The Doughnut for Urban Development

An Appendix

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Doughnut for Urban Development: An Appendix

This Appendix provides supplemental documentation and background information to support the Doughnut for Urban Design: A Manual. The Appendix is therefore seen as an extension of the Manual, with some important distinctions. The Appendix is authored and structured by chapter. As such, each chapter can be seen as it's own universe with unique language, references, and theoretical departure point. The Appendix should not be seen as a "finished" document, but rather the starting point to connect the latest scientific discourse in academia with building industry practice.

The Appendix unpacks topics such as: planetary boundary control variables, how to assess planetary sustainability through life cycle assessment, the academic reference points and calculations behind the allocation principles described in the Manual, knowledge and tools for assessing impacts of buildings of ecosystems, how to account for regenerative practices in the building industry and last but not least how to measure social impact.

You can use this document as a reference as you read through the Manual. We hope it supports better understanding of the concepts presented in the Manual and is a step in your journey to applying the Doughnut principles in building practice.

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Planetary boundaries

01

This chapter provides a full description of the planetary boundaries control variables, a library of impact indicators and benchmarks with data sources for the ecological ceiling of the Doughnut for Urban Development and tools and methodology for assessing planetary impact.

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1. Planetary boundaries

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1.1 Full description of Planetary Boundaries control variables

Scientific understanding of human-led pressures on the stability of the Earth System is constantly improving. Since its introduction (Rockström et al., 2009), the planetary boundaries framework has been advanced at several occasions (Persson et al., 2022; Rockström et al., 2023; Steffen et al., 2015; Wang-Erlandsson et al., 2022). The most recent publication was published just a few days before the Doughnut for Urban Development Manual was sent to the printers. While the manual was based on (Steffen et al., 2015), here we present a compiled set of definitions and variables, describing the planetary boundaries and safe and just Earth system boundaries, shown in table 1.

Table 1. Definitions and variables of the planetary boundaries framework, adopted from (Rockström et al., 2023; Steffen et al., 2015), and marked with clear cells with double borders and shaded cells with single borders, respectively. Cell shading also shows whether planetary boundary has been transgressed where green, yellow and red backgrounds indicate safe, moderate and high-risk zones, respectively.

Domain: state variable (R2023/S2015)	Relevant Earth system change	Planetary boundaries (S2015) Safe and just Earth System Boundaries (ESB) (R2023)	Current global state
Climate			
Global mean surface temperature change since pre-industrial (1850–1900) (R2023)	Climate tipping points; exceed interglacial range; biosphere functioning	Safe and Just: **1.0°C** at high exposure to significant harm Local: Global climate boundary set to avoid regional tipping points and biome degradation	1.2 °C
Atmospheric concentration CO_2 (ppm) (S2015)	Increase of global mean surface temperature	Global: 350 ppm CO_2 (350–450 ppm)	417.06 ppm, 2022 average www.climate.gov
Ocean acidification			
Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (S2015)	NA	≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80% – ≥70%)	~84% of the pre-industrial aragonite saturation state

Domain: state variable (R2023/S2015)	Relevant Earth system change	Planetary boundaries (S2015) Safe and just Earth System Boundaries (ESB) (R2023)	Current global state
Biosphere			
Natural ecosystem area (R2023)	Loss of climate, water, biodiversity Nature Contribution to People (NCP)	Safe and Just: **>50–60%** (upper end) depending on spatial distribution Local: Critical natural ecosystems need to be preserved or restored Global: >50–60% natural ecosystem area (depending on spatial distribution)	45–50% natural ecosystem area
Functional integrity (R2023)	Loss of multiple local NCP	Safe and Just: **>20–25%** of each 1 km2 under (semi-) natural vegetation Local: >20–25% of each 1 km2 under (semi-) natural vegetation; >50% in vulnerable landscapes; at <10%, few NCP remain Global: 100% of land area satisfies local boundary	One third (31–36%) of human-dominated land area satisfies ESB
Genetic diversity. Extinction rate (S2015)	NA	< 10 E/MSY (10–100 E/MSY) but with an aspirational goal of ca. 1 E/MSY (the background rate of extinction loss). E/MSY = extinctions per million species-years	100–1000 E/MSY
Land-system change (S2015) Local biome: Area of forested land as % of potential forest Global: Area of forested land as % of original forest cover	NA	Local biome: Tropical: 85% (85–60%) Temperate: 50% (50–30%) Boreal: 85% (85–60%) Global: 75% (75–54%) Values are a weighted average of the three individual biome boundaries and their uncertainty zones	62%
Functional diversity. Biodiversity Intactness Index(S2015)	NA	Maintain BII at 90% (90–30%) or above, assessed geographically by biomes/large regional areas (e.g., southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups	84%, applied to southern Africa only

Domain: state variable (R2023/S2015)	Relevant Earth system change	Planetary boundaries (S2015) Safe and just Earth System Boundaries (ESB) (R2023)	Current global state
Water			
Surface water flows (R2023)	Collapse of freshwater ecosystems	Safe and Just: Local and global ESB plus align with World Health Organization and United Nations Environment Programme quality standards Local: <20% magnitude monthly surface flow alteration Global: **100%** of land area satisfies local boundary (sums to 7,630 km3 per year global flow alteration budget)	66% of global land area satisfies ESB annually (3,553 km3 per year global alterations)
Groundwater levels (R2023)	Collapse of groundwater dependent ecosystems	Safe and Just: Safe ESB (and ensure recovery) Align with safe plus World Health Organization and United Nations Environment Programme quality standards Local: Annual drawdown does not exceed average annual recharge Global: **100%** of land area satisfies local boundary (sums to 15,800 km3 per year global drawdown)	53% of global land area satisfies ESB (15,700 km3 per year annual drawdown)
Green water (R2023) (Wang-Erlandsson et al., 2022)	Not assessed	Safe and Just: Not assessed Local: Monthly root-zone soil moisture deviates from Holocene variability Global: **<10%** of ice-free land area exceeds boundary	18%
Fresh water use (S2015) Local Basin: Blue water withdrawal as % of mean monthly river flow Global: Maximum amount of consumptive water use (km3 yr–1)	NA	Local: Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25–55%); for intermediate flow months: 30% (30–60%); for high-flow months: 55% (55–85%) Global: 4000 km3 yr–1 (4000–6000 km3 yr–1)	~2600 km3 yr–1

Domain: state variable (R2023/S2015)	Relevant Earth system change	Planetary boundaries (S2015) Safe and just Earth System Boundaries (ESB) (R2023)	Current global state
Nutrient cycles			
Nitrogen (R2023)	Surface water and terrestrial ecosystem eutrophication	<u>Safe and Just:</u> Align with local plus drinking water (<11.3 (10–11.3) mg NO3–Nl−1; globally, **<117 (111–117) Tg N per year**) and any available air pollution (for example, NH3) standards <u>Global:</u> Surplus, <61 (35–84) Tg N per year; total input, <143 (87–189) Tg N per year <u>Local:</u> <2.5 (1–4) mg N l−1 in surface water; <5–20 kg N ha−1 per year in terrestrial ecosystems (biome dependent)	Surplus, 119 Tg N per year; total input, 232 Tg N per year
Nitrogen (S2015) fixation, industrial and intentional biological.	See cell above	<u>Global:</u> 62 Tg N yr–1 (62–82 Tg N yr–1). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr–1
Phosphorus (R2023)	Surface water eutrophication	<u>Safe and Just:</u> Aligns with local and global <u>Local:</u> <50–100mg P per m3 <u>Global:</u> Surplus, <4.5–9 Tg P per year; mined input, <16 (8–17) TgP per year	Surplus, ~10 Tg P per year; mined input, ~17 Tg P per year
Phosphorus (S2015) flow from freshwater systems into the ocean and to erodible soils	See cell above	<u>Local:</u> 6.2 Tg yr–1 mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr–1). Boundary is a global average but regional distribution is critical for impacts. <u>Global:</u> 11 Tg P yr–1 (11–100 Tg P yr–1) into the ocean	~14 Tg P yr–1 ~22 Tg P yr–1
Atmosphere			
Aerosol loading: Aerosol Optical Depth (AOD) (S2015/R2023)	Monsoon systems	<u>Safe and Just:</u> <15 µg per m3 PM2.5 plus local and global ESBs <u>Local:</u> <0.25–0.50 AOD as a seasonal average over a region. South Asian Monsoon used as a case study. <u>Global:</u> Annual mean interhemispheric AOD difference: <0.15	 0.30 AOD, over South Asian region 0.05 annual mean interhemispheric AOD difference

Domain: state variable (R2023/S2015)	Relevant Earth system change	Planetary boundaries (S2015) Safe and just Earth System Boundaries (ESB) (R2023)	Current global state
		Novel entities and chemical pollution	
Disturbance to biosphere integrity by plastic pollution. More variables are found in (Persson et al., 2022)	NA	Ample evidence of physical and toxicological effects, including effects on species distribution and sensitivities. A toxicity-based threshold would be set at PEC/PNEC = 1.	PB transgression is already evident in several regions.
No control variable currently defined (S2015)	NA	No boundary currently identified, but see boundary for stratospheric ozone for an example of a boundary related to a novel entity (CFCs)	NA
		Stratospheric ozone depletion	
Stratospheric O3 concentration, in Dobson units (DU)	NA	<5% reduction from preindustrial level of 290 DU (5%–10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)

1.2 A library of impact indicators and benchmarks with data sources Ecological Ceiling

The database consists of a selection of existing indicators from a diverse set of frameworks and it is an outcome of mapping these indicators into nine planetary boundaries. Some of the most widely used frameworks and certification schemes include DGNB, LEED, BREEAM, EU taxonomy and Environmental Product Declarations (EPD).

1.3 Tools and methodology for assessing planetary impact including complementary control variables.

To operationalise the planetary boundaries framework the following chapters in the appendix delineate how the above planetary boundaries variables and targets can be converted into Life Cycle Assessment (LCA) indicators and translated into national, economic sector, and individual project levels using allocation principles.

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Using LCA for planetary sustainability assessments

02

This chapter provides a description of building life-cycle assessment (LCA) in Denmark and other countries, how to ensure a consistent system scope between allocated target and LCA results, and how to express planetary sustainability targets and LCA results with comparable indicators.

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2.1 Building life-cycle assessment in Denmark and other countries

2.1.1 Introduction to LCA

Life-cycle assessment (LCA) is a standardized method to assess environmental impacts caused by a product or service over its entire life cycle, from its production to its use and final disposal. LCA can be used to assess and compare environmental impacts from individual products as well as entire buildings. The stages of a building's life cycle, according to the EN 15804 standard, include the extraction of raw materials (module A1), their transport (A2), the manufacturing (A3) and transport (A4) of construction products, the construction of the building (A5), its operation and maintenance (B1-B7), as well as the disposal of materials at the end of their service life (C1-4) (see Figure 1).

In theory, an LCA consists of the following steps (Hauschild et al., 2017):

1. Defining the goal and the scope of the assessment. Depending on the specific question that the LCA is meant to answer, different methodological choices might be taken (regarding the system boundaries, data sources, assumptions, and various other parameters).
2. Listing all processes happening throughout the product's life cycle (the life cycle inventory) and all corresponding physical flows to- and from the environment.
3. Linking these processes with corresponding environmental impacts in various impact categories (global warming, eutrophication, ozone depletion, etc). This life cycle impact assessment (LCIA) step relies on so-called characterization factors which indicate how much each flow impacts each category (e.g. what is the climate impact of releasing 1 kg of methane in the atmosphere).
4. Interpreting the results to answer the questions defined in step 1, and iteratively modifying previous steps as new knowledge and new questions arise.

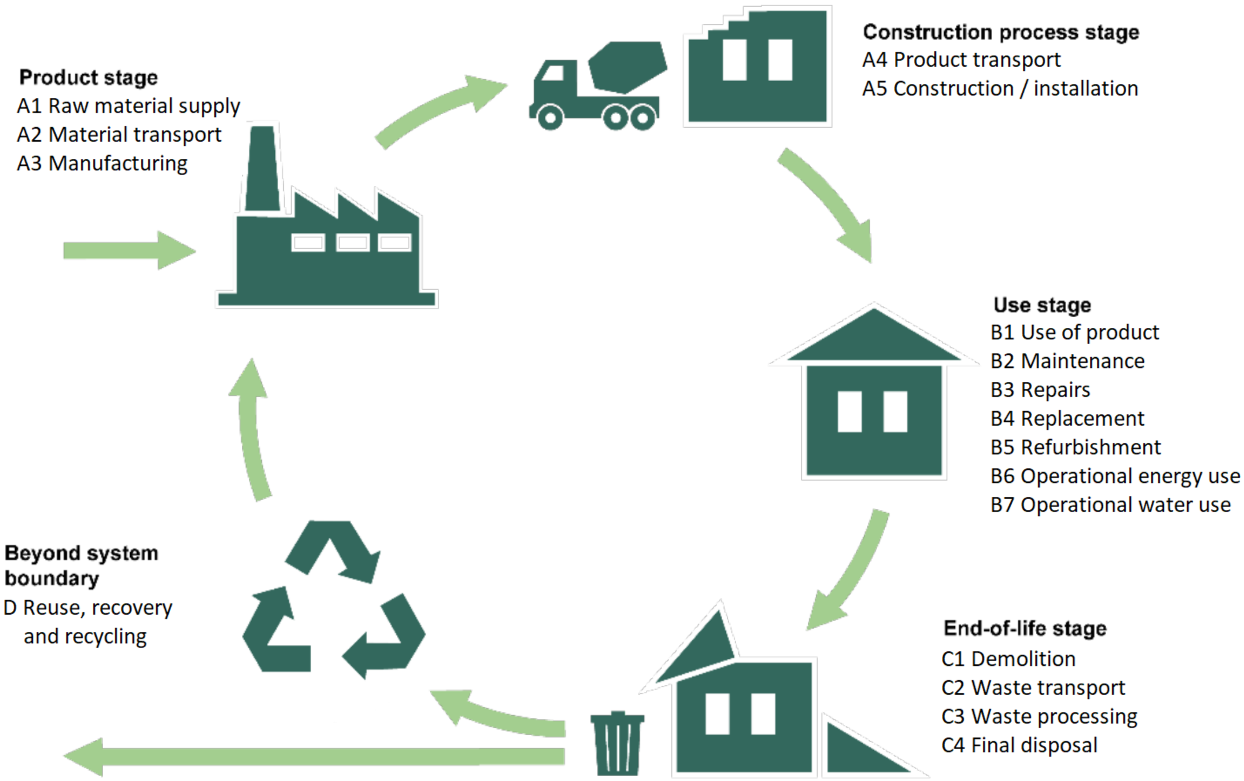

Figure 1 - A building's life cycle according to the EN 15804 standard

A building's impacts can be divided into embodied and operational impacts. The embodied impacts are directly linked to construction products as well as the construction, maintenance and dismantling of the building, covering modules A1-5, B1-5, and C1-4. The operational impacts are linked to the use of energy and water for the building's operation (modules B6-7). The share of the embodied impacts occurring before the building is put into use (modules A1-5) is sometimes called "upfront impacts". Since some projections predict a doubling of the global building stock by 2050, the need to mitigate upfront emissions has gained a lot of attention in recent years.

In practice, building LCAs are often carried out with dedicated tools including list of pre-calculated environmental impacts for a wide range of products and processes. This includes environmental product declarations (EPDs) and generic environmental databases for construction products (such as the German Ökobau database). Practitioners enter an inventory of construction products and materials used in the building, information on the building's dimensions and expected energy and water use, and the tool computes LCA results. Embodied impacts can be estimated based on a bill of materials. Operational impacts can be estimated based on the building's floor area, energy class and use, as well as scenarios for the heat and electricity supply. Some LCA methods used in certification and regulation use the current heat and electricity mix, since these values are verifiable. Other methods use future projections for the energy mix. These future scenarios have a high influence on LCA results, so a conventional, agreed-upon projection should be used. For instance, for Denmark, a value of 52.1 gCO2e/kWh is commonly used for electricity, representing an average of the projected mix over the next 50 years.

Different systems use different approaches to report potential benefits happening beyond the building's life cycle (module D), such as exporting electricity to the grid or reusing materials (although such benefits should always be reported separately and not subtracted from other impacts). This is addressed in more detail in section 5.

2.1.2 National variations

Building LCAs are carried out differently in different countries, due to differences in legal requirements, local certification schemes, available data, and national tools. Of particular importance when comparing LCAs from different countries are differences in which life cycle stages are included in the LCA.

In Denmark, there has traditionally been a focus on life cycle stages connected to the production, replacement and disposal of materials as well as energy use during operation (life cycle stages A1-3, B4, B6 and C3-4), but there is an increasing focus on construction process (A4-5). In countries such as Finland and the Netherlands, more stages related to the use phase and end of life are included. An overview of which life cycle stages are included in various countries' requirements and voluntary certifications can be seen in Table 1, together with the length of the reference study period used in the LCA. This represents a snapshot of building LCA in various countries as of Spring 2023, but the landscape is rapidly evolving.

There are also differences in how a building is described and which building elements are included in the LCA calculation. For instance, sewage systems are usually not included in building LCAs in Denmark and Sweden, but they are included in Norway, Finland, and the Netherlands. Another example is external and internal cladding, which is included in Denmark and the Netherlands, but often omitted in Finland.

Furthermore, different systems use data from different environmental databases, different calculation periods and reference areas, all of which influence the LCA's final results. Finally, different systems might include different impact categories, as indicated in Table 2. With the recent introduction of changes to the EN norms (EN 15804+A2), more detailed impact categories are also being introduced. This includes differentiating between global warming potential coming from biogenic and non-biogenic sources as well as land use, several different toxicity indices for human health and ecosystems, as well as a soil quality indicator to represent changes in land use and artificialization.

