

Planetary Boundaries As A Framework For Course Development: What Does It Take To Design For Absolute Sustainability?

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ABSTRACT: The Stockholm Resilience Center has been developing data to help outline a safe space for human activities for a decade. This includes the activity of producing building materials, constructing and operating buildings, which is one of the most significant contributors to greenhouse gas emissions. The impact categories assessed by the worldwide scientific community at the Stockholm Resilience Center match the categories in the ISO standard LCA. This effort is also an expression of the Paris Agreement, which outlines the CO₂ reduction each nation must achieve by 2030 to keep the temperature rise on the planet below 2.0- or 1.5 degrees C (UNFCCC 2016). Based on this, a team of universities and industry partners examined what it would take for the Danish construction sector to comply. One of the universities in the project described above took the initiative to develop an interdisciplinary course to investigate the necessary set-up to teach how to design buildings whose environmental impact is within planetary boundaries. The article describes the development process and the results of the first test run of the course in the summer of 2023. The course content is explained based on the discussions between the three educational institutions involved in the development and the pre- and post-evaluation of the 26 participating students, as well as semi-structured interviews with the students. The challenge in course development was whether it was even possible to design for and build within the planetary boundary and how to address this open question in a course design. The ideas and reasoning behind these course design decisions, as well as the results from the pilot course, are presented and discussed in the article.

KEYWORDS: Sustainability, Planetary boundaries, Absolute Sustainability, Life Cycle Assessment, Integrated Design

INTRODUCTION

The international platform Earth Overshoot Day shows that Denmark consumes environmental resources equivalent to four Earth-like planets (Global Footprint Network 2024). Our consumption is so high that the Earth's ecosystems cannot keep up. Therefore, we live today with an imminent danger of, among other things, irreversible climate change that will have enormous consequences documented most clearly by the Stockholm Resilience Center (Figure 1). Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to 2100 and this data also derive greenhouse gas emissions scenarios with different climate policies (Figure 2).

Together they draw the contours of a space of solution, but how is this translated into a design process of housing? The construction sector is responsible for 39% of all energy-related CO₂ worldwide (WorldGBC 2019) and is also a significant consumer of scarce natural resources such as sand, metals and wood. Therefore, it is crucial for the planet's future that the environmental impact of construction is significantly reduced. This was the motivation for Aarhus School of Architecture, VIA University College and Aarhus University to invite students interested in architecture, building science, civil engineering, and architectural technology and construction management who have completed at least the 3rd semester to apply for a 2-week masterclass course on the topic: How do we design buildings within the planetary boundaries?

Participation in this masterclass allowed students to expand their professional network and gain the latest new knowledge and sought-after skills, such as preparing environmental life cycle assessments, considering planetary boundaries (Figure 1), absolute sustainability, solution spaces for ambitious sustainability requirements, etc.

In terms of research, the course was an experiment in design processes. It was about discovering if it is possible to design homes within planetary boundaries, choosing strategies, calculating the impact and consumption of the choices made, and integrating them into the design processes to keep track. The topics were 1) Building within planetary boundaries and absolute sustainability, 2) Sustainability, ethics and aesthetics, 3) Interdisciplinary collaboration and co-creation, and 4) Introduction to technology for assessing the building's climate footprint in the early design phase. The goal of the masterclass participants was to gain knowledge, skills and competencies about: 4) Planetary boundaries and their significance for the building sector, 5) Application and interpretation of LCA analyses, 6) Interaction between materials, energy and indoor climate, 6) Software for calculation: LCAByg and ICEbear, 7) Development of interdisciplinary building technology solutions.

1.0 METHOD

1.1 Pedagogical and didactic considerations

The three educational institutions involved all address construction but from very different starting points, which were explored and manifested in the course. Aarhus University's Department of Civil and Architectural Engineering has a classic research-based approach to technical-scientific academic subjects and education. VIA is a professional bachelor's degree focusing on architectural technology and construction management. Aarhus School of Architecture is a 5-year beaux-arts, artistic education. The course development's basis was the question: Is creating a design process ensuring the final building stays within planetary boundaries possible? What would such a design process be like - what information and tools are needed?

