioned in Bjørn and Hauschild [20] these impact categories are considered compatible with Hauschild [22] and are for this reason recommended impact categories for absolute sustainability assessment. Therefore, the characterization factors, for these recommended impact categories, were taken directly from the parent impact assessment methods and only supplemented with absolute normalisation factors, as mentioned in Bjørn and Hauschild [20].
Climate Change (CC, rad.**)	522 kg CO_2 eq. /yr	
Ozone Depletion (OD)	0.078 kg CFC-11 eq./yr	
Freshwater Eutrophication (FE)	0.84 kg P eq./yr	
Marine Eutrophication (EP)	29 kg N eq./yr	
Photochemical Oxidant Formation (POF)	73 kg NMVOC eq./yr	
Freshwater Ecotoxicity (FET)	$1.9 \cdot 10^4$ [PAF]$\cdot m^3 \cdot$day/yr	

2.2 Normalisation – Absolute Sustainability Approach

The impact potential results obtained from an impact assessment are normalised applying the absolute sustainability carrying capacity based normalization factors developed by Bjørn and Hauschild [20], thereby seeking to relate the impact potentials with the earth systems capacity to cope with these impacts. The (absolute sustainable) normalised impact (I^N) for a building (*B*) for an impact category (*i*) is calculated using Equation 1 .1.

$$I_i^N = \frac{I_{B,i}}{CC_{PE,i}} \quad \textbf{(Equation 1.1)}$$

where $I_{B,i}$ is the total annual contribution to the impact potential from the building, *B*, in the impact category *i*, and $CC_{PE,i}$ is the annual person equivalent carrying capacity allocated to the impact category *i* (see table 1).

In an absolute sustainable scenario, all life cycle impacts from a person's direct and indirect activities, i.e. the aggregated person impact profile as known from e.g. [24], should be less than the annual person equivalent carrying capacity, $CC_{PE,i}$. The results from equation 1.1 are unable to provide any information on the building's performance relative to the share of the carrying capacity available to the service of accommodation, and therefore the building as such, in an absolute sustainable scenario. However, when focusing on a certain service, the absolute normalized impact in a certain impact category should relate to the carrying capacity available for a person to use for this specific service which, in this case, is a building ($I_{B,i}^N$):

$$I_{B,i}^N = \frac{I_{B,i}}{CC_{BT,i}} \quad \textbf{(Equation 1.2)}$$

where $CC_{BT,i}$ is the annual carrying capacity allocated to the impact category *i* for the specific building type (*BT*), which in this study is a dwelling. The normalised impacts for each impact category are thereby represented by the total annual impact of the building divided by the allocated annual carrying capacity to the specific building type, i.e. dwellings, within a given impact category. A building is assessed as environmentally (absolute) sustainable if $I_{B,i}^N < 1$, implying that the building has less impact on the environment than the earth system can cope with.

2.3 Allocation of the Carrying Capacity of the Earth System

In order to gain a realistic idea about building performance in an absolute environmental sustainability perspective, it is necessary to quantify the building's share of the world's available carrying capacity. These shares will also assist in guiding the building industry to a more realistic perspective of building sustainability performance relative to an absolute waypoint. The normalisation described in section 0 relates the building's impact potentials to a fraction of the world's available carrying capacity for the service (i.e.

building). This fraction is the so-called share of the total carrying capacity allocated to a specific building type, in this case a dwelling. This share multiplied with the estimated carrying capacity within a specific impact category equals the maximum allowed building impact per year and therefore a measure of the absolute sustainability performance of the building.

There is probably no single objective way to allocate the world's carrying capacity to a building or for that matter any other service, as any allocation method will be perceived as subjective and therefore more or less fair depending on cultural perspective. In our case, the allocation is carried out in two steps:

1. An allocation of the earth system's carrying capacity is conducted on a person equivalent basis (to account for the capacity available for all personal activities), thereby distributing the carrying capacity of the earth system on a per capita basis.
2. An allocation of a part of the person equivalent quantified in 1) to specific building related services, in our case, the provision of accommodation including effects from construction, operating, and maintaining a Danish dwelling. Data on building demolition was not included due to data uncertainty (i.e. prediction of waste system performance half a century from now), context specific conditions, etc. but is expected to have an insignificant impact on the final results.

Concerning the first step, the allocation method is based on an egalitarian approach uniformly distributing the earth carrying capacity entailing that each world citizen receives the same share size. The estimates of the environmental carrying capacity of the earth system are based on the study by Bjørn and Hauschild [20] introducing carrying capacity based normalisation in LCA (see Table 1)**.**

The second step involves allocation of a person equivalent carrying capacity to the specific building types. Our study focuses on the analysis of the dwelling building type, and the second step of the allocation therefore aims at allocating parts of the person equivalent to the service provided by this specific building type. The second allocation step – the allocation of the person equivalent carrying capacity to specific building services could be conducted through various allocation schemes, here we consider two options: Allocation by economic value and allocation by contemporary environmental pressure:

Option 1: Following the economic allocation scheme in step 2, the allocation is conducted according to the building related expenses, relative to a person's total direct and indirect expenses. The more money a person spends on construction, operation, and maintenance of the building as accommodation service, the greater a share of the person's carrying capacity equivalent would be allocated to the service provided by this building.

Option 2: Following the current environmental pressure allocation scheme, allocation is conducted according to the building's environmental impacts compared to the total environmental impacts resulting from a person's total direct and indirect expenses.