Table 1 - Differences in LCA stages covered in different systems

			Product			Construction		Use	Maintenance, repairs, replacement				Heat, electricity, water		User transport	End of life				Beyond the life cycle
Country	**LCA Method**	**LCA study period [years]**	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**C1**	**C2**	**C3**	**C4**	**D**
Denmark	Danish Building Regulation	50	X	X	X						X		X					X	X	X
	Voluntary Sustainability Class	50	X	X	X	X	X				X		X					X	X	X
	DGNB-DK	50	X	X	X	(X)	(X)				X		X					X	X	X
Sweden	Klimatdeklaration 2022	-	X	X	X	X	X													
	Klimatdeklaration 2027	50	X	X	X	X	X		X		X		X			X	X	X	X	
	BREEAM-SE 2017	60	X	X	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)	(X)	(X)	(X)
	NolCO2	50	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	
Norway	TEK17	50	X	X	X	X			X		X									
	BREEAM-NOR 2016	60	X	X	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)	(X)	(X)	(X)
	BREEAM-NOR v6.0	60	X	X	X	X	(X)	(X)	(X)	(X)	X	(X)	(X)	(X)		(X)	(X)	(X)	(X)	(X)
	Futurebuilt Zero	60	X	X	X	X	X	X	X	X	X	X	X					X		
	NS 3720	60	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Finland	Climate Declaration	50	X	X	X	X	X				X		X			X	X	X	X	X
	RTS	50	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	
Germany	DGNB	50	X	X	X						(X)		X					X	X	X
United Kingdom	BREAAM NC 2018	60	X	X	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)		(X)	(X)	(X)	(X)	(X)
	RICS	60	X	X	X	X	X	(X)	(X)	(X)	X	(X)	X	(X)		(X)	(X)	(X)	(X)	(X)
	London Plan WLCA 2022	60	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X
Europe	Levels 2020	50	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)		(X)	(X)	(X)	(X)	(X)
International	BREAAM International: New construction v6	60	X	X	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)	(X)	(X)	(X)
	LEED V4.1	60	X	X	X	X		X	X	X	X	X				X	X	X	X	

Table 2 - Examples of impact categories included in various LCA systems (GWP: global warming potential, ODP: ozone depletion potential, POCP: photochemical ozone creation potential, AP: acidification potential, EP: eutrophication potential, ADPe: depletion of abiotic elements, ADPf: depletion of abiotic fuels, PE_nr: non-renewable primary energy use, PE_tot: total primary energy use, FW: freshwater use, WP: waste production)

Country	LCA Method	GWP	ODP	POCP	AP	EP	ADPe	ADPf	PE_nr	PE_tot	FW	WP
Denmark	Danish Building Regulation	X										
	Voluntary Sustainability Class	X	X	X	X	X	X	X	X	X		
	DGNB-DK-2020	X	X	X	X	X		X	X	X	X	
Sweden	Klimatdeklaration 2022	X										
	Klimatdeklaration 2027	X										
	BREEAM-SE 2017	X	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)
	NollCO2	X										
Norway	TEK17	X										
	BREEAM-NOR 2016	X	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)
	BREEAM-NOR v6.0	X	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)
	Futurebuilt Zero	X										
	NS3720	X										
Finland	Climate Declaration	X										
	RTS	X										
Germany	DGNB	X	X	X	X	X	(X)	(X)				
United Kingdom	BREAAM NC 2018	X	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)
	RICS	X										
	London Plan WLCA 2022	X										
Europe	Levels 2020	X	(X)	(X)	(X)	(X)	(X)	(X)				
International	BREAAM International: New construction v6	X	(X)	(X)	(X)	(X)	(X)	(X)			(X)	(X)
	LEED V4.1	X	X	X	X	X		X				

Many European countries (including France, Denmark, Finland and Sweden) have recently introduced mandatory LCA-based calculations of environmental impact for new buildings. Often, countries that introduce mandatory requirements also introduce a calculation tool to perform the assessment: this is the case for instance of LCAbyg[1] in Denmark or Elodie[2] in France. Some only require that the impact is calculated and reported, while others require the impact to be below a certain limit value. These values can be lowered over time, to make the requirements tighter and meet the conditions of the Paris agreement. Overall, there is a clear trend towards more widespread and demanding mandatory environmental assessments for buildings.

2.2 Ensuring a consistent system scope between allocated target and LCA results

When assessing a building's environmental impacts to ensure the fulfilment of a building-level "planetary sustainability" target, it is important to ensure consistency between the assessment method and the system boundaries included in the target. The methods used to allocate targets and assess impacts at the building level should cover the same processes. For instance, if we establish a climate impact target for buildings where the definition of the building sector includes the transportation of construction materials, then we must also include greenhouse gas emissions from the transportation of materials when assessing whether a building fulfils the target. The allocation principles to establish targets discussed in section 3 are meant to cover the entire built environment and all processes in the life cycle of buildings, although they use different

[1] https://lcabyg.dk/en/
[2] http://elodie.cype.fr/

approaches to define the scope of this sector and these processes. To ensure consistency between the scope of the assessment and the scope covered by the planetary sustainability target, the LCA should therefore be as comprehensive as possible. If the LCA must include activities for which there is little knowledge and scarce data, generic and proxy data can be used to fill this gap. Table 3 below provides some examples of such generic values. Please note that these values might not be representative for other countries than their country of origin (e.g. transport distances for A4 and C2 are representative for Finland only). When available, it is always preferable to use generic data from your national database (e.g. Ökobau[3] in Germany or INIES[4] in France). The values in Table 3 are conservative generic estimates – most are above average, and **project-specific values should always be used if available**.

However, there are also more complex issues related to missing processes far up the project's value chain. Environmental impacts at the building level are often assessed using process life-cycle assessment (PLCA). PLCA relies on a case-specific inventory of all processes necessary for the production, use and disposal of a particular product or service. Each process is then matched with corresponding environmental impacts. For instance, the PLCA for a fibre cement wall panel will list various processes happening throughout the panel's life cycle (mining resources, cement production, crushing at the end of life, etc). The panel's total environmental impact is the sum of the impacts of all processes. However, PLCA entails a "truncation bias": such assessments always disregard some processes considered "negligible" (e.g. energy use from the computers at the company designing the panel) and necessarily stops at some point up the supply chain (e.g. we might not consider the use of metals to produce the machinery to extract the raw materials for the panel). While the sector-level target is supposed to include all relevant processes, it is therefore difficult, if not impossible, to ensure that the PLCA follows the same system boundaries.

On the other hand, input-output LCA (IOLCA) ensures that the assessment uses a comprehensive scope. IOLCA relies on national input-output tables complemented with environmental information. These tables indicate all exchanges of resources between different sectors of the economy, as well as between countries. Because input-output tables are structurally complete, IOLCA guarantees that all exchanges are taken into account in the assessment. However, IOLCA also entails important limitations. First, products are aggregated into broad categories: in the example above, the cement wall panel would likely be assessed as a generic "cement product" - IOLCA is therefore not suited to compare different options for the same kind of product. This strongly limits the usefulness of IOLCA for detailed comparisons. Second, input-output tables represent monetary transactions, so IOLCA inherently assumes that environmental impacts are proportional with costs. Third, emission factors used in IOLCA are associated with high uncertainties and numerous assumptions. Therefore, in practical cases, it will usually be more useful to carry out a process LCA, while remaining aware of the truncation bias.

[3] https://oekobaudat.de/
[4] https://www.inies.fr/

Table 3 – Examples of generic values for the climate impact of missing processes in LCA (Buhl, 2022; Finnish Ministry of the Environment, 2019; Teknologisk Institut & Sweco, 2022)

Missing stage (Finnish data)		**Default emissions (kgCO2e/m2)**
Transportation to site (A4)		10.2
Construction processes on-site (A5)		27.3
Repair processes (excluding the production of materials) (B2-3)		2.16
Demolition processes on-site (C1)		7.8
Transportation of demolition waste (C2)		10.2
Waste processing and disposal (C3-4)		15.6
Missing component (Finnish data)		**Default emissions (kgCO2e/m2)**
Electrical installations and wiring		5.3
Sprinkler system		5.9
Piping		0.5
Operational water supply		2.7
Radiators		6.7
Ventilation system		7
District heating substation		0,5
Missing component (Danish data)		**Default emissions (kgCO2e/m2)**
Drainage	Single-family house	1
	Row house	5
	Apartment building	6
	Office, school, daycare	2
	Other	2,5
Water pipes	Single-family house	3
	Row house	2
	Apartment building	3
	Office, school, daycare	3
	Other	4
Heating, cooling and ventilation (excluding operation)	Single-family house	30
	Row house	26
	Apartment building	26
	Office, school, daycare	42
	Other	55

Previous studies have reported a wide range of differences between PLCA and IOLCA, although the difference is often high. Säynäjoki et al. (2017) mention +75% of climate impact when using IOLCA to assess an apartment building compared with PLCA, Nässén et al. (2007) mention +90% of building embodied energy and Ward et al. (2018) roughly +50% of impact in various relevant product categories. These differences might not be a major concern when using LCA to compare the environmental impacts of two similar products, as the two products are likely affected to the same extent. However, it is more important to be aware of the truncation bias when assessing whether the building meets a planetary sustainability target, as the target is supposed to include a comprehensive scope. Still, it is difficult to define a simple correction factor that could be used to adjust for the truncation bias in PLCA.

One possible way forward is the use of hybrid LCA (HLCA). Different approaches exist for HLCA, but the idea is essentially to use PLCA for all processes for which specific data is available, and use input-output data to "fill the gaps" and account for all processes not covered in the PLCA. Recent projects have developed hybrid LCA databases, complementing specific data from common PLCA databases such as Ecoinvent with input-output data from databases such as Exiobase (Agez et al., 2020). The integration of a hybrid database in common LCA tools (such as LCAbyg in Denmark) could be a way to facilitate assessments that are consistent with sector-level targets. Until such databases are available, the best practice is to be transparent and raise awareness about the existence of these truncations.

2.3 Expressing planetary sustainability targets and LCA results with comparable indicators

The planetary boundaries and LCA are two fundamentally different frameworks describing environmental impacts. The usual LCA impact categories (so-called "midpoint categories") quantify damage related to several measurable environmental phenomena, such as climate change and eutrophication (Rosenbaum et al., 2017). The planetary boundaries are defined to minimize the risk of Earth being pushed out of its Holocene-like state. The planetary boundaries and LCA environmental impact categories cover more or less the same aspects, but converting results from one framework to the other is not trivial. In some cases, LCA impact categories and control variables in the planetary boundaries cover the same aspects but use different units and indicators. For instance, climate change is covered in both frameworks, but LCA uses an indicator of $kgCO_2$ equivalents emitted, while the planetary boundaries use two indicators: the atmospheric concentration of CO_2 and the energy imbalance (so-called *radiative forcing*) at the top of the atmosphere. In other cases, it is difficult to draw a clear line between the two frameworks. For instance, there is no classic LCA category corresponding directly to the "novel entities" boundary.

Several methods have been developed to enable a comparison of LCA results with planetary sustainability targets. In particular, the planetary boundaries can be converted into the same units as the LCA indicators, or LCA results can be communicated in the same units as the planetary boundaries (see Figure 2).

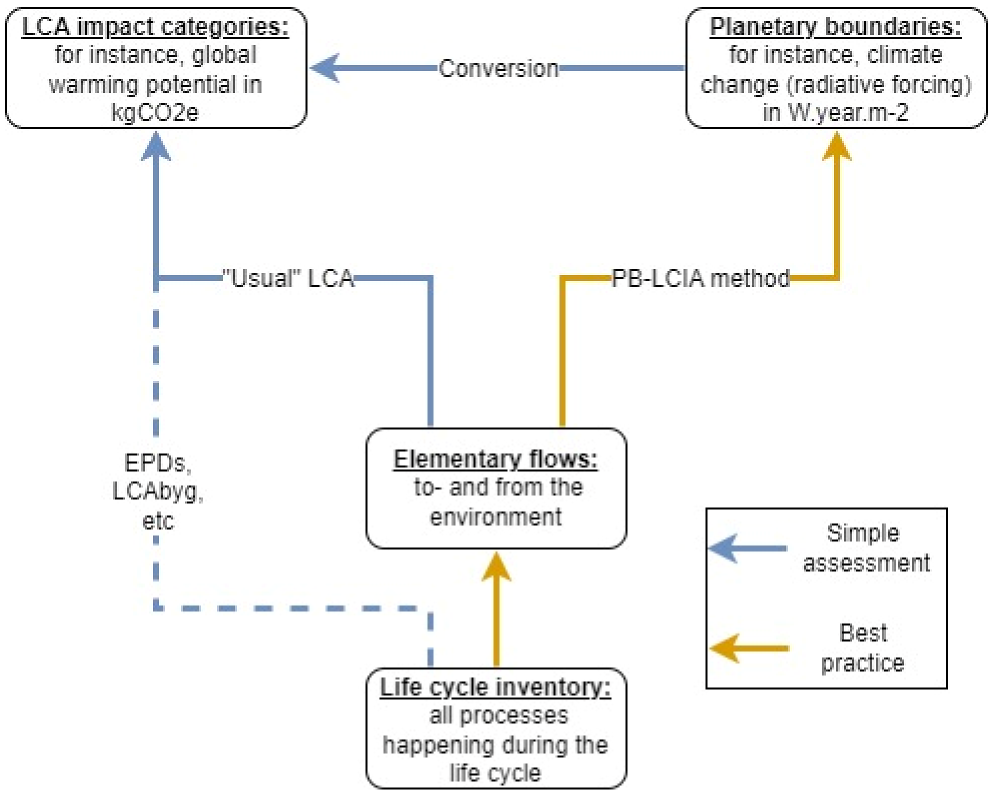

Figure 2 – Two options to match LCA indicators and planetary boundaries

LCA software tools such as OpenLCA and SimaPro allow results to be shown as elementary flows occurring to- and from the environment, i.e. a list of all resources taken from the environment and all emissions emitted to the environment. If elementary flows are available, they can be translated directly into impacts on the planetary boundaries (instead of the usual LCA impact categories) using an appropriate impact assessment method (the yellow path in the figure above). One such method is the "Planetary boundaries-based life-cycle impact assessment" (PB-LCIA) method (Petersen et al., 2022; Ryberg et al., 2018). The method consists in multiplying elementary flows by the characterization factors shown in Table 4. This approach is the most consistent to the planetary boundaries framework, as it does not require any conversion of the planetary boundaries into other indicators. It also has the advantage of working for almost all planetary boundaries (with the exception of the “Novel entities” boundary).

Table 4 – PB-LCIA characterization factors, taken from Ryberg et al. (2018)

Earth System process	**Control variable**	**Environmental flow**	**Emission compartment**	**Characterization factor**	**Unit**
Climate change	Energy imbalance at top-of-atmosphere	CO_2	Air	**3.53×10^{-13}**	$W.yr.m^{-2}.kg^{-1}$
		CO_2, land transformation	Air	**1.18×10^{-15}**	$W.m^{-2}.kg^{-1}$
		CH_4	Air	**1.59×10^{-12}**	$W.yr.m^{-2}.kg^{-1}$
		N_2O	Air	**4.64×10^{-11}**	$W.yr.m^{-2}.kg^{-1}$
		CO	Air	**2.74×10^{-13}**	$W.yr.m^{-2}.kg^{-1}$
		NMVOC, hydrocarbons	Air	**1.06×10^{-12}**	$W.yr.m^{-2}.kg^{-1}$
		NMVOC, partly oxidized hydrocarbons	Air	**7.07×10^{-13}**	$W.yr.m^{-2}.kg^{-1}$
		NMVOC, partly chlorinated hydrocarbons	Air	**3.53×10^{-13}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-11	Air	**4.79×10^{-10}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-12	Air	**1.49×10^{-9}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-13	Air	**8.61×10^{-9}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-113	Air	**7.65×10^{-10}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-114	Air	**1.94×10^{-9}**	$W.yr.m^{-2}.kg^{-1}$
		CFC-115	Air	**7.43×10^{-9}**	$W.yr.m^{-2}.kg^{-1}$
		NF_3	Air	**7.92×10^{-9}**	$W.yr.m^{-2}.kg^{-1}$
		SF_6	Air	**6.71×10^{-8}**	$W.yr.m^{-2}.kg^{-1}$
		HCFC-21	Air	**1.39×10^{-11}**	$W.yr.m^{-2}.kg^{-1}$
		HCFC-22	Air	**1.63×10^{-10}**	$W.yr.m^{-2}.kg^{-1}$
	Atmospheric CO_2 concentration	CO_2	Air	**2.69×10^{-11}**	$ppm.yr.kg^{-1}$
		CO	Air	**4.23×10^{-11}**	$ppm.yr.kg^{-1}$
		CH_4	Air	**7.40×10^{-11}**	$ppm.yr.kg^{-1}$
		NMVOC, hydrocarbons	Air	**8.07×10^{-11}**	$ppm.yr.kg^{-1}$
		NMVOC, partly oxidized hydrocarbons	Air	**5.38×10^{-11}**	$ppm.yr.kg^{-1}$
		NMVOC, partly chlorinated hydrocarbons	Air	**2.69×10^{-11}**	$ppm.yr.kg^{-1}$
		CO_2, land transformation	Air	**8.97×10^{-14}**	$ppm.kg^{-1}$
		CFC-11	Air	**7.85×10^{-9}**	$DU.yr.kg^{-1}$

Earth System process	**Control variable**	**Environmental flow**	**Emission compartment**	**Characterization factor**	**Unit**
Stratospheric ozone depletion		CFC-12	Air	**7.34×10^{-9}**	$DU.yr.kg^{-1}$
		CFC-113	Air	**4.91×10^{-9}**	$DU.yr.kg^{-1}$
		Halon-1211	Air	**5.16×10^{-8}**	$DU.yr.kg^{-1}$
		Halon-1301	Air	**1.15×10^{-7}**	$DU.yr.kg^{-1}$
		CFC-10,CarbonTetrachloride	Air	**5.74×10^{-9}**	$DU.yr.kg^{-1}$
		HCFC-140,1,1,1-Trichloroethane	Air	**1.32×10^{-9}**	$DU.yr.kg^{-1}$
		HCFC-22	Air	**4.83×10^{-10}**	$DU.yr.kg^{-1}$
		HCFC-141b	Air	**1.07×10^{-9}**	$DU.yr.kg^{-1}$
		HCFC-142b	Air	**6.76×10^{-10}**	$DU.yr.kg^{-1}$
		Halon1001, MethylBromide	Air	**7.46×10^{-9}**	$DU.yr.kg^{-1}$
		CFC-114	Air	**3.64×10^{-9}**	$DU.yr.kg^{-1}$
		CFC-115	Air	**3.99×10^{-9}**	$DU.yr.kg^{-1}$
		Halon1202	Air	**1.14×10^{-8}**	$DU.yr.kg^{-1}$
		Halon2402	Air	**5.39×10^{-8}**	$DU.yr.kg^{-1}$
		R-40, methylchloride	Air	**4.03×10^{-10}**	$DU.yr.kg^{-1}$
Ocean acidification		CO_2	Air	**8.22×10^{-14}**	$mol.kg^{-1}$
		CO	Air	**1.29×10^{-13}**	$mol.kg^{-1}$
		CH_4	Air	**2.26×10^{-13}**	$mol.kg^{-1}$
		NMVOC, hydrocarbons	Air	**2.47×10^{-13}**	$mol.kg^{-1}$
		NMVOC, partly oxidized hydrocarbons	Air	**1.64×10^{-13}**	$mol.kg^{-1}$
		NMVOC, partly chlorinated hydrocarbons	Air	**8.22×10^{-14}**	$mol.kg^{-1}$
		CO_2 ,land transformation	Air	**2.74×10^{-16}**	$mol.kg^{-1}$
Biogeo-chemical flows	Industrial and intentional biological fixation of N	NOx	Air	**3.04×10^{-10}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
		NH_3	Air	**8.22×10^{-10}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
		N-tot	Freshwater	**2.44×10^{-8}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
		NO_3^-	Freshwater	**5.51×10^{-9}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
		NO_3^-	Groundwater	**6.45×10^{-10}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
	P flow from fertilizers to erodible soils	Phosphorus	Freshwater	**3.68×10^{-8}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
	P flow from freshwater systems into the ocean	Phosphorus	Freshwater	**8.61×10^{-10}**	$Tg.N.yr^{-1}.kg^{-1}.yr$
Land-system change	Global: area of forested land	Forest transformation	Resource	**1.56×10^{-12}**	$\%m^{-2}$
	Biome: area of forested land	Boreal forest transformation	Resource	**4.44×10^{-12}**	$\%m^{-2}$
		Temperate forest transformation	Resource	**5.26×10^{-12}**	$\%m^{-2}$

Earth System process	Control variable	Environmental flow	Emission compartment	Characterization factor	Unit
		Tropical forest transformation	Resource	**4.41×10^{-12}**	$\%m^{-2}$
Freshwater use	Global: maximum amount of consumptive blue water	Global	Resource	**1.00×10^{-9}**	$km^3.m^{-3}$
	River basin: blue water withdrawal	Arid-Low flow month	Resource	**1.21×10^{-9}**	$yr.m^{-3}$
		Arid-Intermediary flow month	Resource	**1.87×10^{-10}**	$yr.m^{-3}$
		Arid-High flow month	Resource	**1.67×10^{-11}**	$yr.m^{-3}$
		Arid – Average annual flow month	Resource	**1.51×10^{-11}**	$yr.m^{-3}$
		Semi-arid-Low flow month	Resource	**4.51×10^{-11}**	$yr.m^{-3}$
		Semi-arid-Intermediary flow month	Resource	**7.92×10^{-12}**	$yr.m^{-3}$
		Semi-arid-High flow month	Resource	**1.17×10^{-12}**	$yr.m^{-3}$
		Semi-arid – Average annual flow month	Resource	**9.97×10^{-13}**	$yr.m^{-3}$
		Humid-Low flow month	Resource	**4.54×10^{-12}**	$yr.m^{-3}$
		Humid-Intermediary flow month	Resource	**6.30×10^{-13}**	$yr.m^{-3}$
		Humid-High flowmonth	Resource	**8.82×10^{-14}**	$yr.m^{-3}$
		Humid – Average annual flow month	Resource	**7.61×10^{-14}**	$yr.m^{-3}$
Atmospheric aerosol loading	Atmospheric ozone depletion (Global characterization factors)	SO_4^{2-}	Air	**1.67×10^{-13}**	$yr.kg^{-1}$
		SO_2	Air	**6.84×10^{-14}**	$yr.kg^{-1}$
		Dimethylsulfide	Air	**2.49×10^{-14}**	$yr.kg^{-1}$
		PM 2.5	Air	**5.20×10^{-13}**	$yr.kg^{-1}$
		PM 1	Air	**1.08×10^{-11}**	$yr.kg^{-1}$
		PM 10	Air	**9.69×10^{-15}**	$yr.kg^{-1}$
		Generic Carbonaerosols (e.g. organic carbon)	Air	**1.07×10^{-13}**	$yr.kg^{-1}$
		Blackcarbon(e.g.soot)	Air	**1.11×10^{-13}**	$yr.kg^{-1}$
		NO_3 ,Nitrate	Air	**9.73×10^{-14}**	$yr.kg^{-1}$
		NMVOC, urban	Air	**4.83×10^{-15}**	$yr.kg^{-1}$
		NMVOC, rural	Air	**1.93×10^{-14}**	$yr.kg^{-1}$
		NO_2	Air	**3.67×10^{-14}**	$yr.kg^{-1}$
		NOx	Air	**3.67×10^{-14}**	$yr.kg^{-1}$

However, LCA tools most commonly used for building LCA in practice (such as LCAbyg or OneClickLCA) do not show the full breakdown of elementary flows. Instead, they calculate environmental impacts directly based on environmental product declarations (EPDs) and generic environmental data, which show the impact of e.g. 1 kg of bricks in each LCA impact category. Therefore, it is not possible to use the PB-LCIA characterization factors described above together with common building LCA tools. For some planetary boundaries, it is possible to perform planetary sustainability assessments using regular building LCA tools and data by instead translating the planetary sustainability target into indicators that fit LCA impact categories (the blue line in the figure above).