The course developers from the three institutions took a starting point in research and educational development from the field of Integrated Design (Löhnert, Dalkowski, and Sutter 2003). It is rooted in the 1960s rejection of Fordism's fragmentation into separate work processes on an assembly line. Instead, the idea is based on, among others, Kurt Lewin's research at MIT in group dynamics, where an organization should consist of autonomous interdisciplinary units that can regulate and solve problems themselves (Reason and Bradbury 2008). Anne Grete Hestnes (2008), professor at NTNU, led a European research effort under IEA task 23 on integrated energy design processes (NREL 2003), focusing on informing decisions in complex and dilemma-filled areas of building energy and indoor climate (Hestnes 2008). Integrated design as a project management framework has succeeded and is partly mainstream in the Nordic construction industry, where it is implemented and supported by government-developed freeware, and integrated into building legislation. The basic idea is inspired by the Macleamy curve (MacLeamy 2020) (or, more rightfully, the Paulsons curve (1976)) where the hypothesis is that by focusing time and money at the beginning of the design phase to inform decisions maximally, the building energy performance can be radically reduced via passive measures (window-facade ratio, geometry, orientation, utilization of natural ventilation, passive solar heating, thermal mass etc.).

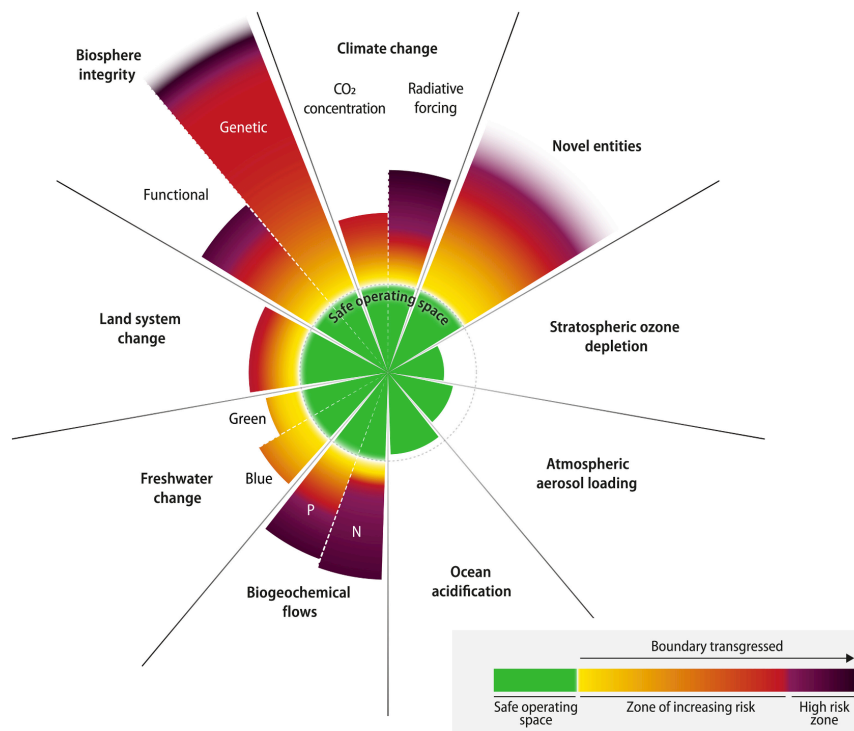


Figure 1: Diagram of safe and just earth system boundaries. Source: (Rockström et al. 2023)