An economic allocation assigns an equal share of the carrying capacity to all impact categories regardless that some products and services would have a natural variation on environmental pressure across the various impact categories. This may consequently introduce non-optimal allocation of impacts for some services. Agricultural activities, for instance, will tend to have a larger relative impact contribution on the nitrogen- and phosphors cycle related impact categories than what would be expected from the building industry. The allocation based on current environmental pressures, on the other hand, disfavours industries or services where an impact reduction has already been carried out; these industries or services will receive a smaller share (despite of the effort to improve their environmental performance) of the capacity allocated compared to industries or services with a higher environmental pressure. The data quantifying societal expenses are made available from national or international statistical databanks whereas sufficient data regarding the environmental pressures of different societal activities are not currently available. We therefore use the economic allocation approach in this paper.

The annual carrying capacity available to the building type dwelling (CC_{DWE}) within a specific impact category (*i*) is calculated according to Equation 1.3:

$$CC_{DWE,i} = CC_{PE,i} \cdot A_{HH,i} \cdot AH_{HH,dwe,i} \cdot R_{BT,ave} \quad \textbf{(Equation 1.3)}$$

where CC_{PE} is the person equivalent carrying capacity according to Bjørn and Hauschild [20], A_{HH} is the share of the person equivalent allocated to the household, $A_{HH,dwe}$ is the share of the household allocated to the dwelling service, and R_{ave} is the average number of residents in the specific building type (BT).

A_{HH} is in this study the share of GDP that the final consumption expenditures of households represented and was identified as 57.1% based on EU-28 conditions in 2013 [25]. The estimation of $A_{HH,dwe}$ was based on the classification of individual consumption by purpose (COICOP) [26]. The two COICOP categories related to the building's life cycle expenses are *CP04 – Housing, water, electricity, gas, and other fuels* and *CP05 – Furnishings, household equipment, and routine household maintenance*.

Table 2 List of subcategories of CP04 and CP05 relevant* to the dwelling, including identification of the share of the subcategory allocated to the dwelling**.** [25,26]

Category	Comments	% of Main Category	Share of Subcategory Allocated to the Dwelling
CP04 – Housing, Water, Electricity, Gas and Other Fuels			
04.1.1 – Actual rentals paid by tenants	For main residence	19.3 %	100 %
04.2.1 – Imputed rentals of owned occupiers	For main residence	51.1 %	100 %
04.5.1 – Electricity	All electricity used	7.1 %	29 %**
04.5.2 – Gas	All gas used	3.9 %	100 %
04.5.3 – Liquid fuels	Domestic heating and lighting oils	1.9 %	100 %
04.5.4 – Solid fuels	Coal, coke, firewood and the like	0.6 %	100 %
04.5.5 – Heat energy	District heating, incl. hire of meters etc.	1.4 %	100 %
Total of category to dwelling	**80.1 %**		
CP05 – Furnishings, Household Equipment and Routine Household Maintenance			
05.1.2 – Carpets and other floor coverings	Loose carpets, fitted carpets, linoleum and the like.	5.4 %	40 %
05.3.1 – Major household appliances	Air conditioners, space- and water heaters, refrigerators, freezers etc.	10.1 %	40 %
Total of category to dwelling	**6.2 %**		

*All other irrelevant consumption categories under CP04 and CP05 were not assigned shares and therefore not included in this table.
**Share of a household's electricity consumption related to building operation [27].

The expenditures accounted for by CP04 and CP05 represent respectively 24.1% and 5.6% of the average total household expenditures [25]. CP04 and CP05 also include expenses not related to the building life cycle within the described boundaries of our system such as electricity consumption for appliances such as TV and radio for example. The two categories are therefore subdivided to identify the share of the categories only related to the building life cycle. From CP05, the expenses related to the building life cycle within the described boundaries of our system were estimated to 80.1%. For CP04, the expenses relating to the boundaries of our system were estimated to amount to 6.2% based on further estimates of the relevant expense shares within each sub-category within the defined boundaries of our building product system – see Table 2. Some of the subcategories are only partially allocated to the dwelling, and not all of these allocations estimates could be substantiated in the literature. A sensitivity study was therefore carried out, investigating the effect of deviation in the allocation of all the subcategories which were only partially allocated to the dwelling. For the Climate Change category, the deviation of +/- 20% in allocation estimates in the subcategories influenced the resulting climate change allocated to the dwelling, $CC_{dwe,cc}$, with +/- 1%. The precision of the estimates made in the subcategories is thus not of great importance to the final results.

$R_{BT,ave}$ was based on estimates from Statistics Denmark [28] for a single-family dwelling and amounts to 2.6 residents.

Based on the estimate of the household consumption allocated to the dwelling service, $A_{HH,dwe}$ was estimated as the sum of the allocations in category CP04 and CP05 using equation 1.4.

$$A_{HH,dwe} = 0.241 \cdot 0.801 + 0.056 \cdot 0.062 = 0.197 \quad \textbf{(Equation 1.4)}$$

2.4 Description of the Case Study

The two case buildings were assessed: a *Standard House (SH)* which reflects the prevailing/contemporary Danish building practice, and the *Upcycle House (UH)* which was built mainly from reused or recycled materials.

SH was built on a line foundation of concrete, with a socket of insulated lightweight concrete blocks, and the ground slab was reinforced concrete on EPS, with wood or tile flooring. The outer walls consist of an inner wall of aerated concrete, mineral wool insulation, and an outer wall of masonry. The roof consists of wood roof trusses with a solid under-roof and roofing tiles, with mineral wool as insulation, and a ceiling of surface mounted plasterboards. The internal walls are aerated concrete with plaster and painted glass felt, and aluminum clad timber windows with triple glazed panes.

The materials used for UH were all recycled or reused products. The house was founded on screw foundations, and two freight containers form the bearing structure. The façade was mounted with plates of composite material and the roof with aluminum plates. The windows were triple glazed, and the internal walls and floors were covered with OSB plates. All insulation used in the house was paper wool insulation made from recycled paper waste.