For instance, the planetary boundary of climate change has two control variables: the atmospheric concentration of CO2 and changes in energy radiation due to the greenhouse effect (so called "radiative forcing"). The related targets are a limit for atmospheric CO2 concentration of 350 ppm, and a limit for radiative forcing at the top of the atmosphere of 1 W/m^2. These limit values can be converted into a limit value for global warming potential in LCA. This is the approach followed in the Manual. LCA results for global warming potential are typically given in $kgCO_2$-equivalent emitted per year. For planetary sustainability assessments where the LCA result is shown in $kgCO_2$-eq, converting the planetary boundary target related to radiative forcing is particularly relevant, since it includes all greenhouse gases, while atmospheric CO_2 concentration only includes CO_2.

Petersen, Ryberg and Birkved (2022) describe a method for converting the planetary boundary limit value related to radiative forcing (i.e. 1 W/m^2) to annual CO_2-eq emissions[5]. The idea is to calculate the "steady state" emissions of various greenhouse gases, which results in a radiative forcing of 1 W/m^2. These emissions were then converted to CO_2-eq using figures from the IPCC on the climate change impact of each greenhouse gas. The emissions of each greenhouse gas were weighted based on their contribution to total radiative forcing, and summed. This method leads to a global limit on annual greenhouse gas emissions of **2.51 Gt CO_2e/year**. Note that this approach relies on a constant annual emission boundary, but other relevant approaches use dynamic emission boundaries (e.g., annual emissions decreasing over time) or cumulative boundaries (e.g., a budget of allowable emissions over the next decades), which leads to different targets. Furthermore, the resulting target depends on choices about what level of risk is acceptable. The 2.51 Gt CO_2e/year is based on a 95% confidence interval regarding the effects of greenhouse gases on the climate, which means there is a 5% chance that the effect of these gases is worse than expected. Another approach mentioned by Petersen, Ryberg and Birkved (2022), based on the previously mentioned PB-LCIA characterization factors, leads to a limit value of 3.63 Gt CO_2e/year, but the value of 2.51 Gt CO_2e/year is chosen as a conservative and precautionary estimate.

Regardless of whether the results are communicated consistently with the planetary boundaries, or whether the planetary boundaries targets are converted into LCA indicators, a share of the global target must then be allocated to the development project. Chapter 3 describes in detail several principles to allocate part of this global target to a particular country, a particular sector of the economy and an individual project.

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Allocating shares of the global climate change boundary

03

This chapter provides an in-depth description of the allocation principles presented in the Manual from national scaling, to sector, to project scaling, and includes a "wish list" for further allocation principle development with a focus on the novel allocation principle sufficiency.

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Allocating shares of the global climate change boundary

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Table of Contents

In this chapter we present further details on data and formulas of the allocation principles presented in the manual Chapter 4.

To interpret the planetary ceiling, in a local context, it needs to be scaled down to a share corresponding to the system of assessment, e.g., the Danish building industry. This scaling is carried out by using different allocation principles, which are based on different distributive justice theories. Allocation principles are a way to assign a share of the planetary ceiling that the assessed system can occupy. This section will focus on the core boundary climate change, but the methods can in principle be adjusted to be applicable for other boundaries as well.

Three steps of allocation have been identified as necessary for assigning a share of the planetary ceiling to a building project.

1. National scaling (from global to national scale)
2. Sector Scaling (from national scale to the building sector)
3. Project scaling (from the building sector to one building)

Below in Table 1 we have listed the included allocation principles along with alternative names or names that previously have been used in other literature.

Table 1: Terminology for allocation principles included in this project, and alternative names from the literature.

Name used in this report	Alternative names	Relevant scale in this project
Equal per capita	Egalitarianism	Global to country
Capacity	Ability to pay; prioritarianism	Global to country
Historical responsibility	Climate dept	Global to country
Sufficiency	Decent living (energy)	Country to sector
Emissions grandfathering	Grandfathering; acquired rights; status quo	Country to sector
Expenditure grandfathering	Utilitarianism; Final consumption expenditure	Country to sector

The allocation principles are all applicable to all countries where the necessary data is available. However, in the following sections we will demonstrate with the example of Denmark.

1 National scaling

To estimate a national budget for Denmark based on the planetary boundaries, we have tested four different principles, which have a basis in different distributive justice theories. Table 2 shows the allocated shares to Denmark for each of these principles for the use of different sets of parameter values (mainly relating to timeframes). This section will briefly describe the principles and show the method for calculating the allocated share of the planetary ceiling for Denmark.

Table 2: Allocated shares of the planetary ceiling to Denmark for each allocation principle included in this project.

Distributive theory behind allocation principle	Allocation principle and time parameters	Allocated share of the planetary ceiling to Denmark
Egalitarian	Equal per capita, 2019	0.08%
Egalitarian	Equal per capita, 2019-2100	0.09%
Egalitarian	Equal per capita, 1960-2100	0.09%
Prioritarian	Capacity - inverse GDP, 2019	0.01%
Prioritarian	Capacity - inverse GDP, 2010-2100	0.05%
Acquired Rights	Contribution to global GDP, 2019	0.26%

Acquired Rights	Contribution to global warming, CO_2-eq emission, 2019	0.09%
Acquired Rights	Contribution to global warming, CO_2-eq emission, 1990 - 2019	0.17%
Climate debt	Contribution to historical emissions 1990-2019, inverse	0.004%
Climate debt	Historical responsibility (remaining share of cumulative CO_2-eq emission budget), 2019	-0.07%

Egalitarian

Equal per capita, 2019:

$$\frac{POP_{country,2019}}{POP_{World,2019}}$$

Where $POP_{Country,2019}$ is the country's population in 2019. In this case, Denmark with a population of approx. 5.8 million people. $POP_{World,2019}$ is the world population in 2019. Population figures for all countries and the world are based on the World Bank, World Development Indicators, as implemented in Riahi et al. (2017).

Equal per capita, 2019-2100:

$$\frac{\sum_{i=2019}^{2100} POP_{country,i}}{\sum_{i=2019}^{2100} POP_{World,i}}$$

Here "equal per capita" is based on figures for 2019 and population projections towards 2100 based on IPCC's SSP1-1.9 pathway for future development. The SSP1-1.9 pathway has been chosen because it is the only one of the IPCC's pathways that meets the Paris Agreement for climate and can thus be said to be climate sustainable. In the equation, we use projections for population from 2019 to 2100 with 5-year intervals. Projections are drawn from the World Bank, World Development Indicators as implemented in Riahi et al. (2017).

Equal per capita, 1960-2100:

$$\frac{\sum_{i=1960}^{2100} POP_{country,i}}{\sum_{i=1960}^{2100} POP_{World,i}}$$

Here "equal per capita" is based on historical population figures for 1960 to 2019 from the World Bank and population projections towards 2100 based on IPCC's SSP1-1.9 pathway for future development. 1960 was used as starting year as the is the earliest year available in the World bank statistics. Both historical data and projections are drawn from the World Bank, World Development Indicators as implemented in Riahi et al. (2017).

Prioritarian

Prioritarian sharing principles hold that those that are worse off should get a larger share of the planetary ceiling while those that are already well off should be allocated a smaller share.

In this sub-section, we approximate this using two approaches both termed Capacity, that is countries with high prosperity, measured as high GDP per capita, is allocated a relatively small share, as they have a relatively high economic capacity, and can therefore better carry out measures to reduce their impacts. Conversely, countries with a low GDP per capita should be allocated a relatively large share, as they have a right to development and need a larger share of the planetary ceiling to facilitate this development. Our approach to expressing Capacity has, to our knowledge, not been done before. Hence, a brief description of the logic of the calculation is required. We start by considering the approach to “capability” used in a study by the European Environmental Agency and the Federal Office for the Environment (EEA & FOEN, 2020). The authors of that study take equal per capita as a starting point and adjust this initial share by the relationship to a country´s inverse GDP per capita to the global inverse GDP per capita. In that way, rich countries get a lower than equal-per-capita share, while poor countries get a higher share. However, we find that the approach in the EEA study does not conserve the global safe operating space. That is, applying the approach to all countries in the world and summing the allocated impact does not equate to the global safe operating space informing the approach. To fix this imbalance issue, we have modified the EEA approach (by summing elements across countries in the denominator).

Capacity – inverse GDP, 2019:

$$\frac{\frac{POP_{country,2019}}{GDP_{country,2019}} \times POP_{country,2019}}{\sum_{country=1}^{193} \left(\frac{POP_{country,2019}}{GDP_{country,2019}} \times POP_{country,2019} \right)}$$

GDP data for 193 countries is here based on the World Bank, World Development Indicators as implemented in Riahi et al. (2017). GDP is expressed in so-called PPP dollars. PPP stands for Purchasing Power Parities. GDP expressed in PPP dollars, takes differences in the price level and purchasing power between countries into account. The unit used (an international dollar) has the same purchasing power in relation to GDP as a US dollar has in the USA. GDP is shown in constant prices with 2005 as reference, which represents a correction for inflation. Hence, the development in GDP over time is solely based on changes in the production volume.

Capacity – inverse GDP, 2010-2100:

$$\frac{\frac{\sum_{i=2010}^{2100} POP_{country,i}}{\sum_{i=2010}^{2100} GDP_{country,i}} \times \sum_{i=2010}^{2100} POP_{country,i}}{\sum_{country=1}^{193} \left(\frac{\sum_{i=2010}^{2100} POP_{country,i}}{\sum_{i=2010}^{2100} GDP_{country,i}} \times \sum_{i=2010}^{2100} POP_{country,i} \right)}$$

This version of the Capacity principle takes countries' future economic development into account.

Historical GDP data for 193 countries is here based on the World Bank, World Development Indicators as implemented in Riahi et al. (2017). GDP projections are based on Dellink et al. (2017) from the OECD and as implemented in Riahi et al. (2017). Population projections for SSP1-1.9 are based on KC and Lutz (2017).

Acquired rights

"Acquired rights" means the distribution must take place based on countries' historical or current acquired rights, such as historical CO2 emission levels or acquired economic development. According to Acquired right, the relative difference in emission levels or economic development among nations should be conserved. It should be noted that allocation based on Acquired rights principles is generally perceived as being unjust and it generally not recommended as a just distributive theory within moral and political philosophy (Caney, 2009) .

Contribution to global GDP, 2019:

$$\frac{GDP_{country,2019}}{\sum_{country=1}^{193} GDP_{country,2019}}$$

Here, the planetary ceiling is distributed based on the principle that countries with high GDP must have a correspondingly large share, because they need that to be able to maintain their activities.

Contribution to global warming, CO_2-eq emission, 2019:

$$\frac{E_{CO2-eq_{country,2019}}}{E_{CO2-eq_{World,2019}}}$$

Here, the planetary ceiling is distributed based on the principle that countries with relatively high CO_2-eq emissions must have a correspondingly relatively large share. This corresponds to a situation where all countries reduce their CO_2 emissions in 2019 by the same percentage. Data for the countries' CO_2-eq emissions are from the World Bank.

Contribution to global warming, CO_2-eq emission, 1843 – 2019:

$$\frac{\sum_{i=1843}^{2019} E_{CO2-eq_{country,i}}}{\sum_{i=1843}^{2019} E_{CO2-eq_{World,i}}}$$

As above, the planetary ceiling is distributed based on the countries' CO_2-eq emissions. But now based on total emissions from 1843 to 2019. Data for CO_2-eq emissions from 1843 to 2019 is based on Our World in Data (Ritchie et al., 2020). 1843 was selected as starting year, as this was the earliest available year in the dataset. We choose the earliest available year to best possible reflect the total contribution to CO_2-eq emission over time.

Climate debts

Contribution to historical emissions 1990-2019, inverse:

$$\frac{\frac{\sum_{i=1990}^{2019} POP_{country,i}}{\sum_{i=1990}^{2019} E_{CO2-eq_{country,i}}} \times \sum_{i=1990}^{2019} POP_{country,i}}{\sum_{country=1}^{193} \left(\frac{\sum_{i=1990}^{2019} POP_{country,i}}{\sum_{i=1990}^{2019} E_{CO2-eq_{country,i}}} \times \sum_{i=1990}^{2019} POP_{country,i} \right)}$$

Can be considered as an inversed "Acquired rights". We say that the countries that have emitted the least CO_2 per capita between 1990 and 2019 must have a correspondingly greater of the planetary ceiling , while the countries that have emitted the most per capita are granted the smallest share. 1990 was selected as starting year, as this was the earliest available year in the dataset.

Historical responsibility (remaining share of cumulative CO2-eq emission budget):

$$\frac{\left[\left(\frac{\sum_{i=1840}^{2019} POP_{country,i}}{\sum_{i=1840}^{2019} POP_{World,i}}\right) \times EB_{CO2-eq_{World}}\right] - \sum_{i=1840}^{2019} E_{CO2-eq_{country,i}}}{EB_{CO2-eq_{World}}}$$

This principle is based on the fact that the world has a total CO_2 budget that we must stay within. The total budget is calculated at 2140 billion tons of CO_2, as we have emitted 1660 billion tons until 2019 (Ritchie et al., 2020) and we have a remaining budget of approx. 440 billion tons if we are to reach the 1.5 degrees target in the Paris Agreement (Tokarska & Matthews, 2021). Denmark has already emitted 4.06 billion tons of CO_2 in 2019, based on Our World in Data (Ritchie et al., 2020). Thus, we emitted more than our budget, so Denmark in principle has a negative budget where we must remove more CO_2 than we emit.

Table 2 shows the different shares of the planetary ceiling allocated to Denmark and Figure 1 below shows the share, allocated to 193 countries in the world based on the different distribution principles.

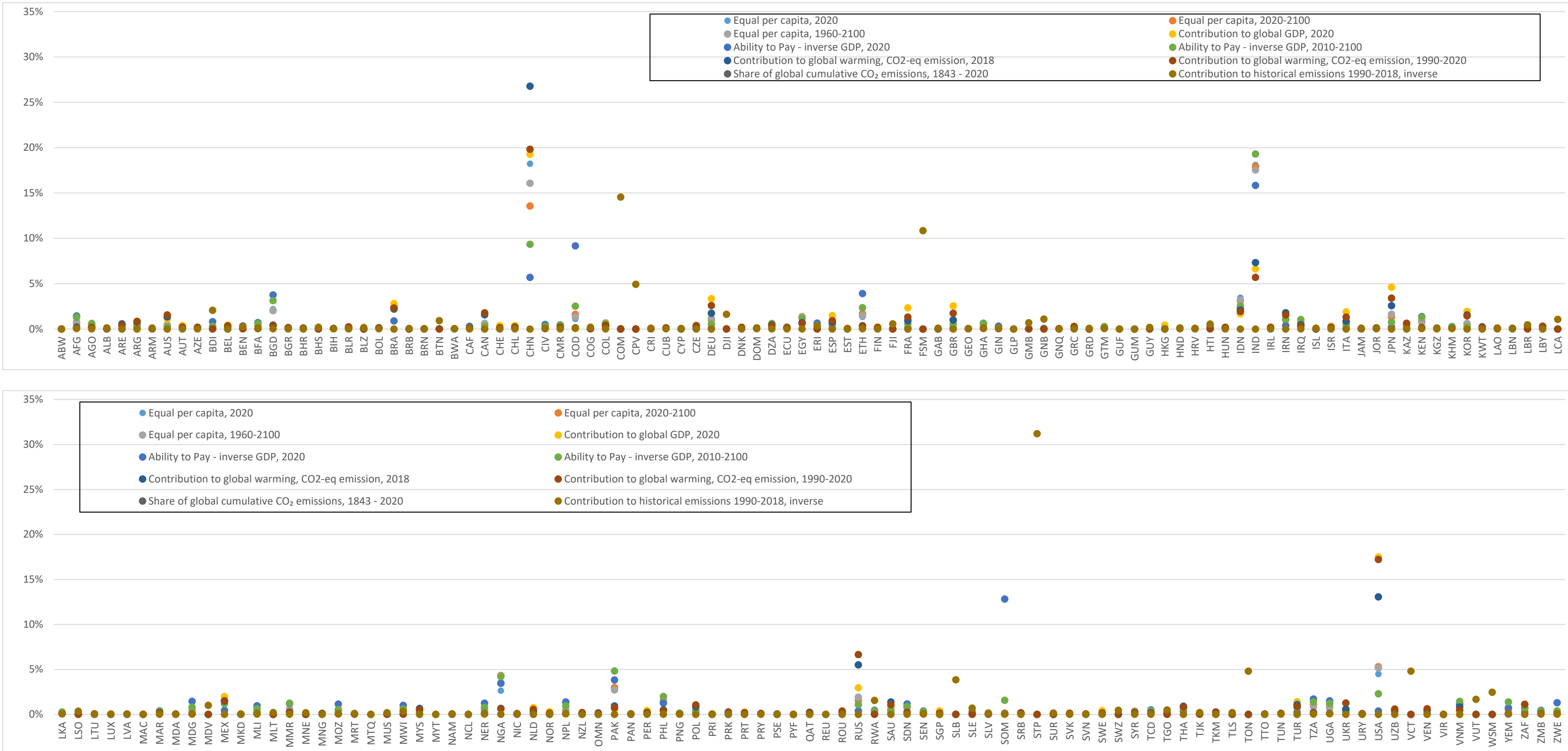

Figure 1 Assigned shares of the planetary ceiling to 193 countries for different allocation principles. Original figure.