Designing within planetary boundaries is even more complex and dilemmatic than creating 'low-energy' buildings with 'passive' measures, mainly because it requires a strong focus on the whole life-cycle environmental performance of the building. Still, the genericness of establishing a knowledge common ground and working in interdisciplinary teams drawn from the research field of integrated design was chosen as the fundamental approach to the design process. LCA (Life Cycle Assessment) is a meta-method developed in the early 1960s that quantifies the environmental impact of processes. LCA for buildings has developed significantly over the past 10 years with the establishment of international standards for methodology, building product EPDs (Environmental Product Declarations), generic databases for building materials (Ecoinvent 2024; Ökobaudat 2018), government-funded software (e.g., LCAbyg) and implementation in building legislation. From January 1, 2023, it became mandatory in Denmark to document the climate footprint of new buildings via LCA. LCA as a meta-method thus also includes the parts that were included in the IEA task 23 integrated design process of the time, where the focus was on energy and indoor climate. Common to the integrated design processes of the 2000s and the complexity of the planetary boundaries is that it is through fast and visualizing software that provides access to simulations and quantifications that an ongoing design process can be informed with the knowledge that can help achieve the goal (creating

buildings that are within the planetary boundaries). The course introduced and used a range of software, as described below.

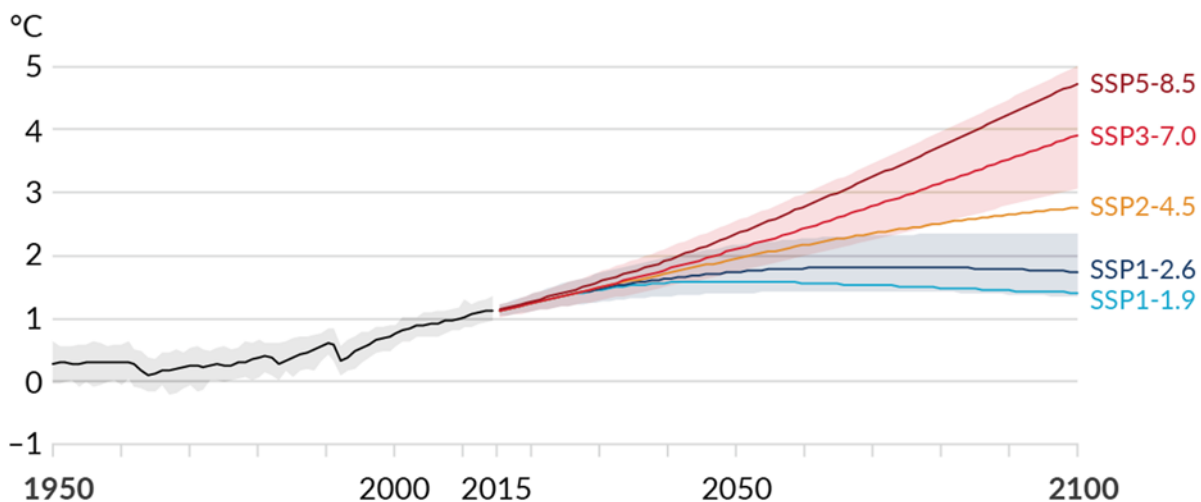


Figure 2: Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies. Source: This figure is a reproduction of Figure SPM.8 from the IPCC 6th Assessment Report WGI Summary for Policy Makers, Source: (Press Office 2023).

A scientific basis for the course development was Aarhus University's research into the impact of housing on the planetary boundaries. Based on this research, it is possible to develop a calculation method that can be used in a design process to establish a CO₂ budget for the building function 'dwelling' that respects the planetary boundaries. In preparation for the course, based on the methodology, a simplified version was further developed in a spreadsheet that the course students were taught to use. The principle and the spreadsheet are described in more detail below.