The UH is in this study intended to represent a realistic best building practice in terms of buildings with low environmental impacts/optimized environmental performance. Both buildings were scaled to have the same net floor area (i.e. 128 m^2) and built on the same location (Hedensted, Denmark).

Both buildings have a primary energy consumption for building operation (heating, ventilation, and domestic hot water) which amounts to 37.8 kWh/m^2 per year according to the Danish standard calculation method [27] of which 35% is consumed as electricity and 65% as heating.

2.5 Life Cycle Assessment

The LCA of the two case buildings described above was carried out using standard procedures in the form of ISO 14040:2006 [16]. The system boundaries were expanded compared with past studies (see table 3) in order to include primary processes of various life cycle phases of the buildings such as construction phase, demolition, and transport. The actual product system was modelled in GaBi 6.0 [21].

2.5.1 Scope and Functional Unit

LCA of buildings is commonly used in environmental building rating systems, e.g. in the Deutsche Gesellshaft für Nachhaltiges Bauen (DGNB) [9], which is the prevailing building rating system in Denmark in terms of sustainability performance. Rating systems like DGNB often include the life cycle stages presented in Table 3, leaving out a range of stages due to lack of representative data, uncertainties, and large data variance, which further complicate environmental benchmarking of buildings. In our study, we seek to widen the scope of the more conventional LCA approaches usually applied in building rating systems. Table 3 specifies the lifecycle stages of a building LCA with the expanded system boundaries (present study) compared to an LCA relying on conventional system boundaries, typically considered in past studies.

A building provides a service in the form of a housing area, typically for a long (i.e. compared to the service life of other products and services assessed in various LCAs) period of time. Therefore, to account for this service, the functional unit for this assessment is defined as a typical Danish single-family dwelling with a net floor area of 128 m^2 and an estimated service-life of 50 years (based on past studies by [9,29,31,32]). See section 2.4 for further detail.

Table 3 Life cycle stages of the building LCA applied in our study (expanded system boundaries) compared to the life cycle stages included in a conventional building LCA. [√] indicates if processes in a life cycle stage are included, [-] indicates if the process of a life cycle stage are omitted, and [(√)] indicates that the processes of a life cycle stage are partially included.

LCA Boundary	**Production Phase**			**Construction Phase**				**Use Phase**							**End of Life/New Product System**					
	Extraction	Transport	Production	Material spilled	Energy consumption	Transport	Land conversion - Site	Maintenance	Replacements	Repair	Modifications	Operational energy	Water	Land use - Site	Transport	Demolition	Waste treatment	Recycling	Landfill	Avoided energy production
Past studies [9,30]	√	√	√	-	-	-	-	-	√	-	-	√	-	-	-	-	√	√	√	√
Expanded – present study	√	√	√	√	√	√	√	-	√	√	-	√	-	√	√	(√)	√	√	√	√

2.5.2 Life Cycle Inventory

The basic inventories of the two case buildings are provided in ref. [30] for the SH and ref. [29] for the UH. The background inventory data were sourced from the Ecoinvent 2.2 database [33] instead of the Ökobaudat database [34] used in both [30] and [29]. In the case, where no relevant building products were available in the database, the product content was estimated based on Environmental Product Declarations (EPD), and the product was then modelled based on the material composition, in accordance with the EPD.

In a few cases, additional assumptions relating to physical properties, such as density or dimensions of the materials, had to be made. Estimation of such missing physical properties was conducted based on material properties of similar products on the market. When material recycling rates had to be estimated, recycling rates representative for the current Danish conditions were applied whenever possible, otherwise most representative data were selected based on geographical relevance.

A spill off material will occur at the construction site; the volume of this is highly dependent on the varying practice of the contractors. A conservative estimate of 1% spill material spill, at the construction site, was applied in this study. Furthermore, an estimated spill of 5% of recycled material was applied to account for effects related to avoided production at the 'end of life' stage. Materials for repair throughout the building service life were assumed to be 1% of the initial material amount used. Only materials exposed to the ambient environment such as roof tiles, plasterboards etc. were assumed to need replacement. In cases, where transport distances from plant to storage were not included in the original Ecoinvent dataset, additional transport from plant to building site was added. The missing transport distances were estimated in accordance with the recommendations provided by Ecoinvent [33] whenever possible and alternatively by estimates based on available information from product manufactures. Further transport was included from building location to disposal site for all materials based on the distance from construction site to the nearest recycling depot.

2.5.3 Life Cycle Impact Assessment (LCIA)

In essence, LCIA seeks to transform the elementary flows of the building product system quantified in the inventory into impact potentials for resource depletion, ecosystem impacts, and impacts on human health. Several recent and older LCIA methodologies are available and can be applied for quantification of the environmental performance [35]. For our comparison the CML 2001 method developed by The Institute of Environmental Science (CML) at Leiden University [36] was used. Historically, this method has frequently been used for assessing Danish buildings, and choosing this method enables us to relate our results to past studies carried out on Danish buildings [29,30,37,38]. For the absolute sustainability assessment, the method presented by Bjørn and Hauschild [20] was used.

3. Results and Discussion

3.1 Case Study LCA Results (Comparison)

Table 4 presents the LCA results found in the literature on the case buildings together with the results obtained in our study. For the SH, the comparative validation of the results obtained in our study was conducted across the five impact categories; Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP) and Eutrophication Potential (EP). For the UH the results obtained from the literature only covered the impact category GWP.