1.1 Allocation principles for demonstration

Following the above analysis and referenced studies, we have chosen to demonstrate the following three methods for allocation of the planetary ceiling to national scale.

1) Equal per capita – An equal distribution of the planetary ceiling (as a resource) between people based on the population in 2019. This method simply distributes the planetary ceiling between the current population without considering human needs, historical environmental impacts or current social inequality.

2) Capacity – A prioritarian distribution based on the idea that the broadest shoulders must carry the heaviest burdens. This is an expansion of the "equal per capita" principle where it also considers the GDP/person. Based on the country's GDP, we calculate each country's GDP per person, which is inverted to show the population per GDP. This means that countries with relatively large wealth per person get relatively little allocated because they have more resources to be able to reduce their environmental impact, and vice versa.

3) Historical responsibility – A distribution based on the remaining share of cumulative CO_2-eq emission budget. The distribution is based on the rationale that countries with a higher historical emission gets a smaller share. Countries with large historical emissions can be in climate dept, which means that they, in theory, have to extract more CO_2-eq from the atmosphere than they emit.

This means that 0.075%, 0.01% and -0.067% of the planetary ceiling is allocated to Denmark for the egalitarian, the prioritarian, and the climate debt distribution respectively.

2 Sector scaling

In the manual Chapter 4, we introduced three allocation principles; Sufficiency, Emissions Grandfathering, and Expenditure Grandfathering. In the following, we will describe these three allocation principles and how they can be applied to allocate to both housing and commercial buildings. For commercial buildings, we have included only buildings for business-to-consumer activities because business-to-business activities provide products and services that are not directly meeting people´s needs. Such allocation based on indirect needs fulfilment is more difficult to quantify, and not many methods exist to do so. We have described one experimental method for allocating to buildings for business-to-business activities, based on the Expenditure Grandfathering principle, but we have not applied it within this study.

We are aware that even though the allocation principle, Sufficiency, comes closest to the principles of Doughnut Economics of the three alternatives, there are still shortcomings and research areas that should be further explored. Therefore, we have prepared a so-called "wish list for allocation in the future", which describes the aspects of allocation that should be further researched, but which have not been possible to include for this publication.

2.1 Sufficiency

This allocation principle is an attempt to apply data that reflects basic human needs to define how much should be allocated to the building sector. We use the data from a study by Millward-Hopkins et al. (2020) on Decent Living Energy (DLE). DLE is an estimate of the minimum final energy requirements for decent living standards for the entire world's population in 2050 within several different consumption groups. There are several different approaches to estimating

DLE, but the one used here, is a "bottom-up" approach by Millward-Hopkins et al. (2020), who have built an energy model based on a framework by Rao and Min (2018).

The energy model is based on inventory scenarios for *decent living standards (DLS)* and is categorized as shown in Table 3. The DLS categories are modelled on a household level, so by using DLE to allocate the environmental ceiling, the allocation is based on the needs that households have for various materials and services.

Table 3: Decent living dimensions and their associated decent living energy (Millward-Hopkins et al., 2020).

Decent living dimension	**Material needs and services**	**DLE [GJ/cap]**
Nutrition	Food	2.70
	Cooking	0.30
	Cold storage	0.20
Shelter and living conditions	House construction	0.80
	Thermal comfort	0.70
	Lighting	0.04
Hygiene	Water supply (domestic water – not for home heating via e.g. radiators)	0.10
	Water heating (domestic water)	1.40
	Waste management	0.10
Clothing	Clothing	0.30
	Laundry	0.30
Healthcare	Hospitals	1.40
Education	Schools	0.40
Communication of information	Telephones	0.00
	Computers	0.10
	Networks + data centers	0.40
Mobility	Vehicles	2.30
	Transport infrastructure	0.80
Other	Infrastructure for energy supply, freight activities and retail	3.30
Total		15.64

In the following, we will outline how DLE can be used to allocate the environmental ceiling to different building types. Following this DLE based allocation principle, an activity is allocated the same share of the planetary ceiling as its share of final energy demand in the DLE scenario. Hence, activities with high final energy demand in a decent living scenario are given more “impact space” than activities with low final energy demand in a decent living scenario.

2.1.1 Housing

For calculation of a share of Denmark's share of the planetary ceiling that can be allocated to housing, the DLE for the categories house construction, thermal comfort, illumination, and water heating from Millward-Hopkins et al. (2020) are used. They are described in Table 4.

Table 4: Decent living categories included for the housing sector, a description of what is included in that category, and the share of total decent living energy.

Category included for housing	**Includes**	**Share of total DLE [%]**
House construction	The embedded energy in the built house incl. maintenance and renovation (Millward-Hopkins et al., 2020; Ramesh et al., 2010). DLE for house construction is based on the estimate of the energy intensity per m^2 during the construction of a building, and the assumption of living space per person (Millward-Hopkins et al., 2020). They estimated the energy intensity based on calculations from several different studies dealing with buildings of different construction materials (Cabeza et al., 2014; Nässén et al., 2012; Ramesh et al., 2010).	5.1%
Thermal comfort	The direct energy consumption in connection with the use phase of a house (Millward-Hopkins et al., 2020). The DLE estimate for thermal comfort is based on heating and cooling degree days from 1964-2013 for 147 different countries, data from "Global Building Performance Network scenarios", and living space per person (Millward-Hopkins et al., 2020). They only focused on data for advanced new buildings, either single-family houses in rural areas or multi-family houses in urban areas, because they wanted to use houses with the greatest possible energy performance (Millward-Hopkins et al., 2020).	4.5%
Illumination	The DLE used for the necessary lighting of the home during the use phase. The estimate is based on assumptions about illuminated living area, how long it is illuminated, how strong the light is and how efficiently the energy is converted into light (Millward-Hopkins et al., 2020). They assume 33% of the residential area is illuminated at a time, 6 hours a day, by 125 lm/m^2 with an efficiency of 150 lm/W.	0.2%
Water heating	The energy required to heat the water used for bathing and sanitation. They base the estimation of DLE for water heating on the daily per person usage, the energy required to heat water, the temperature that the water is being heated to, the heating efficiency, and other physical parameters for energy use (Millward-Hopkins et al., 2020)	9.0%
Housing DLE share of total DLE		**18.8%**

We excluded “waste management” as it was very crudely represented in the Millward-Hopkins et al. (2020) study, and only contributes with 0.6% to the total final energy demand in that decent living scenario (would be event smaller when only considering a fraction of that waste). One assumption that is used by Millward-Hopkins et al. when calculating DLE for all subcategories under "shelter and living conditions", is the assumption of living space per person. It is used to convert from DLE per m^2 to DLE per person. The assumption of living space per person is based on an estimated minimum requirement for space by Rao and Min (2018), who suggest 10 m^2/person for living and 20 m^2 extra per household for kitchen and bathroom facilities. Millward-Hopkins et al. (2020) assumes a household of 4 people, which thus gives 15 m^2 housing per person. 15 m^2 per person is very low for western countries, and if we changed this assumption only to 25 m^2 per person (which has been considered by Kikstra et al. (2021), the share for housing would increase by 5 %-points. Kikstra et al. (2021) investigated how decent living scenarios can be different in different parts of the world, which should be considered for further research on DLE for allocation. However, since the two studies differ from each other in some of their methods for defining DLE, they are not fully comparable, and therefore we use only the DLE values from Millward-Hopkins et al. (2020).

Using the Sufficiency allocation principle based on DLE data, the sector for housing is assigned a share of 18.8%. This must be multiplied by one or more of the methods for allocation from the global to Denmark, to get the share of the planetary ceiling for the housing sector.

2.1.2 Commercial

Not all types of businesses and commercial buildings are explicitly included in the DLE framework of Millward-Hopkins et al. (2020). However, the category "other" covers infrastructure for energy supply, freight activities and commercial buildings. From their supplementary material, it appears that the amount of DLE for commercial buildings corresponds to 4.7%-7.2%. of the total DLE. However, it is not specified where in this range the different countries lie, nor which types of commercial buildings have been included. In this publication we choose a different approach where the DLE for housing is scaled down based on the country’s ratio between energy consumption for a specific business (which is using commercial buildings) and households.

We split the approach into four steps:

1. Calculation of the current energy consumption for construction and use of housing based on national energy accounts.
2. Calculation of the current energy consumption for construction and use of the type of commercial building of assessment based on national energy accounts.
3. Calculation of the ratio between the energy for the commercial building type of assessment and housing.
4. Use the ratio to scale down the DLE for housing to DLE for that specific type of commercial building (assuming that all current types of commercial buildings are equally important in a decent living scenario).

With this approach, we assume that the ratio between the current Danish energy consumption for households and businesses is the same in a decent living scenario.

To calculate the current energy consumption from construction and usage of a building (applies to both housing and commercial), which is done in **step 1** and **2**, we use the formula below:

$$E_{cons+use} = E_{cons} * s_{area,j} + E_{use,i}$$

Where,
$E_{build,cons+use}$: Construction and use energy of a building
E_{cons}: Energy consumption of new buildings, and repair and maintenance of buildings
$s_{area,j}$: The area share of total building stock which is occupied by the type of building of assessment, j.
$E_{use,i}$: The energy consumption of the business, i, which is using the type of commercial building of assessment.
i: type of activity using the commercial building
j: type of building

In **step 3**, we calculate the ratio between current energy for housing and the commercial building by applying the formula below:

$$r_{h,c,i} = \frac{E_{c,i}}{E_h}$$

Where,
$r_{h,c,i}$: ratio between energy for housing and the type (i) of commercial building
E_h: Energy consumption for housing
$E_{c,i}$: Energy consumption for the type (i) of commercial building
i: type of commercial building (e.g., building for retail)

In step 4, we apply this ratio by multiplying it with the DLE for housing that we calculated in section 2.2.1.1. The following formula is applied:

$$DLE_{c,i} = DLE_h * r_{h,c,i}$$

Where,
DLE_h: DLE for housing
$DLE_{c,i}$: DLE for the type (i) of commercial building of assessment

We present the data used as input for the calculations in Table 5 and Table 6.

Table 5: Step 1 and step 2 data applied for calculating a share of the national climate budget to the housing sector. Blue columns represent data input from other sources, and yellow columns represent the calculated data.

Step 1				
Category	Construction + maintenance energy [GJ] (E_{cons})[a]	Area shares of building stock [%] (s_{area})[b]	Energy use phase [GJ] (E_{use})[c]	Energy for construction and use of building [GJ] ($E_{cons+use}$)
Housing	17,524,073	47.11%	264,822,231	273,077,744.06
Step 2				
Retail	17,343,603	2.28%	10,844,741	11,244,921
Service companies		0.17%	582,065	611,182
Sport		0.11%	1,903,283	1,923,367
Restaurants and more		0.27%	9,199,014	9,247,137

a: ENE2HA (Statistics Denmark, 2022a)– data from 2019
b: BYGB70 (Statistics Denmark, 2023a) – data from 2021 (detailed building stock statistics are not available before 2021)
c: ENE2HA (Statistics Denmark, 2022a) – data from 2019

Table 6: Step 3 and step 4 data applied for calculating a share of the national climate budget to housing sector. Blue columns represent data input from other sources, and yellow columns represent the data calculated here.

	Step 3	**Step 4**	
Category	Ratio ($r_{h,c,i}$)	DLE housing [GJ/cap] (DLE_h)[a]	DLE commercial building type, j [GJ/cap] (DLE_c)
Retail	4.12%	2.936	0.121
Service companies	0.22%		0.007
Sport	0.70%		0.021
Restaurants and more	3.39%		0.099

a: (Millward-Hopkins et al., 2020)

The estimated DLE for commercial buildings is then divided by the total DLE in order to calculate the shares of the planetary ceiling to the commercial building sector (for the indicated types of commercial buildings). See the calculated shares in Table 7.

Table 7: Shares of the national climate budget to different types of commercial building sectors based on the Sufficiency allocation principle defined in this study.

Commercial building type	Allocated share
Retail	0.77%
restaurants	0.64%
service companies	0.04%
sport	0.13%

2.2 Emissions Grandfathering

Emissions grandfathering is an allocation principle that is based on the distribution method "acquired rights" which is described under the section "National scaling". As previously mentioned, the distribution can be based on several historical years or a reference year. Here we use a reference year of 2019.

For both housing and commercial buildings, we used the global reporting of Denmark's consumption-based annual emission of greenhouse gasses, which is calculated by the Danish Energy Agency (Energistyrelsen, 2022), because this calculation is divided into detailed consumption categories and industry categories. We use the consumption categories to calculate the share for housing, and the industry categories to calculate the share for commercial buildings.

2.2.1 Housing

The consumption categories we have identified as relevant for housing can be seen in Table 8. These are used to calculate the proportion of Denmark's share of the planetary ceiling for housing.

Table 8: Consumption categories for calculation of a share of the national climate budget for the housing sector with the allocation principle Emissions Grandfathering (Energistyrelsen, 2022).

Consumption group Level 1	Consumption group Level 2	Consumption group Level 3	Share of consumption attributed to the dwelling	Total consumption-based emission from housing (share of total)
Public consumption	Residential and communal facilities	Residential and communal facilities	100%	0.03 (0.05%)

Public consumption	Repair and maintenance of housing	Repair and maintenance of housing	100%	0.01 (0.02%)
Investments	Investment in housing	Investment in housing	100%	2.94 (4.65%)
Households	Housing	Calculated rent of own housing	100%	0.48 (0.77%)
Households	Housing	Rent	100%	0.65 (1.03%)
Households	Housing	Repair and maintenance of housing	100%	0.61 (0.96%)
Households	Electricity, heat, fuels, water and renovation	Electricity	29%*	0.55 (0.86%)
Households	Electricity, heat, fuels, water and renovation	District heating etc.	100%	1.81 (2.86%)
Households	Electricity, heat, fuels, water and sanitation	Liquid fuel	100%	0.68 (1.07%)
Households	Electricity, heat, fuels, water and sanitation	Gas	100%	1.56 (2.47%)
Households	Electricity, heat, fuels, water and renovation	Renovation etc.	100%	0.65 (1.03%)
Households	Electronics and home appliances	Household appliances	40%*	0.11 (0.17%)
Total				**15.94%**

*Based on Brejnrod et al. (2017) (assuming that the shares of consumption attributed to the dwelling is the same for emissions as for expenditure)

Total share for housing is thereby 15.94%.

2.2.2 Commercial buildings

The industry categories relevant for commercial buildings vary depending on which type of commercial building is assessed. Therefore, we have included the same types of commercial buildings as an example, as for the Sufficiency principle.

We applied the below formula to estimate the impact of the different types of commercial buildings used to their shares of the planetary ceiling.

$$I_{cons+use} = I_{cons} * s_{area,j} + I_{use,i}$$

Where,
$I_{build,cons+use}$: Construction and use impact of a building
I_{cons}: Consumption impact of new buildings, and repair and maintenance of buildings
$s_{area,j}$: The area share of total building stock which is occupied by the type of building of assessment, j.
$I_{use,i}$: The consumption impact of business, i, which is using the type of commercial building of assessment.
i: type of activity using the commercial building
j: type of building

The data we used as input to the formula above is described below in Table 9.

Table 9: Data used for calculating the impact of different types of commercial buildings in Denmark 2019 (Energistyrelsen, 2022).

Category	**Construction + maintenance impact [ton CO_2eq] (I_{cons})**	**Area shares of building stock [%] (s_{area})**	**Use phase impact [ton CO_2eq] (I_{use})**	**Impact of construction and use of building [ton CO_2eq] ($I_{cons+use}$)**
Retail	122.75	2.28%	65.04	68.84
Service companies		0.17%	6.50	6.71
Sport (incl. amusement parks, and other leisure activities)		0.11%	8.30	8.44
Restaurants, bakeries etc.		0.27%	78.13	78.47

The emission from commercial buildings in 2019 is then divided by the total consumption-based emission of greenhouse gasses of Denmark in 2019 (also from the Danish Energy Agency (Energistyrelsen, 2022)) to calculate the shares of the national budget to the commercial building sector (for the indicated types of commercial buildings). See the calculated shares in Table 10.

Table 10: Shares of the national climate budget to different types of commercial building sectors based on the Emissions Grandfathering allocation principle.

Commercial building type	Allocated share
Retail	2.49%
restaurants	4.01%
service companies	0.35%
sport	0.31%

2.3 Expenditure Grandfathering

This allocation principle is allocated based on final consumption expenditure data. If consumption can be assumed an indicator for what matters to us, this approach is utilitarian. However, because the data reflects a consumption pattern which has been built up over time, it can also be viewed as acquired rights.

2.3.1 Housing

The total final consumption expenditure is composed of both household consumption, public consumption, and gross capital formation. We used 2019 data from Statistics Denmark, with the titles “Final consumption of households on the economic territory (72 grp) by price unit, purpose and time”, “General government, COFOG by function and time”, and “Demand and supply by transaction and price unit” (Statistics Denmark, 2022b, 2023c, 2023b). The included categories can be seen in Table 11 below.

Table 11: Consumption categories included for calculating a share of the national climate budget for the housing sector in with the allocation principle Expenditure Grandfathering.

Consumption type	Categories	Share assigned to dwelling	Total expenditure (share of total)
Household	Actual rentals for housing	100%	84,289 (3.1%)
Household	Imputed rentals for housing	100%	130,594 (4.8%)
Household	Maintenance and repair of the dwelling	100%	9,623 (0.35%)
Household	Electricity	29%*	6,575 (0.24%)
Household	Gas	100%	4,508 (0.17%)
Household	Liquid fuels	100%	2,061 (0.08%)
Household	District heating etc.	100%	21,331 (0.78%)
Household	Household appliances	40%*	3,509 (0.13%)
Public	Housing development	100%	4,508 (0.16%)
Gross capital formation	Dwellings	100%	2,061 (4.38%)
Total			385,883 (14.19%)

* Based on Brejnrod et al (2017)

This gives 14.19% of our total private and public expenditure on housing.

2.3.2 *Businesses that only sell directly to end users* (Business-to-Consumer: B2C)

For businesses that sell directly to consumers, we estimate the value of the business to people and therefore calculate how large a share of the safe space that the business's buildings should be allocated. The following procedure and formula are used here.

$$SoSOS_{BA,i} = SoSOS_{Nation} * \frac{\frac{Revenue_i}{A_i}}{FCE_{Nation}} * \frac{Expenditure_{Buildings,i}}{Total\ Expenditure_{Business,i}}$$

SoSOSNation is the allocated part to Denmark as presented in Section "National scaling". Revenue per area (Revenue/A) is calculated as 21458 DKK / m^2 based on an average of different types of small business selling directly to consumers (Strømgren & Kristensen, 2022). The total personal and public consumption (FCENation) is DKK 2719 billion for 2019. By dividing revenue per area by the total consumption, we get an estimate of the importance of businesses for people per m^2.

We then calculate how much construction constitutes for businesses. We estimate the total expenses for businesses per m2 by converting revenue to total consumption based on profit margin data (Deloitte Denmark, 2023). This gives total average business expenses of approx. DKK 20300 / m^2 ($Total\ Expenditure_{Business}$).

Business' spending on buildings per m2 is based on a market index as an average of retail trade/shops in the Copenhagen area from July 2021 to July 2022 (Ejendomstorvet & Dansk Ejendomsmæglerforening, 2023). This gives approx. DKK 1815 / m^2 ($Expenditure_{Buildings}$). The building thus comprises approximately 9% of total business expenses. By inserting into the equation above, allocated share of 7.06E-10 per m^2 is obtained for businesses. The share must be multiplied with the allocated share to the country to estimate the allocated share of the planetary ceiling to buildings for B2C buildings per m^2.

This can be multiplied by the area of a specific project to calculate a project specific share.