A beaux-arts academy operates within what Michael Polanyi called 'tacit knowledge' (Polanyi 2009). The ability to bring together several completely different parameters in a site-specific architectural expression is developed in a practice setting, practiced through guidance, described by Donald Schön (1983), among others. Schön synthesizes his observation of the architect's actual design practice: -Making previous experience fit the unique situation - experimenting and testing hypotheses through Virtual (visualized) worlds (Schön 1983). This 'practice situation between teachers and designing students was integrated into the framework for the afternoon teamwork, where professional architects, engineers and LCA practitioners actively entered the design processes but followed the students' lead.

Didactically, it became apparent during the planning process that all involved institutions used problem or project-based learning (Pettersen 2001). Therefore, it was decided that this, together with the ideas from 'integrated design', would be a guiding principle for the organization of the entire course. A didactic relational model by Hiim and Hippe (Hippe and Hiim 2007; 2005) was used as a dialogic framework in the research group's course planning. The model consists of six factors that educators should consider: Learning assumptions, framework factors, objectives, content, the learning process and assessment (Hippe and Hiim 2007). One of the strengths of this model is the absence of hierarchy among the factors, so all factors influence and are influenced by each other, allowing for an iterative process during the planning and decision-making processes. All six factors were discussed and considered, but some became more important than others. For example, establishing common learning goals and objectives was one of the most significant factors when choosing the content that each institution presented. Consideration was given to what knowledge and skills the students already have and what would be appropriate learning content that a) brings new knowledge and is not repetitive, and b) is not too distant for students from the other institutions to understand and work with. Living up to both principles proved difficult as the students from the different institutions had different prior knowledge and skills. At the same time, it was necessary to establish some common basic level of knowledge and skills for all students to empower and prepare them for the course challenges and learning exposure ahead. Therefore, repeated content was accepted by the institutions' students, thus attempting to establish a common ground for students' knowledge level, while invited external lecturers would deliver new knowledge, and all students would be able to understand and work with the new information.

2.0 RESULTS

2.1. Creating a radical common ground

Based on a year of development work (described above), the course was organized so that half of the teaching time was used to create a professional common ground, which was a radical choice. The lecturers divided the students into interdisciplinary design teams (5 people), and a design task was set: a home for two adults and two children that respects the planetary boundaries of Denmark. Each day started in plenary with speakers (invited and

internal), followed by training on the chosen topics (LCA, energy and indoor climate, 'the good but few m²'). In the afternoon, the design teams focused on the project. After the first week, there was a mid-term critique with invited critics from the construction industry. Calculations and designs were presented to the same invited critics on the last day.

Table 1: Two-week course plan. Source: (Authors 2024)

Week 1	Monday	Tuesday	Wednesday	Thursday	Friday
Theme	Planetary boundaries	LCA and square meters; <i>Flexible, creative and long-lasting buildings</i>	LCA and materials	LCA and energy; <i>Energy in the future</i>	Pitch and discussion
Content	<ul style="list-style-type: none"> Welcome Sustainability and planetary boundaries How will we live when the sustainability crisis is solved? 	<ul style="list-style-type: none"> What does it take to feel rich on a few square metres? What is the sustainability in around-the-clock functions and flexibility? 	<ul style="list-style-type: none"> Introduction Background Norm and legislation LCAByg (LCAByg 2023) EPD 	<ul style="list-style-type: none"> Energy and indoor climate ICEBear BE18 (SBI 2024) 	<ul style="list-style-type: none"> Idea pitches Discussion about the future of the professions considering the climate crisis
Student activities	Icebreaker, planning of the upcoming weeks, debates of today's lessons	What are the good square metres? Portfolio reflections, and development of basic concepts	Portfolio reflections, basic considerations for the choice of materials based on the LCA and EPD	Portfolio reflections, considerations about the energy sources, energy calculations and considerations about the indoor climate	
Week 2	Monday	Tuesday	Wednesday	Thursday	Friday
Theme	LCA and circular economy; <i>Tectonics of reuse and transformation</i>	LCA and biomaterials	LCA and design process	Lesson free day reserved for project work	Final pitch
Content	<ul style="list-style-type: none"> LCA concerning phases C and D Reuse of buildings and/or materials 	<ul style="list-style-type: none"> Biodiversity and construction techniques Biomaterials and different scenarios in phase C and D 	<ul style="list-style-type: none"> LCA as a design and decision-making tool What does LCA tell us, and what does it not tell us? 		
Student activities	Portfolio reflections, considerations about a deeper LCA strategy with focus on phase C and D	Portfolio reflections, further development of concepts	Portfolio reflections, critical debate of the LCA as a method, further concept developments		