The impact potentials calculated in our study are noticeable higher than those in the reference studies, irrespective of the impact category. The GWP obtained for the SH is 25% higher than the impact potential in the reference study while the GWP on the UH found in our study is approx. 300% higher than the corresponding value in the literature. For the SH, larger deviations are seen in the remaining four impact categories as well. It is important to highlight that the inventory used in this study is based on the inventory data from the two reference studies [29,30]. There are several factors the deviations could be attributed to: Choice of database, inventory assumptions, software tool, as well as boundary system. The database used in the current study is EcoInvent, where the datasets used in the reference studies are based on Ôkobau.dat and

ESCUO. Though the inventory of this study is based on inventories from the reference studies, there are still different assumptions in physical properties and dataset choice that could vary leading to further deviations in results. It is a well-known fact that differences in software tool and inventory database are also sources of deviation [39,40], as are differences in boundary conditions. For the large deviation in GWP in the UH, it should be noted that a large part of the materials are wood-based and that all materials are recycled, which increased the deviation.

Table 4 Annual impact potentials for the current study compared to those of the reference studies using CML2001 method [29,30]. Impact potentials are for the entire building.
(GWP - Global Warming Potential, ODP - Ozone Depletion Potential, POCP - Photochemical Ozone Formation Potential, AP - Acidification Potential, EP - Eutrophication Potential)

		Standard[1]			**Upcycle**[2]		
		Current Study	***Previous Study*** [30]	***Deviation***	***Current Study***	***Previous Study*** [29]	***Deviation***
GWP	[kg CO_2eq/yr]	577	460	+25%	293.4	72.8	+303%
ODP	[kg R-11eq/yr]	$5.2*10^{-5}$	$1.7*10^{-5}$	+206%	No information available in reference study		
POCP	[kg Ethene eq/yr]	0.35	0.17	+106%			
AP	[kg SO^2eq/yr]	3.5	2.0	+75%			
EP	[kg PO^4eq/yr]	0.85	0.22	+286%			

[1] 120-year service life
[2] 50-year service life

3.2 Carrying Capacity Available to the Building

The carrying capacities for a single-family house based on economic allocation are presented in Table 5 as the maximum allowable annual impact of an absolute sustainable single-family house. Therefore, a single-family house with less impact on the environment than the calculated carrying capacity values based on planetary boundaries is considered to be absolute sustainable. For example, in order not to exceed the planetary boundary for CC, the annual impact of a dwelling must not exceed 152 kgCO_2-eq. The carrying capacity values for a range of impacts potentials are provided in Table 5.

Table 5 Annual allocated carrying capacity per single-family house, $CC_{BT,i}$, with an average of 2.6 person per dwelling.

Impact Category	$CC_{BT,i}$	**Unit**
Terrestrial acidification (TA)	670	mole H^+ eq./yr
Water depletion (WD)	89	m^3/yr
Land Use Soil Erosion (LUS)	0.52	ton eroded soil/yr
Land Use Biodiversity (LUB)	4369	m^2·year/yr
Climate change (CC, temp.*)	287	kg CO_2 eq./yr
Climate change (CC, rad.**)	152	kg CO_2 eq./yr
Ozone Depletion (OD)	0.02	kg CPC-11 eq./yr
Freshwater eutrophication (FE)	0.13	kg P eq./yr
Marine Eutrophication (EP)	9	kg N eq./yr
Terrestrial Eutrophication (TE)	815	mole N eq./yr
Photochemical oxidant formation (POF)	14	kg NMVOC/yr
Freshwater Ecotoxicity (FET)	2912	PAF·m^3·day/yr

* Threshold, temperature increase, 2 °C

** Resilience, radiative forcing increase, 1 W·m^2

3.3 Absolute Sustainability of Case Buildings

The focus of our study is to assess the environmental performance of buildings from an absolute sustainability perspective. As explained in the methodology section, we have obtained LCA results for our case study building within the impact categories suitable for absolute sustainability assessment, in accordance with the recommendations presented by Bjørn and Hauschild [20]. Based on the methodology presented by Bjørn and Hauschild [20], impact assessment results for both the UH and the SH are represented in Table 6 for a 50 year and 120 year service life, with and without use phase energy.

The impact potentials obtained for the SH and UH vary considerably within certain impact categories. For example, the difference between SH and UH amounts to a factor 2.9 in CC and a factor 3.0 in OD, both detected in the scenario 50 year service life excluding use phase energy. Within most impact categories like LUS and FET only minor variations between the UH and SH results are observed for scenarios excluding the use phase. The major contributions to all impact categories a (as would be expected) originate from use phase energy consumption, i.e. to a lesser extent from the construction of the buildings**.** The energy consumption is identical for the two case buildings. Therefore, a change from conventional to upcycled/recycled materials, in categories where the impacts from construction are smaller than those resulting from energy consumption (i.e. all of the impact categories covered by our study), will affect the total impact to a lesser degree.

The CC impact contribution from the SH is 2376 kgCO_2eq per year applying a 50-year service life including use phase energy consumption. When the use phase energy consumption is excluded, the impact potential drops approx. 56 %. If the service life of the building is increased to 120 years, the impact is distributed over a longer period and thereby yields an impact of 595 kgCO2eq per year for the entire building when the use phase energy is excluded. The service life thus has considerable influence on the annual impact. It is therefore a paramount step towards a more fair absolute sustainability assessment to estimate a realistic building service life.