2.3.3 Businesses that do not only sell directly to end users (Business-to-Business: B2B & Business-to-Many: B2M)

For businesses that do not sell directly to consumers (i.e., Business-to-Business (B2B) companies), we suggest a method developed by Oosterhoff and colleagues (Oosterhoff et al., 2023) which allows us to determine the indirect value that products and companies have for us. A mining producer of copper has, for example, not any great direct value to humans. But because copper is included in virtually all electronic products that we use today, mines that extract and produce copper have a very large indirect value. It is important to take both the direct and indirect value into account when we talk about planetary sustainability and how much of the planetary ceiling to allocate to different products, companies, or industries. Oosterhoff's method is based on global multi-regional input-output (MRIO) models, which provide an overview of the global economy and the interconnections among industries through buying and selling across the world.

The method by Oosterhoff and colleagues can be used to determine how large a portion of the planetary ceiling should be allocated to a specific industry in the world (SoSOS_B2M_industry). A company is then allocated a share based on its market share of the overall industry. Secondly, the business needs to estimate its expenditure for buildings relative to their total expenditures. These data are highly project specific and can be done by specific clients:

$$SoSOS_{B2B_{Business_{Buildings}}} = SoSOS_{B2M_{Industry}} * \frac{Revenue_{Business}}{Revenue_{Industry}} * \frac{Expenditure_{Buildings}}{Total\ Expenditure_{Business}}$$

However, due to the specificity, it is currently not practical for deriving general limit values per m^2 that can be used by a developer, as the developer will have little knowledge about the actual users of the constructed buildings. Hence, this approach is recommended used for specific companies that want to evaluate the sustainability of their buildings, but not yet for developers and investors that have little information about the final building's users.

3 Project scaling

As described in the manual, we suggest two indicators for project scaling. One is based on the current building stock in Denmark, and the other is based on the population of Denmark. However, commercial buildings are not associated with a specific number of people so therefore, only a per m^2 target is defined for those.

The sector scaling using the presented approach for business-to-consumer buildings using Final Consumption Expenditure includes a scaling down to per m^2, and therefore no further allocation is needed. However, when using Sufficiency and Emissions Grandfathering, we need to divide with the area of current buildings stock of the specific building type of assessment.

The current building stock are extracted from Statistics Denmark from the dataset called "Bygninger og deres etageareal efter område, enhed, anvendelse og tid" and we use the data from 2021. Table 12 shows the areas used to calculate the per m^2 targets for climate change:

Table 12: Area of total buildings stock of different types of buildings in Denmark (Statistics Denmark, 2023b)

Type of building	**Area (m^2)**
Housing 2021	298,839,000
Retail, 2021	14,486,000
Restaurant, café, casino etc., 2021	1,742,000
Private service company and other building for service professions, 2021	1,054,000
Other building for sports etc., 2021	727,000

The population used to calculate the per person targets for climate change is the Danish population of 2021 which is 5.857 million people (The World Bank, 2021). See Table 13 for the project level targets for housing in Denmark, and Table 14, Table 15, and Table 16 for the project level targets for commercial buildings in Denmark.

3.1 Housing

All numbers are in the unit of kg CO_2eq/yr either per m^2 or per person.

Table 13:The allocated shares of the national climate budget to the housing sector, both per m^2 and per person, calculated by applying a combination of different allocation principles.

	Allocation principle	Sufficiency	Emissions grandfathering	Expenditure grandfathering
Per m2	Historical responsibility	-1.06	-0.90	-0.80
	Capacity	0.15	0.13	0.11
	Equal per capita	1.18	1.01	0.90
Per person	Historical responsibility	-53.95	-45.81	-40.77
	Capacity	7.73	6.57	5.85
	Equal per capita	60.43	51.31	45.67

3.2 Commercial buildings

Table 14: Allocated shares of the national climate budget for different commercial building sectors, expressed per m^2, by applying the Sufficiency allocation principle. All numbers are in the unit of kg $CO_2eq/(yr*m^2)$.

Sufficiency	Retail	Restaurants etc.	Service companies	Sport
Historical responsibility	-0.90	-6.14	-0.67	-3.06
Capacity	0.13	0.88	0.10	0.44
Equal per capita	1.01	6.88	0.75	3.43

Table 15: Allocated shares of the national climate budget for different commercial building sectors, expressed per m^2, by applying the Emissions Grandfathering allocation principle. All numbers are in the unit of kg $CO_2eq/(yr*m^2)$.

Emissions grandfathering	Retail	Restaurants etc.	Service companies	Sport
Historical responsibility	-2.89	-38.69	-5.54	-7.13
Capacity	0.41	5.55	0.79	1.02
Equal per capita	3.24	43.34	6.20	7.98

Table 16: Allocated shares of the national climate budget for B2C sectors, expressed per m^2, by applying the Expenditure Grandfathering allocation principle. All numbers are in the unit of kg $CO_2eq/(yr*m^2)$.

Expenditure grandfathering	Business-to-consumer
Historical responsibility	-1.19
Capacity	0.17
Equal per capita	1.33

4 Wish list for allocation principles

The wish list for allocation principles contains aspects, that could lead to future improvement in allocation approaches.

4.1 Improving the use of scenarios for the Sufficiency allocation principle

As stated earlier, the data applied for the Sufficiency allocation principle is decent living energy by Millward-Hopkins et al. (2020) which is based on scenarios for what a decent life is. However, there is a couple of shortfalls in the definition of these scenarios, which could be addressed in further development of these or similar scenarios.

First of all, there are some types of needs are not included in the scenarios for decent living, e.g., culture, religion and political engagements. Such needs are currently not included in the study by Millward-Hopkins et al. (2020), but should be addressed in future research. It is definitely a shortfall of the decent living scenarios that they rely on one view of what functions and services are required to live a decent life when they might be very different across the world.

Second, more disaggregated categories in the decent living scenarios should be explored to better allocate to different types of commercial buildings (e.g., buildings for business-to-business activities which is currently not included in this publication). Commercial buildings are included in the Millward-Hopkins et al. (2020) study as a part of the "other" category, and it could be relevant to explore further what it covers, and how it can be disaggregated.

Third, we used buildings´ share of total final energy consumption within a decent living scenario to allocate a share of the planetary ceiling to buildings. In this approach, activities involving large amounts of final energy consumption are assumed to need a large share of the planetary ceiling and vice versa. We consider this assumption good for climate change, since a big share of global greenhouse gas emissions are caused by energy consumption. However, the assumption that a high final energy consumption, in a decent living scenario, translates to a high share of the planetary ceiling is not good for all impact categories. For example, impacts on Biosphere integrity are often a function of land-use more so than final energy consumption. Hence, future work on the application of decent living scenarios to allocate the planetary ceiling should go beyond the use of final energy consumption as a proxy for the need of the planetary ceiling, for example by estimating the actual impacts on planetary boundary categories of decent living scenarios.

4.2 Restricted consumption budget

The following two suggestions relate to what consumers would prioritize when their consumption budget is restricted.

4.2.1 Coin voting

The currently most used indicators for how we value things is final consumption expenditure. But in high income countries (such as Denmark), this indicator is not a good proxy for what is actually important to people because a big part of their total spending relates to luxury products. It is therefore relevant to examine how people would prioritize their budget if it were very restricted.

We suggest a scenario where participants are asked to distribute a limited number of coins among different consumption categories according to what they find most necessary. This could be done both in an online survey format or in a physical experiment. In both cases, people with relevant backgrounds should be a part of designing the method (e.g., philosophers, anthropologists, engineers etc.).

4.2.2 Elasticity of final consumption expenditure

Another way could be to test the elasticity of the FCE by examining the data generated during the recent (around 2022 and 2023) large increase in inflation. This will show how the consumption expenditure changes when people's money is worth less than before. This is closely connected to the concept of "marginal utility" which together with the "marginal cost" is used to describe when a consumer is prone to purchasing a certain thing/service. If the marginal utility is larger than the marginal cost, the consumer will buy and vice versa. By looking into FCE affected by large increase in inflation (large increase in the marginal cost), it is possible to investigate the size of marginal utility. It can therefore better help in the investigation on whether FCE is a proper proxy for our needs.

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Assessing impact on ecosystems

04

This chapter provides a description of how to assess impact on ecosystems with a focus on biosphere integrity, which includes assessing biodiversity on and off-site as well as assessing other aspects of functioning ecosystems, such as land use change, freshwater use and pollutants.

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4 Assessing impacts on ecosystems

Functioning ecosystems are directly linked with the core planetary boundary of biosphere integrity. But functioning ecosystems also depend on and affect sustainable abiotic processes in the hydrosphere, climate, and nutrient cycling. Measuring the impact of an urban development on ecosystem functioning from a planetary perspective is therefore complex. It calls for attention to multiple impact areas (as described in the Manual) and for a range of relevant indicators. In this chapter, we describe some of the relevant methods today which may be used to assess the impacts of urban development on various components of ecosystems, both on the project site as well as throughout the value chain. This is a field of knowledge and practice in rapid development, and there are still no international or national standards for downscaling planetary biosphere impact or even national measures of biodiversity. We expect that standards on biodiversity will be put forward in the near future and encourage developers and practitioners to catch up on this regularly.

4.1 Biosphere integrity

The planetary boundary for biosphere integrity is divided into two parts. The first part highlights the loss of functional diversity, representing the role of the biosphere in Earth-system processes. It is measured by two control variables called Biodiversity Intactness Index (BII) and Human appropriated net primary production (HANPP). The BII assesses the change in population abundance across many taxa and functional groups caused by human activities (Steffen et al., 2015). HANPP is a measure of human alterations of photosynthetic production in ecosystems and the harvest of products of photosynthesis, and thus a measure of change in energy flow in living material caused by human activities. Translating BII and HANPP into a local context as a measure for urban development impacts on functional biodiversity can be done with indicators such as abundance of selected species groups as well as area of natural ecosystems.

The second part of this planetary boundary for biosphere integrity corresponds to genetic diversity and is represented by the control variable of global extinction rate, in species per 1000 years (Steffen et al., 2015). In order to translate the planetary boundary for genetic diversity to the level of an urban development project, change in abundance of rare and endangered species, can be surveyed on the project site as well as estimated for the project's entire value chain.

The following sections describes tools and methods that can be used to assess the impact of an urban development project on biosphere integrity on-site and throughout the entire life cycle, respectively.

4.1.1 Biodiversity onsite: the Biodiversity Metric

The planetary boundaries global target as well as UN and EU biodiversity strategies advocate for an allocation of land area for natural ecosystems also on developed land and in urban areas. Reaching such targets requires changes in planning practices and decision makers' priorities, since land is under pressure from many human needs in these areas. An example of such a change is the UK Environment Act of 2021, under which all planning permissions granted in the UK (with a few exemptions) will have to deliver at least 10% biodiversity net gain on the project site or in a local context. Biodiversity net gain is measured and documented using a Biodiversity Metric tool (see Natural England, 2023, for more details about the methodology).

The Biodiversity Metric calculates biodiversity loss and gain for terrestrial and/or intertidal habitats, in relative "biodiversity units". It is currently the best available method for practitioners to calculate the impact of urban development on biodiversity. The method has been adopted by BREEAM certification schemes and in a Swedish protocol in 2022 (Climb 2022) and has been translated to Danish urban areas and launched as a pilot version of a Danish national urban nature survey method (ConTech Lab 2023).

The Biodiversity Metric is a habitat-based approach used to assess an area's value for biodiversity before and after development. Habitats are first mapped, their area measured, and the habitat condition assessed based on factors such as species diversity, structure, hydrology etc. indicating biological quality. A biodiversity score is then calculated in relative biodiversity units for each habitat. The value takes into account predefined **habitat weights** (rare and threatened habitat types received a higher score), the habitat's **condition** as well as its **strategic significance** in a local context (if the habitat has for instance been identified as a green corridor in a local plan, it receives a higher score). Furthermore, gains in biodiversity established by a development (e.g. adding new vegetation in an industrial area), must be secured for at least 30 years to be included as a positive biodiversity score. Biodiversity measures receive a lower value (so-called "**risk multiplier**") if they are carried out in remote areas, if their benefits happen far in the future or if they involve a risk of failure. Comparing biodiversity units from a biodiversity baseline survey with the project plan and eventually the constructed project shows the net gain or loss in biodiversity.

A biodiversity net gain target for an urban development on site requires consideration of the biodiversity present before the start of the project. If areas with natural vegetation or habitats with high value for biodiversity are present, it will be harder to make up for a loss during construction and thereby to reach a biodiversity net gain. In particular, habitats that are highly threatened and scarce are considered irreplaceable, and need a distinct case-by-case assessment.

Alongside the EU Taxonomy targets for new constructions on ecosystems and biodiversity, this is a strong incentive to prioritize development on already developed land in order to avoid impacts on existing biodiversity and to achieve a net positive result on site.

The process for working with biodiversity monitoring during development using the Biodiversity Metric requires the following activities (see Figure 4.1), which should be carried out by a qualified professional ecologist:

- Baseline survey of biodiversity: habitat and species mapping as well as condition assessment.

- Calculation of baseline biodiversity units with the Biodiversity Metric (open source spreadsheet tool, available at https://publications.naturalengland.org.uk/publication/6049804846366720)
- Providing input to landscape planning and design to ensure preservation of existing nature qualities and development of enough new habitats suitable for local flora and fauna.
- Calculation of biodiversity units for proposed urban development plan including habitats on ground as well as on buildings.
- Field survey after construction to evaluate actual biodiversity result.

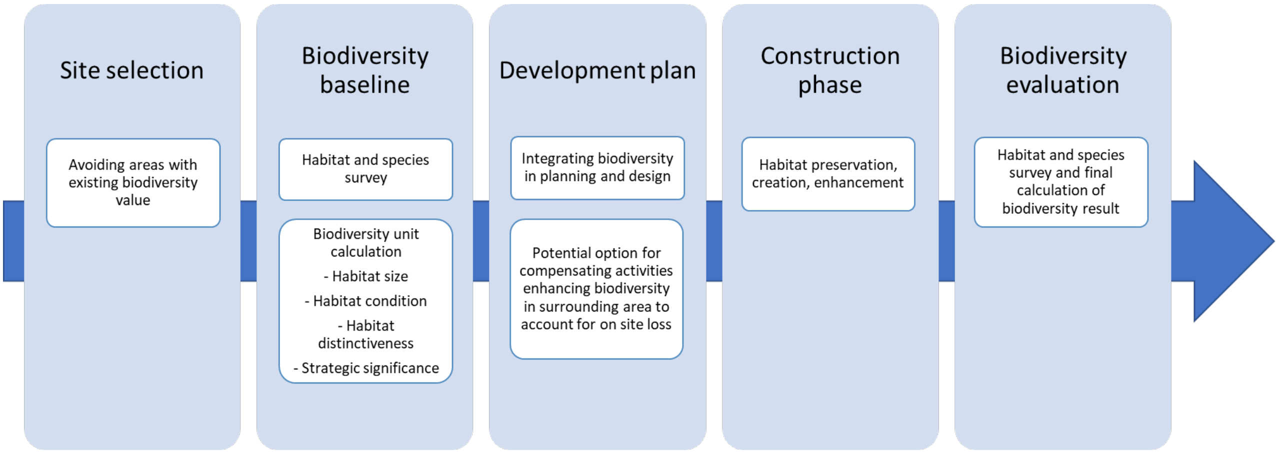

Figure 4.1 – Assessment processes for local biodiversity units

4.1.2 Biodiversity throughout the value chain: the Life Cycle Biodiversity tool

The largest impact on global biodiversity from urban development often happens outside the project site and the city itself. Extraction of resources such as sand, gravel, water, stone, iron, peat, energy and water consumption etc. degrades natural ecosystems nationally and globally. Waste from construction activities causes pollution and degradation of for example soil and aquatic ecosystems beyond the project boundaries, and energy use accelerates climate change which has a negative impact on ecosystems worldwide. It is therefore crucial to assess and reduce biodiversity impacts throughout the project's entire value chain and life cycle, considering off site habitat and species impacts through land use change as well as emissions to air, sea and freshwater from the production, installation and disposal of construction materials.

Models and methods to account for value chain impacts on biodiversity are being developed by different institutions for different sectors. For the real estate and construction sector, frameworks from Science Based Targets for Nature (SBTN)[1] and Taskforce for Nature Related Financial Disclosure (TNFD)[2] are dealing with this complex assessment and reporting, although the methodology and guidelines are not yet completed. These frameworks are strongly linked to and inspired by similar versions for climate change (TCFD and SBTi). Impacts on biodiversity from upstream and downstream offsite activities differs from climate impacts in that they are locally specific. Biodiversity impact from land use change caused by e.g. resource extraction in one region affects certain ecosystems and species that differ from the impact from a similar extraction in another part of the world. Therefore, geographic location of impacts is ideally necessary for value chain assessments on biosphere integrity. However, in practice, there is often insufficient data to map and quantify impacts on diverse species and ecosystems throughout the entire value chain, considering the complexity of the issue. For practical reasons and to enable comparison, a single indicator representing local losses of species in all

[1] https://sciencebasedtargetsnetwork.org/guidance-highlights/
[2] https://framework.tnfd.global/

affected areas is used: the “species.year” indicator. This indicator represents a local loss of species integrated over time. It should be read as "species lost locally multiplied by years" and not "species per year". Other indicators are possible (e.g. representing global species extinction risks instead of local losses of species), but this indicator is useful as it still relates to the local dimension of biodiversity loss, and has more available data.

Life cycle assessment (LCA) is the most relevant method to account for environmental impacts throughout the entire value chain. However, as of Spring 2023, common building LCA tools and databases do not include impact categories corresponding directly to biosphere integrity. Below, we propose two different solutions to carry out this assessment. This topic is evolving rapidly, and new tools, databases and methods are being developed (as indicated for instance by the recent introduction of new impact categories in the norm EN 15804+A2). Therefore, readers are encouraged to check for updates whenever starting a new analysis.

Both solutions are implemented in a simple spreadsheet tool, the Life Cycle Biodiversity tool, available together with the Doughnut for Urban Development manual. In the Life Cycle Biodiversity tool, users enter information about a specific building or project, including information on land use on the project area before and after the project, a bill of materials, and information on operational energy use. The tool’s input interface is set up with a structure similar to the Danish LCAbyg tool, enabling easy data entry for Danish users, but parameters can also be entered manually. Based on these parameters, the tool estimates the project’s impact on biodiversity over the entire life cycle, including on-site impacts and impacts throughout the entire value chain, in species.year. The point is to enable a comparison of biodiversity impacts from local land use change and from the use of various materials. However, it should be noted that the assessment of on-site impacts in the Life Cycle Biodiversity tool is much coarser and superficial than with the Biodiversity Metric described in the previous section. Therefore, the LCA tool is not meant to replace the Biodiversity Metric tool, but to offer a complementary approach for the purpose of comparing impacts from different life cycle processes. The descriptions below are based on a beta version of the tool, which might be updated after release.

4.1.3 Using third party environmental data

The first solution to calculate biodiversity impacts for the entire life cycle is to use detailed LCA data that allow for calculations of biodiversity impact. Programs like SimaPro and OpenLCA can be used to calculate impacts on so-called “endpoint categories”. Endpoint categories directly quantify impacts on the three areas of protection of human health, ecosystems and natural resources, instead of the more common “midpoint categories” tied to physical aspects (like climate change, acidification, eutrophication, etc) (Rosenbaum et al., 2017). This provides a direct calculation of impacts on biodiversity. Similarly, LCA databases like Ecoinvent and Sphera/GaBi include environmental data for a range of generic products. Selecting data using the “ReCiPe 2016 endpoint” method in these databases will provide information on biodiversity impact for all products. If the LCA is carried out using software such as SimaPro or OpenLCA, the analysis of biodiversity loss can be carried out directly in the LCA software, using the LCIA method ReCiPe 2016 Endpoint.