2.2. Architecture

Architects often handle the earlier design phases (geometry, window-facade ratio, orientation), and integrated design research has proven to significantly impact energy, indoor climate, and, thus, environmental impact. There is, of course, the overarching consideration that if a building has aesthetic qualities, users will be interested in maintaining and taking good care of the building. In a sense, this will result in a form of 'avoided new construction' because it extends the lifespan of the building. In this sense, good architecture is essential to 'staying within planetary boundaries', but it is difficult to operationalize in a multidisciplinary design team. It is the overall goal, so to speak, while more concrete sub-goals are needed in an incremental design collaboration. That is why we chose to focus on 'few m²' as a theme.

A research result from Aarhus University showed that if the assumption is that the environmental impact from materials and building operation of buildings in general is reduced by 84%, then 20 m² per person would be at the planetary boundary. This should be contrasted with 54 m² per person (Statistics Denmark 2024) – the average in Denmark today. Large homes have always been a sign of social ambition. Therefore, the size of buildings, understood as m² of housing per person, is central to the basic equation behind LCA: Impact = population growth x affluence x technological development. I=PxAxT (Hauschild, 2018).

A key element of architectural quality is whether the user experiences feeling happy, wealthy, dignified, safe, proud and delighted with their surroundings. These qualities have to do with whether the user of a building experiences themselves as living in surroundings that provide the experience of affluence (the 'A' in the IPAT equation). Therefore, it was decided that the School of Architecture's teaching should focus on architectural strategies to achieve the quality of 'affluence' with minimal environmental impact on very few m² per person. The architectural profession has a vast repertoire of strategies that create a sense of wealth; the Palace of Versailles: sumptuous materials (glass, mirrors, gold), high ceilings, large rooms, views over large parklands, symmetry, lavish and ornamental details, etc. The goal was to learn how to 'filter' architectural strategies that give the experience of affluence, but do so in a way that does not require a Palace of Versailles. They can be summarized in the following categories:

- Creativity in m² programming (using the same spaces for multiple functions and using design thinking to question functional needs).
- Movable multifunctional architectural elements
- Sharing with others, so it does not have to be included in every home.
- Close to nature and 'protected' outdoor spaces (the m² with the least CO₂ emissions are in the natural climate - gardens, urban spaces, parks).

The results of the 'feeling affluent in a few m²' approach could be seen in the projects of the interdisciplinary teams. For example, one team worked with the strategy of placing 2-3 families in 1960s detached houses, where today, often only 2 elderly live. However, affluence was achieved by intertwining the gardens into park-like landscapes that the homes opened up to and by ensuring that each family had large spaces in their homes because functions like laundry and utility rooms could be shared. Others worked on the experience of affluence by having large, high-ceilinged multifunctional spaces where 'functions' such as sleep/rest were established in spatial 'super furniture' that gave way to large, bright spaces with access to nature. Staying in unheated garden spaces expanded the possibilities for users without increasing the number of m² built, which were features explored by several teams.