The results listed in Table 6 are normalized using the annual allocated carrying capacity per single-family house from Table 5 as normalization references and expressed in terms of percentage of the carrying capacity utilized in Table 7. Both case buildings exceed the available carrying capacity of LUS, CC and FE. In the 50-year service life scenarios including use phase energy consumption, the LUS impact potential of the SH corresponds to 999% of the carrying capacity, while for the UH the LUS impact potential corresponds to 989%. In the same scenario, and in terms of the CC, the SH impact corresponds to 1563%, while the UH corresponds to 1111% of the carrying capacity based on a planetary boundary derived from radiative forcing. For the FE impact category, the impact potentials obtained for both buildings correspond to 524% and 454%, respectively, of the carrying capacity. Both buildings are close to the carrying capacity within the impact categories FET and WD. The SH utilizes 74% of the WD carrying capacity for and 94% of the FET, whereas the UH utilizes slightly less; 61% for WD and 87% for FET. To sum up, both buildings in the 50-year service life scenarios - including use phase energy consumption - are exceeding the carrying capacity of three of the eleven included impact categories (LUS, CC (both assessment approaches) and FE) and is close exceed the carrying capacity of FET.

One of the reasons why impact contributions within certain categories did not exceed the carrying capacity is that the carrying capacity based normalization reference is not yet spatially differentiated [20], and therefore the impact categories, addressing local/regional impacts, tend to quantify environmental performance in accordance with an overall/worldwide average carrying capacity. It should be noted, when interpreting the results, that the impact relevance in practice is dependent on the location of the building, source of raw material, and energy mix of the local electricity/energy grid.

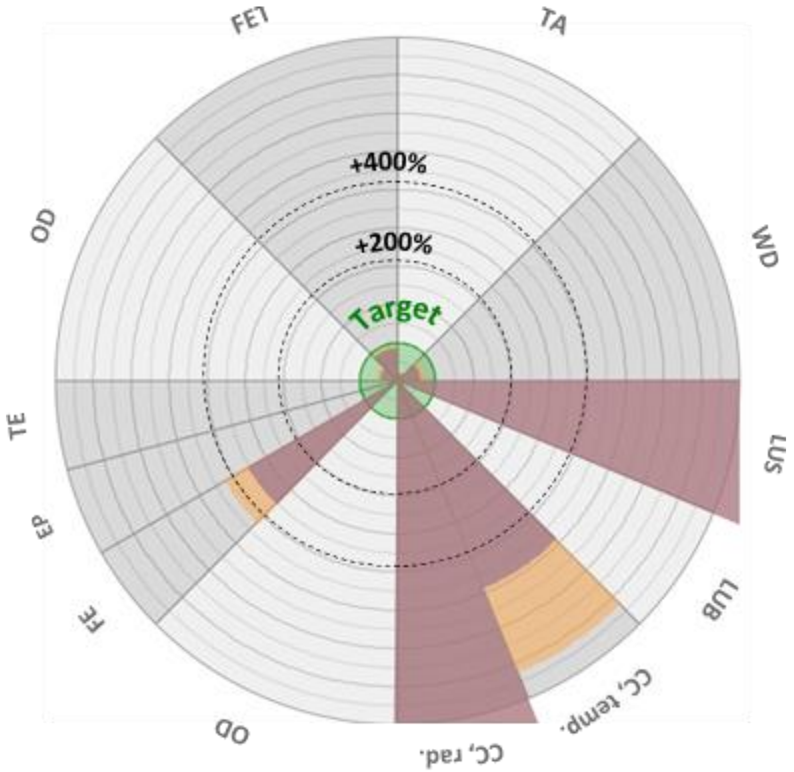
Table 6 Annual impact assessment results obtained for the two case buildings, $I_{B,I}$, for a living area of 128m^2. The impact potentials are obtained applying a 50-year or a 120-year service life for the buildings and either including or excluding the impact potentials relating to the energy consumption during the entire servie life. UH is Upcycle House and SH is Standard house.

(TA – Terrestrial Acidification, WD – Water Depletion, LUS – Land Use Soil Erosion, LUB – Land Use Biodiversity, CC – Climate Change, OD – Ozone Depletion, FE – Freshwater Eutrophication, EP – Marine Eutrophication, TE – Terrestrial Eutrophication, POF – Photochemical Oxidant Formation, FET – Freshwater Ecotoxicity)

		$I_{B,i}$ *50-Year Service Life Incl. Use Phase Energy*			$I_{B,i}$ *50-Year Service Life Excl. Use Phase Energy*			$I_{B,i}$ *120-Year Service Life Incl. Use Phase Energy*			$I_{B,i}$ *120-Year Service Life Excl. Use Phase Energy*		
Impact Category	**Unit**	SH	UP	**SH/UP**	SH	UP	**SH/UP**	SH	UP	**SH/UP**	SH	UP	**SH/UP**
TA	mole H^+ eq./yrs.	178	153	**1.2**	83	59	**1.4**	151	142	**1.1**	56	48	**1.2**
WD	m^3/yrs.	66	54	**1.2**	23	11	**2.1**	56	50	**1.1**	13	7	**1.9**
LUS	ton eroded soil/yrs.	5	5	**1.0**	0,09	0,04	**2.3**	5	5	**1.0**	0,05	0,02	**2.5**
LUB	m^2·year/yrs .	1055	914	**1.2**	357	216	**1.7**	918	870	**1.1**	220	172	**1.3**
CC	kg CO_2 eq. /yrs.	2376	1690	**1.4**	1047	361	**2.9**	1923	1547	**1.2**	595	218	**2.7**
OD	kg CFC-11 eq. /yrs.	$2*10^{-3}$	$1*10^{-3}$	**2.0**	$9*10^{-5}$	$3*10^{-5}$	**3.0**	$1*10^{-4}$	$1*10^{-4}$	**1.0**	$5*10^{-5}$	$2*10^{-5}$	**2.5**
FE	kg P eq. /yrs.	0,7	0,6	**1.2**	0,2	0,1	**2.0**	0,6	0,6	**1.0**	0,1	0,09	**1.1**
EP	kg N eq. /yrs.	0,6	0,5	**1.2**	0,2	0,1	**2.0**	0,5	0,5	**1.0**	0,1	0,08	**1.3**
TE	mole N eq. /yrs.	90	74	**1.2**	41	25	**1.6**	75	69	**1.1**	26	21	**1.2**
POF	kg NMVOC/y	8	6	**1.3**	3	2	**1.5**	6	6	**1.0**	2	1	**2.0**
FET	PAF·m^3·day/yrs.	2723	2527	**1.1**	1206	1010	**1.2**	2258	2202	**1.0**	741	685	**1.1**