Alternatively, the Life Cycle Biodiversity tool can facilitate this calculation. The tool estimates how much the development affects biodiversity over time, in species.year. The tool can be opened with spreadsheet programs such as Microsoft Excel, and can be used as a supplement to an LCA prepared with conventional building LCA tools. However, the tool relies on generic data from the Ecoinvent database v3.9.1, which is not publicly available. The user would therefore have to purchase a license for Ecoinvent, and insert the corresponding data into the spreadsheet manually.

The first step to use the tool is therefore to enter manually all the relevant environmental data from Ecoinvent. This is a time-consuming step, but it only needs to be done once (it doesn't need to be repeated for all new projects). The "Data" tab in the tool indicates the names of all ecoinvent processes that can be used to facilitate this process.

Then, users need to enter building-related information in the "Input" tab. This can be done easily by copying information exported from LCAbyg, or the information can be entered manually. The impact on biodiversity of various material types and building parts is shown in the "Results" tab.

4.1.4 Converting LCA results into impacts on biodiversity

A second solution exists, which does not require purchasing third-party data. It is possible to convert impacts from common building LCA tools like LCAbyg into impacts on biodiversity. This can be done using "midpoint-to-endpoint characterization factors", which link each usual LCA impact category (climate change, eutrophication, acidification, etc) with corresponding impacts on biodiversity, human health and natural resources. Essentially, this solution entails multiplying results in each LCA impact category by an appropriate conversion factor to calculate the corresponding impact on biodiversity (Huijbregts et al., 2017a,b). These factors are reported in Table 4.1. The three perspectives represent sets of assumptions and methodological choices, e.g. about how far into the future impacts are considered and how precautious the assessment should be. The individualistic perspective is based on short-term interest, impact types that are undisputed, and technological optimism regarding human adaptation. The hierarchist perspective is based on scientific consensus regarding the time frame and plausibility of impact mechanisms. The egalitarian perspective is the most precautionary perspective, considering the longest time frame and all impact pathways for which data is available. More information is available in the dedicated ReCiPe 2016 report on characterization (Huijbregts et al., 2017b) .

The advantage of this solution is that these factors are freely available, and can be used in combination with open-source tools and data. Furthermore, this method can use specific data that accurately represent the products used in the project, such as EPDs, instead of more generic data from the databases used above. This method can be implemented in the Life Cycle Biodiversity tool using the "LCA Conversion factors" tab. Users can simply enter LCA results for all relevant environmental impact categories for their project, and the tool converts the results into biodiversity impacts (by default using the hierarchist conversion factors in Table 4.1). However, this can only be done if the user has access to LCA results covering all relevant environmental categories for the building (global warming, photochemical ozone formation, acidification, toxicity, water consumption, land use and eutrophication).

A major drawback is that some LCA impact categories that matter for biodiversity are missing from conventional building LCA tools and databases (for instance ecotoxicity, land use and water use are missing in LCAbyg). For many products, this makes a relatively small difference. For these products, users can adjust their results by multiplying material amounts in their LCA (before converting LCA results with the biodiversity tool) by the correction factors provided in Table 4.2. The correction factors were derived from generic environmental data on a sample of 110 relevant construction products. They should only be considered as a rough approximation, and it should be noted that they may vary between countries (since impacts in various categories depend on e.g. transport distances and energy mixes). For biogenic products in particular, the difference is very important, as most of the biodiversity impact of these products comes from land use changes. For these products, it is *not* recommended to rely on conversion factors if land use data are missing in the LCA. Instead, users should look for generic data that directly includes impacts on biodiversity, as described in the previous section.

Table 4.1 – Midpoint-to-endpoint characterization factors, adapted from (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al., 2017a)

Conversion factor	Unit	Perspective		
Terrestrial ecosystems		Individualistic	Hierarchic	Egalitarian
Global Warming - Terrestrial ecosystems	Species.year/kg CO2 eq.	5.32E-10	2.80E-09	2.50E-08
Photochemical ozone formation - Terrestrial ecosystems	Species.year/kg NOx eq.	1.29E-07	1.29E-07	1.29E-07
Acidification - Terrestrial ecosystems	Species.year/kg SO2 eq.	2.12E-07	2.12E-07	2.12E-07
Toxicity - Terrestrial ecosystems	species*yr/kg 1,4-DBC emitted to industrial soil eq.	5.39E-08	5.39E-08	5.39E-08
Water consumption - terrestrial ecosystems	species.yr/m3 consumed	0.00E+00	1.35E-08	1.35E-08
Land use - occupation	Species.yr/annual crop eq	8.88E-09	8.88E-09	8.88E-09
Freshwater ecosystems				
Global Warming - Freshwater ecosystems	Species.year/kg CO2 eq.	1.45E-14	7.65E-14	6.82E-13
Eutrophication - Freshwater ecosystems	Species.year/kg P to freshwater eq.	6.10E-07	6.10E-07	6.10E-07
Toxicity - Freshwater ecosystems	Species·yr/kg 1,4-DBC emitted to freshwater eq.	6.95E-10	6.95E-10	6.95E-10
Water consumption - aquatic ecosystems	Species.yr/m3 consumed	6.04E-13	6.04E-13	6.04E-13
Marine ecosystems				
Toxicity - Marine ecosystems	Species·yr/kg 1,4-DBC emitted to sea water eq.	1.05E-10	1.05E-10	1.05E-10

Table 4.2 – Correction factors to account for missing impacts from land use, ecotoxicity and water use. LCA results (or material amounts) for each material should be multiplied by these correction factors if the original LCA did not include impacts linked with land use, ecotoxicity and water use. These factors are rough estimates. Red values correspond to biogenic materials, for which results are very inaccurate.

Product type	Multiply converted results by…
Aggregates	1.4
Bricks and clay tiles	1.2
Concrete	1.1
Electricity supply	1.5
Glass	1.1
Gypsum fibreboards	1.15
Particle boards	1.25
Fibreboard (cellulose fibre, with little to no gypsum)	2.85
OSB	7.15
Plywood	5.55
CLT	12.5

Product type	Multiply converted results by…
Sawn wood	20
Wooden furniture, doors	2
Wood wool (loose)	25
Wood wool (cement-bonded boards)	2.75
Glass wool, stone wool	1.15
Heating (natural gas)	1
Heating (heat pump)	1.1
Heating (biomethane)	1.2
Heating (other)	1.1
Installations (embodied)	1.15
Metal products	1.15
Fibre cement	1.2
Cement	1.05
Mortar and plaster	1.1
Polystyrene	1.1
PV panels	1.3
Transport processes	1.8

4.1.5 Expressing impacts of local land use change in species.year

Even though the purpose of the Life Cycle Biodiversity tool is primarily to calculate upstream and downstream impacts on biodiversity, the tool also includes a calculation of the impact of local land use change, in species.year. The purpose is to use the same indicator as for upstream and downstream impacts, in order to be able to compare them and sum them together to calculate impacts over the entire life cycle. Users enter information on land use types on the project area before and after the project in the "Input" tab. The tool calculates impacts from converting land from one type to another, and from occupying the land for a given period of time (usually, the same time horizon as the reference study period used in LCA should be used, often 50 or 60 years).

Huijbregts et al. (2017b) provide coefficients to calculate the impact of local land use change as a local loss of species. Two types of coefficients are used. *Transformation coefficients* represent the one-time impact of converting land *from* a natural habitat type into an artificial habitat type. Conversely, the impact of regenerative activities that convert land *to* natural habitat types is calculated by taking the opposite value for each coefficient (since negative values represent a beneficial impact for biodiversity). *Occupation coefficients* represent the impact of occupying the land over time, and not allowing it to return to a natural state. To assess a project's impact linked with land occupation over time, the impact of land occupation before the project is subtracted from the impact of land occupation after the project. The impact of transformation occurs once and does not depend on a time horizon, while the impact of occupation is calculated for each year of occupation during a chosen study period. These coefficients are summarized in Table 4.3.

Table 4.3 – Land use transformation and occupation coefficients, adapted from (Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Zijp, et al., 2017a)

Habitat type	Transformation coefficients (in species.year/m^2)
Unexploited forest	3.26E-07
Grassland (natural, non-use)	3.33E-08
Shrubland	3.33E-08
Wetland (non-use)	3.33E-08
All other land use types	0
Habitat type	**Occupation coefficients (in species.year/(m^2 and year of occupation)**
Used forest	2.66E-09
Unexploited forest, grassland or wetland	0
Pasture (man-made)	4.88E-09
Shrubland	2.66E-09
Annual crops	8.88E-09
Permanent crops	6.22E-09
Mosaic agriculture	2.93E-09
Urban and industrial land	6.48E-09

The project's impact from local land use is therefore:

$$\sum_{l}(A_{l,before} - A_{l,after}).T_l + (A_{l,after} - A_{l,before}).O_l.\tau$$

Where l is a land use type, $A_{l,before}$ and $A_{l,after}$ are the area of this particular land use type before and after the project respectively, T_l and O_l are the transformation and occupation coefficients for this land use type respectively, and τ is the duration of occupation.

4.2 Other aspects of functioning ecosystems

Besides biosphere integrity, functioning ecosystems also strongly depend on some of the other planetary boundaries. This section briefly describes how onsite and offsite impacts related to other aspects of functioning ecosystems can be assessed.

4.2.1 Land use change

In the planetary boundary framework, land use change is defined as impact on ecosystems with strong link to climate change, which is delimited to change in forest area. The control variable for land use change is the area of remaining forest cover, for tropical, temperate and boreal forest biomes. The variable is thus constrained to the most important biogeophysical processes in land systems that directly regulate climate (Steffen et al., 2015).

Change in forest area can be measured both on the project site as well as in the value chain, where forest may be cleared for resource use such as timber or sediment extraction in forested area. Forest area may be measured with a GIS tool and analysis of orthophotos from different phases of the development (baseline, construction, operation or drawings of expected vegetation including trees). The canopy cover of newly planted trees can be projected to a mature state with growth models for trees as for example available in the Biodiversity Metric from Natural England (Natural England, 2023).

Changes in forest area throughout the life cycle cannot easily be calculated. However, it is likely that the coming years will see an increase in available data for land use impacts in LCA. Recent changes to the EN 15804+A2 norm have led to the inclusion of an indicator for soil quality, which can be used as an indicator of impacts on land use. However, the indicator is still quite new as of 2023, with limited data available.

4.2.2 Freshwater use

The global control variable for freshwater use is defined by the consumption of blue water from rivers, lakes, reservoirs, and renewable groundwater stores, as well as the withdrawal of mean monthly river flow on the water basin scale (Steffen et al., 2015). Another parameter in the hydrological system, which has been introduced in the Planetary Boundary framework is that of green water. Green water covers freshwater present as terrestrial precipitation, evaporation and soil moisture.

Freshwater use in the urban development may cause impacts on functioning of ecosystems within the water basins of the water source. Groundwater extraction has implications for water levels in wetland habitats, lakes and rivers and surface water use. The use of rainwater also influences the natural water cycle and water availability for natural ecosystems and local species.

The impact of freshwater use from urban development is measured as the volume of water used in construction, both on site and throughout the value chain as well as impeded natural infiltration in the developed area (fraction of surface water not infiltrated locally). This is related for instance to soil artificialization. Data on freshwater use throughout the entire life cycle of construction products can be found in EPDs and generic environmental databases consistent with the EN15804+A2 norm.

4.2.3 Pollutants

Three planetary boundaries deal with pollutants: aerosols (which affect human health and the climate), novel entities (which create risks of long-lasting negative effects) and nitrogen and phosphorous flows (which cause eutrophication). In general, either the volume of produced pollutant, the concentration of the pollutant in the environment, or the actual effect of the pollutant is measured. Translating this into a local dimension is done with indicators such as the amount of pollutants used in or leaching from the development (ex. fertilizers), as well as indicators for waste handling focusing on avoiding pollutants spreading to the environment (ex. plastics). Regarding the impact of pollutants throughout the life cycle, relevant impact data can easily be found in generic environmental databases or EPDs consistent with the EN15804+A2 norm. Notably, practitioners can look for data related to the impact categories of "hazardous waste disposed", "radioactive waste disposed", "eutrophication potential", "acidification potential" and "photochemical ozone formation". However, there is currently no common LCA impact category related to novel entities.

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Accounting for regenerative practices and positive environmental impact

05

This chapter provides an overview of how to account for regenerative practices and positive environmental impact as related to building-related activities, including a discussion on the positives and negatives of cap-and-trade emission allowances, carbon offsets, as well as biodiversity and biocredit offset schemes.

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5 Accounting for regenerative practices and positive environmental impact

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5.1 Introduction

Regenerative activities, i.e. activities carried out to provide a positive impact on the environment, are an essential part of working with Doughnut principles for two reasons. First, from a qualitative point of view, the Doughnut principles aim to shift perspectives away from the idea of only *doing less bad*. Rather, having a positive impact becomes an essential part of the project. Furthermore, from a quantitative point of view, the planetary sustainability targets are very ambitious. Some of the allocation principles for climate change lead for instance to negative targets. It is therefore unavoidable to discuss how to account for "negative emissions" and processes having a positive environmental impact. This topic is usually addressed through the lens of "compensation" or "offsetting", for instance in frameworks such as Greenhouse Gas Protocol and Science-Based Targets Initiative. However, we deliberately avoid these terms to make an essential distinction between the necessity to reduce negative impacts, and the aim to provide positive impacts. Both are necessary to be consistent with Doughnut Economics principles, but they are distinct issues. This section covers how a developer can achieve positive environmental impacts by carrying out or funding regenerative activities.

Broadly speaking, we can distinguish between three possible types of regenerative activities: building-related activities, third-party credits, and emission allowances on a cap-and-trade market such as the EU Emission Trading System (ETS). However, these solutions are not all equally viable. There are pitfalls and disagreements regarding what practices can legitimately be considered to contribute to beneficial environmental impacts, and a real risk of greenwashing if such claims are not carefully monitored using strict criteria of rigor and transparency.

As a general rule, benefits from regeneration should *never* be subtracted from the assessed environmental impacts of a building; they should be reported separately.

5.2 Building-related activities

The most straightforward type of regeneration comes from activities with a positive environmental impact carried out as part of the building project.

Certain processes happening in a building's life cycle might affect other systems outside of the building. In particular, a building producing renewable electricity might export electricity to the grid, and some building components might be reused or recycled when they are decommissioned. Both of these processes provide environmental benefits, but these benefits happen beyond the boundaries of the building's life cycle. Design practices that truly enable these benefits (such as design for disassembly) can be considered as regenerative activities. According to the EN 15804 norm, benefits beyond the building's life cycle *cannot* be subtracted from the building's environmental impacts: they can only be reported separately. This is the approach chosen for all regenerative activities in the Doughnut for Urban Development manual (as opposed to classic offset programs relying on the idea that positive impacts are *subtracted* from negative impacts).

For instance, if **solar panels** are installed on the building and produce electricity in excess of the building's needs, the remaining electricity can be exported to the grid. If we consider that this replaces electricity on the grid based on the average projected mix for Denmark in the next 50 years, the building can be considered to have a positive impact of 52 gCO2e/kWh exported electricity (this value depends on several important assumptions and methodological choices).

To some extent, facilitating the reuse and recycling of construction materials at the end of their service life through "**design for disassembly**" can also be considered a regenerative activity whose benefits should be accounted for. However, it is crucial to avoid double-counting: if the building uses recycled or reused materials and benefits from lower impacts during the production stage (module A), benefits from reuse and recycling at the end of the service life (module D) should *not* be accounted for. If particular precautions have been taken to ensure that building components are easy to disassemble without damage and are easy to reuse, benefits corresponding to 10% of these components' impact can be claimed. In this case, the same impact should be attributed to the reused component when assessing the building in which it is reused.

This 10% value is entirely arbitrary. It was chosen for consistency with new criteria used in the DGNB certification. The purpose is to encourage both the purchase of reused materials and design principles that encourage reuse in the future. In other words, both the building designed for disassembly and the future building reusing materials get a share of the benefits. This share is not equal in order to discount for uncertainties about whether or not the product will actually be reused. In other words, the building designed for disassembly gets a lower share of the benefits because these benefits only occur far into the future. It should be noted that research by Eberhardt et al. (2020) as well as the French label E+C- have proposed higher values (e.g. accounting for benefits equal to one third of the components' impact). Ultimately, this choice depends on a key question: To what extent do we want to give a higher priority to the use of reused materials today (versus facilitating reuse in the future)? It is important to use consistent values to keep these assessments comparable, which is why the 10% value was chosen for consistency with DGNB.

A final aspect that deserves consideration is the storage of carbon in **biogenic building materials**. Such materials are produced from trees, hemp and other plants. These plants absorb CO_2 during their growth. In theory, as long as the biogenic materials remain in the building stock, they could therefore be considered to have a positive climate impact. However, there are two caveats to this claim. The first is that long term end of life scenarios for materials are uncertain. To account for a long-term positive climate impact, the carbon needs to be stored permanently, or at least for a very long time, e.g. over a century (although in the short term, even temporary storage provides some climate benefits). Nowadays, the most common approach in

LCA is to consider that biogenic carbon is released at the end of the service life, resulting in net zero biogenic carbon emissions over the life cycle (Ouellet-Plamondon et al., 2023). However, in the future, if it is assumed that biogenic products are not incinerated and are instead handled in a way that enables long-term carbon storage, it could be argued that using biogenic construction materials leads to significant climate benefits. This depends on uncertain assumptions about the future. The second caveat is that an increased use of biogenic construction materials could create a high competition for limited biogenic resources, especially considering the rising demand for bio-energy. Currently, LCA for biogenic building materials struggles to take into account the risk that an increase in demand could affect the dynamics of carbon storage in forests (if it leads to an increase in the exploitation of forests). The actual impact likely depends on the rotation period of the biomass and on which particular forestry practices are used (e.g. intensive clear-cutting might increase the release of soil carbon (Mayer et al., 2020)). There is no strong consensus on the long-term benefits of carbon storage in biogenic products, so it is not recommended to account for a positive impact of biogenic carbon storage at this point.

5.3 Cap-and-trade emission allowances (EU ETS)

Another mechanism worth mentioning is cap-and-trade systems, such as the EU ETS. In a cap-and-trade system, total emissions from specific sectors of the economy are capped to a maximum amount and emission allowances are allocated to organizations within these sectors. Organizations that have lower emissions than their allowance can sell excess allowances. One way to compensate for emissions is therefore to buy and cancel emission allowances on the ETS. However, historically, there has been a large oversupply of allowances on the market. This meant that purchasing allowances had very little effect on actual emissions, as most organizations were able to stay well under their emission quota without making any change to their activity. The EU ETS has been revised in 2019 to address this oversupply, and the allocation of allowances will decrease each year in order to meet the EU's GHG emission target (a 55% reduction by 2030 compared to 1990). As of 2022, an oversupply of allowances remains in the EU ETS, and it is unclear whether the new mechanisms introduced will manage to address this. If the ETS allowances are not oversupplied in the long term and can demonstrably make a difference in the emissions of organizations within the ETS, then the purchase of allowances can be considered a valid mechanism to reduce greenhouse gas emissions. However, there is currently weak evidence that this will be the case, and the purchase of ETS allowances should therefore **not** be used to make claims about "negative emissions" in planetary sustainability assessments.

5.4 Carbon offsets

"Carbon offsets" are certificates emitted by organizations who carry out an activity that directly reduces GHG emissions or increases carbon storage. They are controlled by a third party, and purchased by other organizations to claim the corresponding climate benefits.

5.4.1 Types of carbon offsets

When it comes to the purchase of "carbon offset" certificates, many offsets rely on either biological storage of carbon or Carbon Capture and Storage (CCS). Biological storage usually relates to agricultural and forestry activities aiming to reduce emissions from biological carbon stores and increase storage in biogenic materials. Emissions from biological carbon stores can be reduced for example by restricting the ploughing of agricultural land, which reduces the emissions of soil-bound carbon. Increasing storage in biogenic materials entails using plant photosynthesis to remove and store CO_2. This can be done, for example, through replanting of felled forest (reforestation) or by planting new forest (afforestation). One major concern with forestation offsets is that their climate benefits are unclear in the long term, since it is possible that the trees will e.g. burn or be cut down in the future. However, if done well it can provide many co-benefits – including for biodiversity.

A particularly promising direction for carbon storage is the production and use of *biochar* from the pyrolysis of organic matter. Producing biochar yields oils and gases that can be used as fuels, while biochar itself can be added to soil to improve soil properties, or mixed into e.g. concrete as a partial substitute for cement. Since biochar is made of carbon, if it is stored in a very stable form in the soil or in materials, if can be considered a long-term solution to remove carbon from the atmosphere. A possible downside is that producing biochar can require a lot of organic matter. For a given amount of biomass, simply burning the biomass would provide more energy than producing biochar and using the resulting biproducts as fuels. Biochar is a promising solution, especially in energy systems that are already relatively decarbonated. However, its benefits are highly dependent on its stability and the amount of biomass needed for its production (Azzi, 2021; Fawzy et al., 2021).

On the other hand, CCS relates to processes in which CO_2 is captured and stored. CCS is often used in conjunction with the direct burning of fossil fuels. In such cases, the technology simply prevents emissions, and thus no negative emissions are generated. CCS can also be used in connection with, for example, the burning of biomass, called Bio-Energy with Carbon Capture and Storage (BECCS). However, the sustainability of BECCS is heavily dependent on how the biomass is produced, and upscaling BECCS could require large areas of land (Fajardy & Mac Dowell, 2017). There are concerns about the feasibility of upscaling BECCS in a sustainable way, especially considering other competing uses of biomass. CCS can also entail the direct technological removal of CO_2 from the atmosphere, called Direct Air Carbon Capture and Storage (DACCS). The first large-scale DACCS plant was opened in Iceland in 2021. DACCS could become a major carbon removal technology, although some economic and technical challenges (e.g. related to the energy use of the DACCS process) remain to be addressed (Breyer et al., 2019; Fasihi et al., 2019). CCS can potentially contribute to negative emissions. The captured CO_2 can be stored temporarily, for example as Power-to-X or by embedding it in materials such as plastic, chemicals or concrete. The CO_2 can also be stored permanently in e.g. underground storage.

Finally, *enhanced weathering* is a carbon storage solution that entails grinding silicate minerals into small particles. This considerably increases the area of contact between silicates and the ambient air. Silicates have a natural ability to absorb CO_2 over time, and enhanced weathering speeds up and amplifies this process. Ground silicate minerals can be used in agriculture to improve soil health, or they can be spread on beaches to help combat ocean acidification (Hartmann et al., 2013).

5.4.2 Quality criteria for offsets

When using carbon offsets to account for a positive climate impact, it is necessary to only pick high quality offsets, i.e. offsets where there is a high level of confidence that purchasing the offset will actually lead to climate benefits. In practice, the following criteria are indicative of the quality of a carbon offset[1]:

- **Additionality**: Would the activity providing climate benefits likely happen even without selling the offset? If it would, then the offset is not additional, and purchasing it does not provide clear climate benefits. For instance, carbon offsets related to the preservation of a forest are only additional if the forest would likely be cut down otherwise. Offsets related to activities that are legally required or economically profitable on their own are not additional, since the activity would likely still happen without the offset.
- **Accurate measurement**: A high quality carbon offset must have assessed its climate benefits based on scientifically sound and robust data and methods, and monitor these benefits over time. In

[1] For more information, see the Carbon Offset Guide: https://www.offsetguide.org/high-quality-offsets/

particular, the organization should accurately account for both the direct and indirect impacts of its activity, and should only account for environmental benefits that are *additional* (see above).

- **Permanence**: A high quality carbon offset should provide benefits from avoided emissions or stored carbon that are unlikely to be reversed in the future (at least in the coming century). For instance, offsets related to forestation are not permanent if there is a high risk of large forest fires in the area.
- **Exclusivity**: It is important to make sure that only one actor claims climate benefits from a particular activity to avoid double-counting. Most carbon offset schemes have mechanisms in place to avoid situations where an offset would be issued or purchased twice.
- **No harmful side effects**: The activity related to the offset should not cause significant environmental or social harm.

It should be noted that many offsets that had been quality-checked by third party programs have been criticized for being unreliable or harmful. This concerns for instance offsets related to forest protection, where some organizations generated climate offsets by claiming to protect forests that were not under threat in the first place (no additionality). In other cases, offsets linked with afforestation led to the displacement of local populations. It is therefore particularly important to carefully check the quality of carbon offsets before purchasing them.

To be consistent with the Doughnut principles, **carbon offsets and similar schemes should not be subtracted from actual emissions**. Rather, they should be reported separately. In other words, purchasing high-quality offsets can potentially lead to positive impacts, but they are not a way to reduce impacts – rather a potential option for funding carefully selected regenerative activities.

5.5 Biodiversity offset schemes and Biocredits

Organizations and individuals engaging with biosphere regeneration might want to purchase certificates representing a positive impact on biodiversity, separately from the project. Two mechanisms exist for this purpose: biodiversity offsets and biocredits. However, the two concepts have important differences.

Biodiversity offsets are similar to carbon offsets. Essentially, an organization carrying out a project that causes ecosystem damage funds a restoration or preservation project somewhere else, in order to claim a "net zero impact" on biodiversity. Offsets might be useful for compliance with a certification or regulation, e.g. to compensate for impacts that cannot easily be avoided, but they have fundamental incompatibilities with the principles of Doughnut Economics. Biodiversity offsets are based on the idea that damage in one location can be compensated by regeneration somewhere else. The first issue with this notion is that "biodiversity" is not as easily measured as e.g. greenhouse gas emissions for carbon offsets. Biodiversity indices are often combinations of many indicators, which complicates comparison. While climate change is a global phenomenon, where absorbing one ton of CO_2 in one location can directly make up for emitting one ton of CO_2 somewhere else, biosphere integrity is inherently local. Clearly, preserving an area of tropical forest while developing a wetland in Scandinavia does not lead to a neutral impact on the biosphere or for local populations. Finally, biodiversity offsets have sometimes been used as a "license to damage": projects that would not have been approved without offsets have been allowed to proceed only because the company purchased offsets. For these reasons, **the notion of offsetting impacts on biodiversity clashes with the principles of Doughnut Economics**.

On the other hand, **biocredits** are a novel type of mechanism that might offer opportunities to finance ecosystem preservation and restoration efforts at the global level without some of the issues mentioned above. Biocredits might be generated by projects restoring a damaged ecosystem, preserving an ecosystem that is at risk of damage, or in order to support preservation efforts by local communities in ecosystems that are not at immediate risk of damage. A key difference is that biocredits do not rely on any equivalence between damage in one area and restoration in another. Importantly, purchasing biocredits can only be done as a fully positive contribution to regeneration efforts, as **biocredits explicitly cannot be used for claims of offsetting**. Furthermore, biocredits are explicitly designed to **channel funding towards indigenous people and local communities actively working with ecosystem preservation**. One of the main challenges of biocredits is ensuring that the funding generated is actually received by local communities and indigenous people, and that these cash flows actually benefit them (by e.g. improving their agency and access to critical resources, and by taking into account power imbalances and the interests of multiple local stakeholders). For this reason, the involvement of local stakeholders throughout the entire process is an essential component of biocredit schemes (Ducros & Steele, 2022).

Biocredits are not yet widespread, but several organizations have already set up biocredit schemes. Since measuring "biodiversity" is complex and entails many arbitrary choices, the definition of a biocredit is complex and differs from one system to the next.

Ducros & Steele (2022) provide an overview of schemes established by Terrassos, ValueNature and Wallacea Trust. Terrassos places a high emphasis on reducing risks of extinction, and ensuring connectivity with other neighbouring ecosystems. The scheme defines biocredits based on an area's risk category (is it an endangered ecosystem?), whether the area is being preserved or restored (restoration is valued higher than restoration in this scheme), whether the measure implemented improves connectivity with neighbouring ecosystems, and for how long the measure is being carried out. Biocredits are generated after specific milestones have been reached in each preservation or restoration project. Terrassos uses additionality criteria that also consider the respect of local traditions, improvements in land tenure rights or investment opportunities, as well as the risk of negatively affecting other areas.

ValueNature places a higher emphasis on technological solutions to measure biodiversity values and generate biocredits. They define biocredits based on flora and fauna "intactness" indicators, weighted by carbon stocks present in the area and by the presence of threatened species. These intactness indicators are measured using remote sensing technologies such as satellite imagery, as well as camera traps and bioacoustics sensors (which identify the presence of vocal species from the sounds they make). ValueNature intends to implement the trade of biocredits using a blockchain-based distributed ledger. Their system is still under development, but the intention is that relying on remote sensing and decentralized ledgers should allow automating the process to a large degree and ensuring a high level of transparency. In turn, this should reduce the costs of monitoring and delivering the biocredits, and allow 80% of the biocredit price to be delivered to local biodiversity custodians.

The Wallacea Trust developed an open-source method that other actors can use to assess biocredits as well (Wallacea Trust, 2022). Biocredits are based on assessing a basket of at least five biodiversity metrics for the site, considering the species richness, importance (e.g. whether it is endangered) and abundance. One biocredit corresponds to a 1% improvement or avoided loss in the median value of the basket of metrics, which means that these biocredits can be compared across regions. The way this scheme sets prices and tracks e.g. additionality and double-counting is largely similar to carbon credits, and many projects can generate both biocredits and carbon offsets. At least 60% of the biocredits' price must be paid to local stakeholders.

As of Spring 2023, biocredits represent a promising but not yet mature system to finance conservation and regeneration efforts. As the system develops, some challenges will need to be addressed (Ducros & Steele, 2022):

- Additionality: Just like for carbon offsets, there is a need to show that purchasing a given biocredit will indeed provide benefits that would not have happened without that biocredit. However, a biocredit might provide conservation benefits without directly improving biodiversity (by rewarding, funding and strengthening ongoing conservation efforts or reducing threat to an area). Therefore, biocredits need to consider a broader definition of additionality.
- Leakage: One risk of biocredits is that they might negatively affect areas that are not covered by biocredits (for instance if biocredits help preserve an area from logging but the logging activity instead takes place in a neighbouring area). This needs to be considered when setting additionality criteria (something that e.g. Terrassos explicitly does).
- Quantifying the value of biodiversity: monitoring biodiversity in a reliable and transparent way can be complex and expensive. Remote sensing technologies can help automate this process and reduce costs, as seen with ValueNature. Conversely, Ducros & Steele (2022) also argue that biocredit schemes should integrate social and cultural components to their valuation of biodiversity, to better take into account the point of view of indigenous people.
- Setting up a functioning market: generating sales for biocredits remains a high priority in these emerging schemes. At the same time, since biocredits explicitly cannot be used for offsetting, there is a need to screen buyers to ensure that they do not purchase biocredits to make such claims. Furthermore, there is a need to strengthen transparency on the credit market, and to ensure that the sales benefit local communities and indigenous people (including strengthening land tenure rights and their agency to use traditional knowledge). This last point requires attention to the diversity of local communities, as they might be comprised of sub-groups with different needs.

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Social indicator measurement

06

This chapter works to answer the question "What is social impact?" and discusses quantification of social impact, structuring of the social foundation of the Doughnut for Urban Development, social tools and indicators, as well as existing frameworks that have influenced the Doughnut for Urban Development.

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Social Indicator Measurement

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In this chapter, we elaborate on the process for developing the 48 social impact areas and the structure of the social foundation of the Doughnut for Urban Development. Then, we outline the link between doughnut economics and the Sustainable Development Goals. Finally, we introduce our Tools & Indicator Library, which will enable developers to practically apply the Doughnut for Urban Development.

Compared to planetary impact, social impact is not as easily quantifiable and is inherently more subjective in its nature. What defines a good community or a good workplace depends on the person you ask and the local context. Therefore, we must be careful in our approach, to avoid the risk of only focusing on impact we can measure or impact that is relevant in our own context only.

At the same time, we must also recognise that one of the main reasons why the state of social impact in urban development is still far behind of where we should be is the very fact that quantitative impact management is nascent, making it hard for stakeholders such as investors to formulate specific and ambitious requirements. The has led to a larger focus on planetary sustainability and only a handful of social indicators such as indoor climate – which is highly relevant, but not sufficient on its own.

1.1 What is positive social impact?

Our proposed way of evaluating if an urban development project lives up to the social foundation is to follow the EU Taxonomy hierarchy of impact. We see the EU Taxonomy (European Commission,

2020) as a new common language for risk and sustainability management across Europe and its anchoring in national legislation furthermore makes it a highly credible and well-researched framework, we have therefore used it as a starting point.

The EU Taxonomy defines three levels of impact:

1. **Minimum Safeguards (MS):** a set of minimum standards that must be fulfilled under areas such as respect for human rights

2. **Do No Significant Harm (DNSH):** a set of criteria that must be met for an activity not to create "significant harm", such as a waste recycling threshold to be met

3. **Substantial Contribution (SC):** a criterion that must be met for an activity to have a substantial positive contribution in an impact area compared to the industry average, such as being in the top 15% of energy efficiency.

With the Doughnut for Urban Development, we encourage developers to apply the same logic within each of the social impact areas we define below, though with one important difference: we do not think developers can claim to have a "Substantial Contribution" unless their activity is truly regenerative in practice. This entails having a substantial *positive impact* rather than simply minimising negative impacts, as illustrated in Figure 1.

Figure 1: Defining social sustainability

In other words, we use the following definitions in the Doughnut for Urban Development:

1. **Minimum Safeguards (MS): Is** considered as a minimum bar for what is ethically and legally required within an impact area such as respect of local law

2. **Do No Significant Harm (DNSH)** is a contribution within an impact area that serves to fully eliminate *significant* adverse impacts. The activity might still have *immaterial* adverse impacts, but efforts have been made to manage and reduce material adverse impacts

3. **Substantial Contribution (SC)** is a positive contribution within an impact area that is truly regenerative. It does not merely serve to be sustainable, but actively enhances the social outcome that is pursued

1.2 Quantifying social impact

In future work, we hope to be able to add numbers on what it means to reach Minimum Safeguards, Do No Significant Harm and Substantial Contribution within each of the impact areas. That has, however, not been possible in this publication due to the limitations described above.

The 3-tiered approach should therefore only be seen as a guiding principle to activate project teams when they discuss their positive and adverse impacts across the impact areas and push for regenerative outcomes.

That also means that the Doughnut for Urban Development should not be seen as a certification or a framework that is possible to "comply" with – instead, it should inspire the pursuit of holistic impact assessment and serve as a practical tool.

1.3 The structure of the Social Foundation

With the Doughnut for Urban Development, we offer 48 impact areas across the Doughnut's original 12 dimensions. Alongside the impact areas, we have mapped and listed impact methodologies and tools, and built an indicator library with benchmarks that will enable participants in the urban ecosystem to advance their social impact strategies and make it easier to put value on and track social impact performance.

In some areas such as Health, the list of tools, indicators and benchmarks found in existing work is long and impossible to fully capture. In other areas such as Food or Political Voice, existing work is limited. We therefore encourage readers and users of the social foundation to use additional external social impact areas where relevant.

The 4 categories and 12 dimensions of the social foundation

In the Doughnut for Urban Development, the 12 social dimensions of the original Doughnut have remained unchanged, but we have decided to group these in 4 categories to simplify communications and highlight some of the important attributes of the 12 dimensions. The 4 categories and 12 dimensions are:

- **Responsible:** For a developer to be responsible, they should consider the positive and adverse impact on dimensions including Income & Work, Peace & Justice and Political Voice, ensuring that tenants, workers, local communities, and other key stakeholders have their rights respected and are treated fairly, alongside pursuing positive impact such as local economic activity and community empowerment

- **Equitable:** For a developer to be equitable, they should consider the positive and adverse impact on dimensions including Equality in Diversity, Social Equity and Education, ensuring that diversity of all kinds is respected, that value creation is distributed fairly, and that housing is developed for the most marginalised members of our society, alongside pursuing positive impact such as contributions to the education of workers

- **Inclusive:** For a developer to be inclusive, they should consider the positive and adverse impact on dimensions including Health, Housing and Community & Networks, ensuring that housing is accessible for all groups of society, that physical and mental health is respected for both tenants and workers, and that local communities are thriving and inclusive, alongside pursuing positive impact such as open innovation and knowledge sharing

- **Connected:** For a developer to create projects that are connected, they should consider the positive and adverse impact related to the dimensions of Food, Water and Energy, ensuring that stakeholders have their basic needs met in a clean, safe, and affordable way, that pollution risks are eliminated, and that ecosystems are protected, alongside pursing positive impact such as urban farming and access to local produce

The 48 impact areas

For each of the 12 dimensions, we have identified 4 “impact areas” – two of which are identified through a Local Lense and two of which through a Global Lense, to ensure a truly holistic framework covering the full project life-cycle and value chain. The social foundation lenses are understood in terms of local aspirations and global responsibilities, asking:

- **The local-social lens:** *How can all the people in this development thrive?*
- **The global-social lens:** *How can this development respect the well-being of all people?*

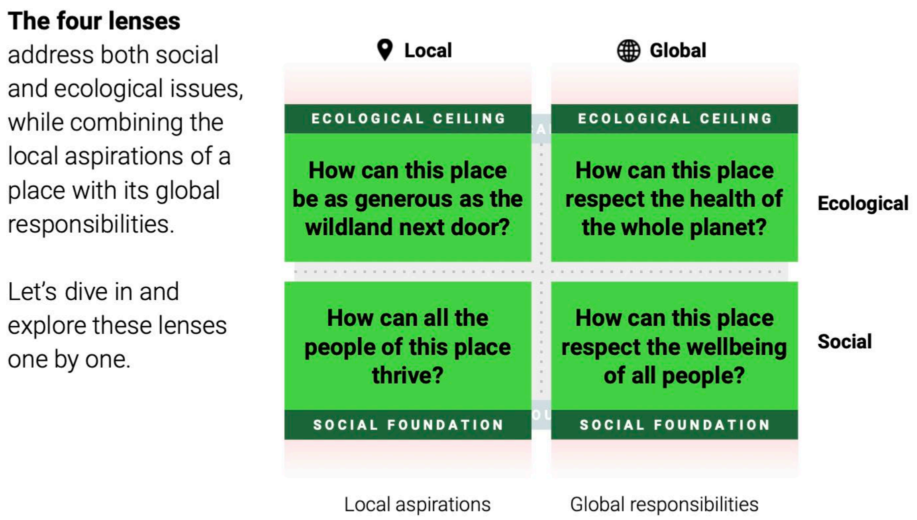

Figure 2: The four lenses framework (The Doughnut Economics Action Lab)

An “impact area” is an area in which a participant in the urban ecosystem has a risk of adverse impact or an opportunity to create positive impact, if they approach the area with the right impact management strategies and tools. In some dimensions, we have been forced to keep the impact areas more "high level” seeing the many subdimensions. That is, for example, the case of the Health dimension, which has many nuances, and should therefore be approached thoughtfully.

As highlighted before, we do not claim that the 48 impact areas compose an exhaustive list nor that we have prioritised the right things to ensure minimisation of adverse impacts and maximisation of positive impact. We hope, though, that the overview provides a sound starting point with the opportunity for broad application seeing the multidisciplinary approach, the comprehensive research done in advance of the impact area identification, and the diverse group of stakeholders involved in the process.