Table 7 The normalized results expressed in terms of percentage of normalizing reference value utilized, indicating the case building's utilization of the target values for a dwelling. The results are displayed with a 50-year or a 120-year service life of the buildings and either including or excluding the impact potentials relating to the energy consumption during the entire service life. The circular diagram illustrates the results with a 50-year service life with all impacts included. (UH - Upcycle House, SH - Standard House**)**

$I_{N,B}$ – *50-Year Service Life, Incl. Use Phase energy*



	$I_{N,B}$ 50 Year Service Life - Incl. Use Phase Energy (Illustrated)		$I_{N,B}$ 50 Year **Service Life** – Excl. Use Phase Energy		$I_{N,B}$ 120 Year **Service Life** –Incl. Use Phase Energy		$I_{N,B}$ 120 Year **Service Life** - Excl. Use Phase Energy	
	UH	SH	UH	SH	UH	SH	UH	SH
TA	23%	27%	9%	12%	21%	22%	7%	8%
WD	61%	74%	13%	26%	56%	63%	8%	15%
LUS	989%	999%	7%	18%	985%	991%	4%	10%
LUB	21%	24%	5%	8%	20%	21%	4%	5%
CC, temp.	589%	828%	126%	365%	539%	670%	76%	207%
CC, rad.	1111%	1563%	237%	689%	1017%	1265%	143%	391%
OD	0.5%	1%	0.1%	0.4%	0.4%	0.5%	0.1%	0.2%
FE	454%	524%	93%	163%	429%	471%	93%	109%
EP	5%	6%	1%	2%	5%	6%	0.9%	2%
TE	9%	11%	3%	5%	9%	9%	3%	3%
POF	47%	57%	14%	24%	43%	47%	10%	14%
FET	87%	94%	35%	41%	76%	78%	24%	25%

Upcycle House (Circular Diagram)

Standard House (Circular Diagram)

Exceeded Boundary (Table)

3.4 Path to Absolute Sustainable Buildings

Table 7 reveals a need for action to bring the environmental impacts of contemporary single-family dwellings in Denmark (SH with a 50-year service life scenario, including use phase energy consumption) below the estimated carrying capacity level. Table 7 also shows that the SH utilize 365-689% of the available CC carrying capacity in the 50-year service life scenario even when all use-phase energy related impacts are ignored, compared to the UH which utilizes 126-237% of the available CC carrying capacity in the same scenario. This indicates that a narrow focus on impacts, resulting from the building's energy consumption, is insufficient and must be combined with other initiatives in order to reach absolute sustainability. The need for an approach combining technological solutions with behavioural changes has most recently been presented by de Koning et al. [41] as the one way to reaching the IPCC 2 °C target [23].

In the following, we evaluate the effect of a range of measures aiming at minimizing environmental impacts of the contemporary dwelling: minimizing impacts from building construction, reducing energy consumption during use phase, and reducing the living area per person by building smaller apartments/houses or increasing the household size in accordance with the results presented by Kalbar et al. [24].

To reduce the impacts per m^2 building resulting from use phase related energy consumption the approach to absolute sustainable buildings can be split into two measures; reducing the building's energy consumption per m^2 and/or reducing the impact intensity per energy unit. The impact intensity per energy unit can be reduced through utilization of decentralized renewable energy production such as small scale wind power, photovoltaics etc. but also through a transition of the public energy supply towards more sustainable energy sources such as biofuel, wind power, photovoltaics, hydro power etc.

In Table 8 four paths for the contemporary absolute sustainable single-family house are outlined. In Path 1actions are taken along all of the three identified measures (i.e. energy, area, and materials). The absolute sustainable building in terms of CC contribution can be obtained by reducing the impacts from construction by 89%, from energy consumption by 80%, and the living area per person by 60%. It should be kept in mind that over the last few decades the energy consumption per m^2 in the use phase of buildings in Denmark has been gradually reduced thereby shifting more of the relative impact burden towards other life cycle stages and elementary flows of the building system. Despite the fact that many of the building materials used today are relying on fossil resources and produced using considerable amounts of fossil energy, reducing environmental impacts from materials is a challenge only recently acknowledged by the building sector [3,4,6]. Path 1 was designed to hold the largest impact reduction potential for the impacts related to construction, and accordingly construction is the life cycle stage where the greatest reduction potential is observed for Path 1. Reducing the living area of the case buildings by 60% corresponds to a reduction to around 20 m^2 (in total living area) per person, which here is considered culturally challenging but physically possible. The reduction of 60% of the current living area should be considered in the light of the current living area trends, where the average living area is increasing: In 1981 the average living area per person was 42.9 m^2 in Denmark, while in 2014 this area had increased by around twenty percent to 52.1 m^2 [42].

In Paths 2, 3, and 4 respectively, construction impacts, energy consumption impacts, and living area are alternately kept at their current level. Suggestions on how to reach absolute sustainability are then formulated relating solely to reduction along the two remaining measures. Path 2 (keeping construction related impacts constant) reveals that a reduction of 90% of the energy consumption, and an significant 87% reduction of the living area, corresponding to a remaining living area as little as 6.4m2 per person, is needed if continuing at the current impact level from construction. If on the other hand the living area of 49.3 m2 per person is kept constant as in Path 3, reductions of 97% and 91% of construction and energy consumption related impacts, respectively, are needed.