Methodology: how we identified the 48 impact areas

The 48 impact areas are the product of four separate workstreams that have come together:

1. A down-scaling of the original 12 dimensions of the Doughnut to maintain the link from the global level to the urban development level
2. Our mapping and analysis of existing frameworks to ensure that we build on top of existing best-practice while making adoption accessible and aligned with ongoing work

3. Three multidisciplinary workshops with a broad group of participants in urban development – from researchers to engineers, architects, developers and human rights experts
4. A Sounding Board process in which our drafts and ideas have been critically examined and further developed to uncover blind spots and nuance our contributions.

Collectively, these four steps have enabled us to develop the 48 impact areas in a well-researched way, drawing on a combination of existing best-practice and innovative thinking to push the social impact field towards new territory.

We hope to engage with the wider urban development ecosystem going forward, as we do not see the 48 impact areas and the associated Tools & Indicator Library as something set in stone. Rather, we wish for this project to continue evolving as new social impact frameworks, tools, and best practice emerges. Similarly, we hope that the spirit of open-source sharing persists and that examples of successful application of the Doughnut for Urban Development are shared widely with the rest of the urban development ecosystem.

The link between the UN SDGs and Doughnut Economics

In order to maximise our potential grasp of both the local and the global lenses, we used the UN Sustainable Development Goals as a starting point for the social foundation. Adopted in 2015 as part of the 2030 Development Agenda, the 17 goals formulate the overall path for sustainable development from 2015 to 2030. The goals replaced the Millenium Development Goals – eight goals for 2015 adopted by the UN in 2000.

The Doughnut was developed in 2012 and published in the Oxfam paper: A safe and just space for humanity. It was further developed during the UN Rio+20 conference on Sustainable development in 2012.

The SDGs were developed from 2011 to 2015, and it is therefore, not surprising that the 12 social dimensions of the doughnut are closely linked to the 17 global goals and the 169 sub targets. In the illustration below, Kate Raworth points to the similarities between the goals, their targets and the dimensions of the doughnut.

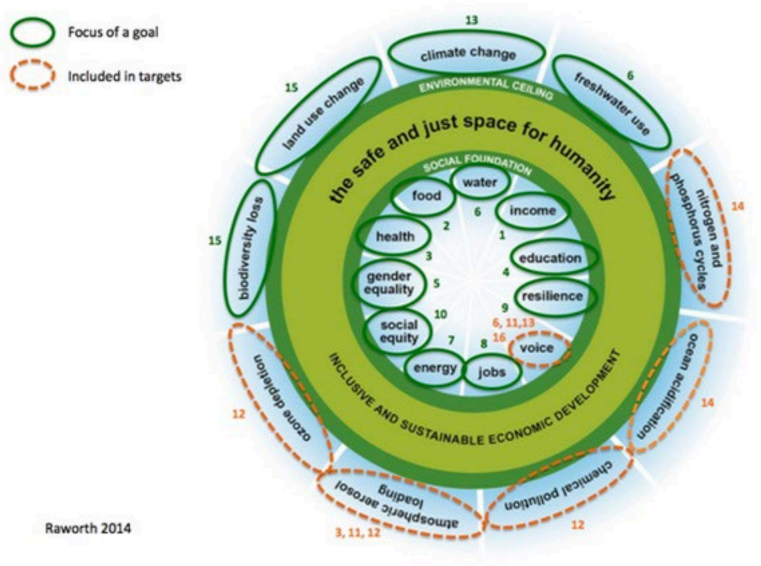

Figure 3: The link between the SDGs and the Doughnut (Kate Raworth, 2014)

There is, as mentioned, a strong overlap between the SDGs and the Doughnut, with the main differences being the Doughnut's stronger focus on planetary boundaries. The SDGs have four goals (6, 13, 14, 15) with a direct focus on planetary boundaries, and 13 goals that focus on social development.

The doughnut, on the other hand, has 9 dimensions on planetary boundaries, and 12 (previously 11) dimensions on the social foundation. From a social point of view, the SDGs create a better holistic social understanding of the doughnut's dimensions. Moreover, as illustrated above, all the social dimensions in the doughnut are covered by at least one SDG or sub target.

The 17 Global Goals are powerful as they are widely adopted and known across the world. Nations have committed to the 169 sub targets that make up the binding core of the goals, and the goals have been embedded in all parts of society – from the 17 overall goals guiding nation states to UN Global Compact and the SDG Action Manager (developed in collaboration with the B Lab) guiding companies to maximise their impact.

An important aspect of the SDGs is their focus on the sustainable development of the entire planet, which yield paradoxes in some of the goals: while many countries in the global south are still combatting SDG 2 – Ending Hunger, the leading problem in many other countries is not the lack of food but rather severe obesity and excessive food waste. This is reflected by some national adaptations of the SDGs, such as the Danish adaptation from 2020[1] and has also influenced the link between the SDGs and the Doughnut for Urban Development.

In 2020 the Danish Government, the 2030-panel, and Statistics Denmark commissioned the Danish adaptation of the SDGs. A large consortium of consultancies, researchers and experts joined to develop the translation, public hearing and data verification process. The report identified 197 additional sub targets for Denmark. The datapoints identified are currently tracked by Statistics Denmark, and in 2022 a status report was developed.

When applying the SDGs for data indicators and data points, a specific emphasis was made in order to use the Doughnuts Local and Global lenses, to maintain our focus on both local and global social sustainability.

1.4 Social Tools & Indicator Library

In the following section, we will introduce the social tools and indicator library. We furthermore describe the concept of Do No Significant Harm and Minimum Safeguards in the EU Taxonomy, which we expect will be central concepts in urban development in the many coming years.

The purpose and scope of the tools and indicator library

The tools and indicator library has been developed to inspire developers on how to practically measure, monitor and evaluate the social impact.

[1] Gør verdensmål til vores mål - 197 danske målepunkter for en mere bæredygtig verden, https://verdensmaalene.cdn.prismic.io/verdensmaalene/a7eb98a7-7218-4235-b98c-8170723e009c_VoresMaal.pdf

With the indicator library we wish to provide a *long* list of impact areas and indicators. We encourage ambitious developers to evaluate and measure indicators across all relevant impact areas. However certain impact areas and indicators may not be relevant in all settings. Moreover, there will be a difference in the hierarchical importance of certain impact areas, depending on the local social and urban context.

Finally, we strongly encourage developers to use available benchmarks and industry data sources to ensure that their performance is comparable.

1.5 Existing frameworks that have influenced the Doughnut for Urban Development

Global impact management frameworks – downscaling to the business and the plot

Globally, there are a relatively large amount of impact frameworks, often with a focus on either social or environmental impact, but also with a more general and or broad/holistic focus.

A distinction necessary to mention is, as with the SDGs and the Doughnut, the different scale that the frameworks operate within. The SDGs were developed to portray sustainable development through a global lense, with a local nation adaptation. Other impact frameworks/urban life indices, such as MONOCLE's, BCG's, the Economist, etc. work at a city level.

However, for our purpose, we are operating at a much more downscaled local level. Our local adaptation of the Doughnut is not a city, but a city district, and even a single plot and building. Thus, the framework needs indicators the developer can influence through the impact areas.

For the development of the Doughnut, we have considered company specific impact frameworks such as:

- the B Impact Assessment developed by B Lab
- the Global Reporting Initiative
- the IRIS+ framework by the Global Impact Investing Network
- the Impact Management Project among others

The power of these frameworks includes their wide industry adoption, ensuring that when we present the 48 impact areas of our Doughnut and the accompanying indicator library with benchmarks.

Similarly, they ensure consistency, alignment, and the opportunity for benchmarking – something that is critical in impact management to ensure we compare apples to apples and avoid an unnavigable jungle of different frameworks and indicators that are impossible to understand. In other words, our alignment with existing work strengthens adoption and enables the identification of leaders and laggards when it comes to social impact in urban development.

The SDG Data Portal

Beyond the alignment between the SDGs and Doughnut Economics described above, we note that the SDGs have a global indicator database developed by the UN including more than 200 indicators with more than 600 datasets. The full data portal can be accessed via unstats.un.org/sdgs/dataportal

Urban development specific tools like DGNB and BREEAM

The next important level of impact frameworks we have considered, are the ones measuring urban development. The built environment has some of the most comprehensive impact management frameworks, which guide developers and operators in promoting social and planetary sustainability while maintaining good governance around e.g. data transparency or worker rights.

Some of the most widely used frameworks and certification schemes include:

- DGNB, the certification scheme developed by the German Green Building Council
- LEED, the certification developed by the U.S. Green Building Council
- WELL, the certification of the International WELL Being Institute
- BREEAM by the Building Research Establishment

Within the project group, the main focus has been on the certification systems applied in Denmark, e.g. DGNB and WELL. And in the project group behind the Doughnut for Urban Development, we have been fortunate to have both Kasper Guldager Jensen (Home.Earth) and Harpa Birgisdottir (BUILD), who previously wrote the "Guide to Sustainable Building Certifications", a comprehensive review of the most widely used certifications schemes. We have therefore been able to draw extensive insights into the Doughnut.

The strengths of the urban development specific frameworks and certifications are their context-specificity, their quantitative data foundations, and their broad adoption enabling benchmarking and comparison.

They are – however – limited by their focus on what happens during the construction phase and on the local site specifically, with less focus on the entire project life-cycle and full value chain – the global lens of the doughnut. Moreover, they focus on the building, and the majority of the indicators are directed towards e.g. construction, materials, in-use, etc. rather than social impact areas. For DGNB the 2023 manual for new buildings and major refurbishments and the 2020 manual for urban areas, more than half of the impact areas focus on the above-mentioned impact areas.

Most of the certification schemes have developed a type of in-use certification, however the focus in often on the specific building, and not on the relationship with the urban system.

Local and regional legislation – building codes and the EU Taxonomy

The final layer of existing work we have considered is the rapidly developing legislative body around urban development. Considering the magnitude of the challenges the built environment is facing today – from the significant impact on our planet to the severe lack of affordable quality housing in cities – it is only natural that lawmakers have seen an opportunity to accelerate the green and just transition.

The EU Taxonomy plays a central role, as it offers a detailed and legally grounded taxonomy for how an economic activity– such as constructing a building – can be sustainable. It is furthermore closely connected to the flow of capital to urban development (particularly via the Sustainable Finance Disclosure Regulation) and the reporting and impact management strategies of companies (particularly via the Corporate Sustainability Reporting Directive).

At the time of writing, the Taxonomy has identified the "Substantial Contribution" and "Do No Significant Harm" Criteria for 2 of 6 impact areas around planetary sustainability, with the remaining 4 of 6 areas under development. Similarly, a Social Sustainability taxonomy is under development. Based on the final reports alongside the working group papers published by the EU, the Doughnut for Urban Development is highly aligned with the EU Taxonomy, which strengthens its applicability.

Similarly, we have surveyed local building codes in the development of the project to draw inspiration and seek benchmarks or indicators that are relevant to the Doughnut. We have, though, refrained from using local indicators in the final overview to ensure that the Doughnut for Urban Development is not limited by national-specific standards, but can be applied at least at an European level.

The latest EU Taxonomy Compass with the specific technical screening criteria across Substantial Contribution and Do No Significant Harm is accessible here: ec.europa.eu/sustainable-finance-taxonomy/taxonomy-compass

The concept of Do No Significant Harm and considerations on minimum requirements

As part of the coming EU legislation on the Corporate Sustainability Due Diligence Directive, the EU taxonomy and the CSRD mentioned earlier, a set of social minimum safeguards have been established for alle business striving to conduct sustainable business practices. The main social minimum safeguards identified are the:

- The OECD Guidelines for Multinational Enterprises
- The UN Guiding Principles on Business and Human Right
- The principles and rights from the eight fundamental conventions in the Declaration of the International Labour Organisation on Fundamental Principles and Rights at Work
- The International Bill of Human Rights

As a minimum, any work related to the social foundation of the Doughnut would need to adhere to these minimum safeguards.

Moreover, the EU taxonomy introduced the concept of: Do No Significant Harm (DNSH), which has been highly relevant in the development of the applicability of the doughnut. The concept is simple in its design; for the EU taxonomy, six environmental goals have been identified. In order to be aligned with the sustainability definition of the EU taxonomy, an economic activity, e.g. a building, will have to make a substantial contribution to one of the six environmental goals. Furthermore, the building will need to ensure, that no significant harm is done to the remaining five environmental goals.

Together, the social minimum safeguards and the DNSH criteria ensure a holistic approach to the economic activity.

1.6 Closing remarks

Collectively, our research of the frameworks listed above and the multidisciplinary expert workshops have led to the development of the social foundation of the Doughnut for Urban Development and the associated 48 impact areas.

Before you dive into the database, we wish to note one last time that we do not claim that the 48 impact areas compose an exhaustive list. With social impact, there is no one size fits all. Context and adaptation to local and project conditions is key.

We hope, though, that the overview provides a sound starting point with the opportunity for broad application seeing the multidisciplinary approach, the comprehensive research done in advance of the impact area identification, and the diverse group of stakeholders involved in the process.

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Tools, Open Resources, and Rights to Copy

07

This chapter includes a description of the tools developed alongside the Doughnut for Urban Development, why we created open resources and why we believe in ‘Rights to Copy.’

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Chapter 7: Tools, Open Resources, and Rights to Copy

In the spirit of Doughnut Economics, we invite industry professionals and researchers to explore the tools we have developed during our 2-year project. These tools aim to empower professionals to delve into the concepts of Doughnut Economics and take transformative action.

The tools are founded based on DEAL's three guiding principles:

1. Exploratory in scope: The tools encourage exploration and experimentation. They provide a starting point for users to dive into Doughnut Economics and apply it to their specific contexts.
2. Guiding with content: The tools offer clear guidance on how to use them effectively. They define the steps, outline what can be achieved with each tool, and highlight important considerations and potential pitfalls to watch out for.
3. Evolving with practice: The tools are designed to evolve and improve over time. While they are not exhaustive, they are continuously refined based on feedback and real-world application. They reflect the dynamic nature of Doughnut Economics and the need for ongoing learning and adaptation.

The tools are therefore at an exploratory stage, and do not aim to cover every aspect comprehensively. However, they provide concrete instructions on what can be done today and how to do it. They are developed based on tested practices, for example incorporating indicators from existing frameworks, standards, and certifications. Importantly, these tools are meant to be used, adapted, and shared back with the community. In summary, the tools developed for this project are meant to empower industry professionals and researchers to embrace Doughnut Economics.

What are we sharing?

For the publication we explore three main creations: the life-cycle biodiversity tool, the doughnut for urban development, and the database.

- **The life-cycle biodiversity tool**, described in more detail in Chapter 4 of the Appendix. The tool's primary objective is to assess the holistic impact of urban development projects on biodiversity, both on-site and off-site. This tool takes into account the direct impact on biodiversity of land use change on the project site, as well as indirect impacts through the project's entire supply chain (e.g. from the extraction and manufacturing of construction materials). It is a useful complement to the freely available Biodiversity Metric tool developed by Natural England[1], which is more comprehensive but only covers on-site impacts. By

[1] https://publications.naturalengland.org.uk/publication/6049804846366720

considering the broader ecological context, the biodiversity tool aims to promote a more holistic approach to urban planning that is in line with doughnut economic thinking.

With the life-cycle biodiversity tool and the Biodiversity Metric tool, urban planners and developers can evaluate the potential ecosystem consequences of their projects and make informed decisions to foster healthy ecosystems. Both tools can help quantify and identify mitigation and regeneration measures to enhance biodiversity within the project scope.

- **The doughnut for urban development** is a concept borrowed from the broader framework of doughnut economics and is decribed and visualised in The Manual. This powerful visualization represents the essential needs that urban development projects should fulfil to achieve sustainability and well-being for both people and the planet. The urban development version draws inspiration from a range of frameworks, certifications, and standards that outline sustainable practices in various aspects of urban development.

  The doughnut for urban development sets requirements to ensure that projects meet fundamental social needs, such as access to affordable housing, healthcare, education, and clean water, while also addressing environmental concerns. By incorporating best practices and lessons learned from various sources, this holistic approach encourages urban development projects to go beyond compliance and strive for excellence in sustainability. The principles outlined in the appendix provide guidance and benchmarks for urban planners and developers, enabling them to align their projects with the broader goals of doughnut economics.

- **The database** is a comprehensive resource overview that provides a wealth of information on the indicators relevant to doughnut economics and sustainable urban development. This database serves as an open resource freely accessible to professionals seeking to implement sustainable practices in their own projects. It offers in-depth insights into the frameworks, certifications, and standards that have inspired the development of these indicators. By adopting an open approach and making the database accessible, the aim is to foster collaboration, knowledge sharing, and the widespread adoption of sustainable urban development practices. Professionals can leverage the database to explore various indicators, learn from successful case studies as illustrated in the manual, and identify the most relevant frameworks and certifications for their specific projects. This open resource encourages innovation and allows practitioners to build upon existing knowledge and experiences, accelerating progress towards sustainable urban development.

Together the tools form a comprehensive set of resources within the 'Doughnut for Urban Development' project. They enable urban planners, developers, and other stakeholders to assess the impact on biodiversity and align projects with sustainability principles.

Why are we sharing?

Inspiration from other industries has fuelled our motivation to share our work openly. One example being Vandkunsten Architects, known for their open-source approach, stating, "We share a lot - our knowledge, our time, our resources - and believe that sharing is a vital part of sustainable behaviour." This philosophy resonates with us, and we firmly believe that by sharing our tools and resources openly, we can accelerate progress in the urban development industry.

The open resources we provide in this chapter and appendix are intended to empower urban industry professionals. We invite them to not only utilise the tools as they are, but also contribute to their further development. By embracing an open approach, we can collectively pool our knowledge and expertise, driving innovation and pushing the boundaries of sustainable urban development.

Furthermore, we recognize the importance of the “right to copy” in enabling progress and collaboration. Traditional copyright models often restrict the sharing and adaptation of ideas, hindering the collective effort towards sustainable change. By advocating for the “right to copy”, we encourage the dissemination of our work, allowing for the creations of new solutions. In this spirit, we invite professionals from the industry, and other industries to be inspired by our approach and freely adapt our methodologies, fostering a cross-pollination of ideas and approaches.

We envision a future where open resources and the “right to copy” become the norm across industries. By embracing these principles, we can create a culture of collaboration, innovation, and knowledge sharing, which are essential components for building a regenerative and equitable economy. Let this chapter serve as an invitation to join us in this transformative journey towards a doughnut economy, where tools, open resources, and the right to copy empower us all to create a better world.

In practice, we publish the book under Creative Commons and all tools under GNU GPLv3, ensuring that urban industry professionals can utilise and contribute to their further development, however only in open source.

Additional resources and credits

08

Doughnut for Urban Development / Manual

The Doughnut for Urban Development Manual is available for free, by digital download in both Danish and English. Please share it with relevant stakeholders in your professional network.

Doughnut for Urban Development / Appendix

The Doughnut for Urban Development Appendix is available for free, by digital download in both Danish and English. The Appendix includes deep dives into the content described throughout this book. This is where you can find the 'Off-Site Biodiversity Tool.'

Doughnut for Urban Development / Database

Doughnut for Urban Development Database is the detailed frameworks and references behind the impact areas described in the social foundation and ecological ceiling. You can download for free and adjust as you build your own library of impact indicators.

Doughnut for Urban Development / Toolkit

Doughnut for Urban Development Toolkit follows the 'Doughnut Unrolled' methodology and can be used to facilitate workshops with relevant stakeholders in your next urban development project.

Additional Resources

Participating organisations:
Aalborg University - BUILD, Danish Technical University, Doughnut Economic Action Lab (DEAL), Green Building Council - Denmark, EFFEKT, Home.Earth, SLA, Sweco, Stockholm Resilience Centre and Vandkunsten

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DOUGHNUT ECONOMICS ACTION LAB

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AALBORG UNIVERSITY

Stockholm University
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EFFEKT

Vandkunsten

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GREEN BUILDING COUNCIL DENMARK