Table 8 Scenarios where the three parameters construction, use phase energy consumption, and living area are modified to reach absolute sustainability for the SH. To keep consistency, the living area is kept identical to the maximum required reduction for all impact categories, since a reduction of living area would affect all impact categories. The remaining two parameters are modified freely between the impact categories. I is the value of the parameter after achieving desired reduction, R is the reduction in percentage required to limit the impact inside the carrying capacity, $\boldsymbol{I_{B,i}^{N}}$ (%) is the percentage of carrying capacity occupied by each indicator.
(TA – Terrestrial Acidification, WD – Water Depletion, LUS – Land Use Soil Erosion, LUB – Land Use Biodiversity, CC – Climate Change, OD – Ozone Depletion, FE – Freshwater Eutrophication, EP – Marine Eutrophication, TE – Terrestrial Eutrophication, POF – Photochemical Oxidant Formation, FET – Freshwater Ecotoxicity)

	CC, temp		**CC, rad.**		**TA**		**WD**		**LUS**		**LUB**		**OD**		**FE**		**EP**		**TE**		**POF**		**FET**	
	I	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**
	kgCO2eq		**kgCO2eq**		**mole H+eq**		**m3**		**ton eroded soil**		**m2*yr**		**kg CPC-11eq.**		**kg P eq.**		**kg N eq.**		**mole N eq.**		**kg NMVOC**		**PAF*m3 *day**	
The Standard House																								
Construction impact/m2/year	8.2	-	8.2	-	0.7	-	0.2	-	$7E^{-4}$	-	2.8	-	$7E^{-7}$	-	$2E^{-3}$	-	$2E^{-3}$	-	0.3	-	$3E^{-2}$	-	9.4	-
Energy impact/m2/year	10.4	-	10.4	-	0.7	-	0.3	-	$4E^{-2}$	-	5.5	-	$6E^{-7}$	-	$4E^{-3}$	-	$3E^{-3}$	-	0.4	-	$4E^{-2}$	-	11.9	-
Living area m2 per person	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-	49,3	-
$I_{B,i}^{N}$ (%)	**828**		**1563**		**27**		**74**		**999**		**24**		**1**		**524**		**6**		**11**		**57**		**94**	
Path 1: Actions in all Fronts																								
Construction impact/m2/year	2.5	70	0.9	89	0.7	0	0.2	0	$1E^{-4}$	80	2.8	0	$7E^{-7}$	0	$7E^{-4}$	60	$2E^{-3}$	0	0.3	0	$3E^{-2}$	0	9.4	0
Energy impact/m2/year	3.1	70	2.1	80	0.7	0	0.3	0	$1E^{-2}$	75	5.5	0	$6E^{-7}$	0	$2E^{-3}$	49	$3E^{-3}$	0	0.4	0	$4E^{-2}$	0	11.9	0
Living area m2 per person	19.7	60	19.7	60	19.7	60	49.3	60	19.7	60	19.7	60	19.7	60	19.7	60	19.7	60	19.7	60	19.7	60	19.7	60
$I_{B,i}^{N}$ (%)	**99**		**100**		**11**		**30**		**100**		**10**		**0.3**		**100**		**3**		**4**		**23**		**37**	
Path 2: With Current Construction Methods																								
Construction impact/m2/year	8.2	0	8.2	0	0.7	0	0.2	0	$7E^{-4}$	0	2.8	0	$7E^{-7}$	0	$2E^{-3}$	0	$2E^{-3}$	0	0.3	0	$3E^{-2}$	0	9.4	0
Energy impact/m2/year	2.5	76	1.0	90	0.7	0	0.3	0	$3E^{-2}$	24	5.5	0	$6E^{-7}$	0	$4E^{-3}$	0	$3E^{-3}$	0	0.4	0	$4E^{-2}$	0	11.9	0
Living area m2 per person	10.4	79	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87	6.4	87
$I_{B,i}^{N}$ (%)	**100**		**100**		**3**		**10**		**100**		**3**		**0.1**		**68**		**1**		**1**		**7**		**12**	
Path 3: With Current Living Area per Person																								
Construction impact/m2/year	0.8	90	0.2	97	0.7	0	0.2	0	$2E^{-5}$	97	2.8	0	$7E^{-7}$	0	0.0	90	$2E^{-3}$	0	0.3	0	$3E^{-2}$	0	9.4	0

	CC, temp		CC, rad.		TA		WD		LUS		LUB		OD		FE		EP		TE		POF		FET	
	I	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**	**I**	**R**
	kgCO2eq		**kgCO2eq**		**mole H+eq**		**m3**		**ton eroded soil**		**m2*yr**		**kg CPC-11eq.**		**kg P eq.**		**kg N eq.**		**mole N eq.**		**kg NMVOC**		**PAF*m3 *day**	
Energy impact/m2/year	1.5	86	0.9	91	0.7	0	0.3	0	$4E^{-3}$	90	5.5	0	$6E^{-7}$	0	0.0	77	$3E^{-3}$	0	0.4	0	$4E^{-2}$	0	11.9	0
Living area m2 per person	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0	49.3	0
$I_{B,i}^{N}$ (%)	**100**		**100**		**27**		**74**		**100**		**24**		**1**		**100**		**6**		**11**		**57**		**94**	
Path 4: With Current Energy Consumption																								
Construction impact/m2/year	0.1	99	0.1	99	0.7	0	0.2	0	$7E^{-6}$	99	2.8	0	$7E^{-7}$	0	0.0	0	$2E^{-3}$	0	0.3	0	$3E^{-2}$	0	9.4	0
Energy impact/m2/year	10.4	0	10.4	0	0.7	0	0.3	0	$4E^{-2}$	0	5.5	0	$6E^{-7}$	0	0.0	0	$3E^{-3}$	0	0.4	0	$4E^{-2}$	0	11.9	0
Living area m2 per person	10.4	79	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90	4.9	90
$I_{B,i}^{N}$ (%)	**100**		**100**		**3**		**8**		**100**		**2**		**0.1**		**53**		**1**		**1**		**6**		**10**	

3.5 Sensitivity of Results

Besides being sensitive to the chosen system boundaries, our results are sensitive to a range of assumptions made in relation to the assessment. Along with being sensitive to the scope of the assessment (i.e. the service life of the building), inventory data source used, and impact assessment method applied, the results are clearly also sensitive to the choice of planetary boundary set used. The boundaries in this study relate directly to the carrying capacities presented in Table 5, and therefore the global normalization factors presented in Table 1. One may question whether a different set of boundaries would affect the results presented in Table 7 in such a way that a business-as-usual scenario (i.e. continuing prevailing contemporary building practice) could come much closer to the carrying capacities.

Focusing on the global normalization factor for climate change, we rely on two normalization factors:One representative for a steady-state temperature increase of 2 °C climate change above pre-industrial levels, and a factor representative for 1 W/m^2 corresponding to a steady-state temperature increase of 1.06 °C above pre-industrial levels, see Table 1, according to Bjørn and Hauschild [20]. The data in Table 7 indicates that the assessment results are sensitive to the choice of global normalization factor; it may vary the outcome of the assessment with approx. a factor of two. From our point of view, the two normalization factors for climate change are representing different ambitions related to the climate change issue; 1.06 °C above pre-industrial levels represent a highly desirable but also highly ambitious scenario, while 2.0 °C above pre-industrial levels most likely represents a more realistic scenario, and, according to Bjørn and Hauschild (2015), also represents the scenario with the highest political acceptance. Despite this distinction, the contemporary science and the results presented in Table 7 indicate that a business-as-usual scenario (i.e. building practices similar to the SH), in both climate change scenarios, is highly unlikely to be assessed as absolute sustainable, irrespective of the choice of planetary boundary set.

The sensitivity of the results towards both the carrying capacity as well as the calculated impact from the buildings are investigated with the SH as reference. The carrying capacity is assumed to be 15% less than those used in this study, combined with an increase of 15% in the calculated impacts of the building compared to those determined in this study. These deviations would increase the transgression of the GWP from a factor 15 to a factor 20. On the other hand, if the carrying capacity is assumed 15% higher and the building impacts 15% lower, the transgression on GWP would decrease from a factor 15 to a factor 10. Though the sensitivity towards both carrying capacity estimates as well as building impact are high, it does not affect the overall conclusion [43].

3.6 Limitations and Future Prospects

In our study, we adopted the absolute carrying capacity based normalization approach proposed by Bjørn and Hauschild [20] and applied it for assessing a building's sustainability performance in absolute terms. We developed an allocation key, yielding the per person carrying capacity per year, to be applied for the housing needs of one person for one year. The developed approach is based on an economic allocation approach, which obviously holds advantages and disadvantages. However, defining a method for allocating the world's carrying capacity across a range of consumption segments is probably more a political task than a scientific task.

In addition, while allocating the carrying capacities as well as carrying out the actual LCA, the system boundaries must be kept constant across the entire assessment in order to achieve a useful basis for the absolute normalisation. A building is associated with many indirect impact causing aspects such as e.g. specific building design which promotes energy saving behavior. A building located close to public transportation could reduce impact from transportation induced by the residents. Defining system boundaries for an entire assessment is here and generally a challenging and still unresolved issue [44,45].

Temporal aspects are not included in our study. In case temporal issues should be included, an important parameter to be given high priority is population growth. The world's population is steadily growing thereby affecting the average carrying capacity per person. By 2050 the global population will have increased to approximately 9.55 billion [46]. This will mean a decline of 28% from 2010-2050 of the carrying capacity per person due to population growth alone, making population growth an important factor to consider if projecting future scenarios of sustainable building design. Therefore, the results of our study need to be considered keeping in mind that temporal issues have not been considered.

The method, proposed in this paper, provides a way to estimate how to quantify sustainability goals for buildings based on the world's environmental carrying capacity. During the transition, the building sector is currently undergoing, in order to become (more) sustainable, a quantification of sustainability targets is essential, and could help quantify and guide the building sector on the path to absolute sustainable building design. Quantifying the maximum absolute impacts from buildings could be used in relation to the development of dynamic sustainability standards for the next 50-100 years, and help evaluate initiatives in the right (dynamic) perspective.

4. Conclusions

A method for an absolute sustainability assessment of buildings has been outlined in this paper. The method outlines target values across eleven impact categories. According to the approach, a building is found sustainable if its annual environmental burden is less than the allocated share of the earth carrying capacity.

The two case buildings assessed in the paper exceeded three (nearly four) target values of the eleven impact categories included in the study. Worst-case excess was for the case building representing prevalent Danish building practice, which utilized 1563% of the Climate Change carrying capacity. Different paths for reaching absolute sustainability for this case building were proposed using three measures: Minimizing impacts from building construction, minimizing impacts from energy consumption during use phase, and reducing the living area per person. In an intermediate path, absolute sustainability could be obtained by reducing the impacts from construction by 89%, use phase energy consumption by 80% and the living area by 60%. Furthermore, the service life of the building was identified to be highly influential on the annual impact, and estimating a realistic building service life is considered an important step towards a more fair absolute sustainability assessment.

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