2.3. Building science

The involved researcher and lecturer from Aarhus University presented a concept of the planetary boundaries and how current Danish buildings perform using the limit for annual emissions of CO₂ equivalents globally allocated to the function of 'dwelling' as described in the paper by Brejnrod et al., (2017) to the students. Furthermore, a generic method for allocating the globally allowed annual emissions of CO₂ equivalents with respect to the planetary boundaries to the function of 'dwelling' was presented together with a spreadsheet where the method was implemented (Figure 3). This spreadsheet is intended to enable the students to discuss moving from a global budget that respects the planetary boundaries to a budget for the function of 'dwelling' in Denmark. The students, therefore, had to discuss the magnitude of the global budget, which may vary depending on the method applied to calculate it (Petersen, Ryberg, and Birkved 2022) and how to deal with the trajectory of the global population, which may increase or decrease the personal budget depending on what growth scenarios is chosen. Next, they had to consider how much of a personal budget is fair to allocate to the function of 'dwelling' and whether there are some social reasons to differentiate the personal budget depending on, e.g. geographic location, historical considerations, equality versus equity, etc. Finally, the students could generate a budget for their project's annual emission of CO₂ equivalents, which depends on how many people the building will be designed for. This budget could be 'per year' or 'per m² heated living area per year'; in case the latter, the budget would be dynamic depending on how many people per m² the students were designing for. The budget described above was the benchmark for the outcome of the LCA conducted for the building design of the students (see section 2.4).

The students were also presented with a building performance simulation tool named ICEbear (Lauridsen, Petersen, and Purup 2014) that can be connected to geometric models made in SketchUp, Rhinoceros/Grasshopper, and REVIT. ICEbear can perform integrated hourly simulations of the indoor operative temperature, air quality, daylight, and corresponding energy needed for the chosen geometry in any climate using only a few user inputs. This tool enabled the students to consider thermal comfort, daylight conditions, and energy needs while proposing building designs. The calculated energy need was the input to the B6 phase in the LCA calculation (see section 2.4).

	A	B	C	D	E	F	G	H	I	J	K	L
1	Variabel i formel	Enhed	Værdi		Note							
2	SoS_global	kg CO ₂ -ækv/år	2,51E+12		Scenario AR+(95%) i ref. https://arxiv.org/abs/2209.00118							
3	P_global	Antal personer	8223573750		Egalitær fordeling af jordens budget (FN befolkningsstatistik, 95% fraktil for 2025)							
4												
5	Alpha	-	0,215		Forsøg på utilitaristisk fordeling ved brug af Europæisk COICOP (fx er 0.215 alfa for det "at bo")							
6	Beta	-	1		Politisk faktor, der omfordeler SoS af den ene eller anden grund							
7												
8	P_byg	Antal personer	4		Antal personer, der har andel i bygningen							
9	A_byg	m ²	110		Hvor mange m ² vil man bygge?							
10												
11	Safe Operating Space	kg CO ₂ -ækv/m ² /år	2,4		Safe operating space for bygningen							
12	Safe Operating Space	kg CO ₂ -ækv/år	262		Safe operating space for bygningen							
13												
14												
15												
16												
17												

$$SoS_{byg} = \frac{SoS_{global}}{P_{global}} \cdot \alpha_{byg} \cdot \frac{1}{A_{byg}} \cdot P_{byg} \cdot \beta \quad [kgCO_2eq/m^2/år]$$

Figure 3: Screenshot of the spreadsheet developed to operationalize the principal discussion on allocating the globally allowed annual emissions of CO₂ equivalents with respect to the planetary boundaries to buildings – in this case, the function of 'dwelling'. Source: (Steffen Petersen 2024)

2.4. Life Cycle Assessment

The choice of building materials has a significant impact on the overall environmental impact of a building and is closely linked to the technical execution of the construction. The two areas - material selection and assumptions for passive energy and indoor climate solutions, as well as the number of m² inflict environmental impacts- are demonstrated in an LCA. LCA is thus the most central field in the course. VIA UC organized the LCA workshop. The content consisted of two parts: A) a presentation of the background, legislation, norms, theory and methodology of LCA, and B) an introduction to LCAByg software.

Part A was based on current legislation, EN15978, which is a standard for the Assessment of environmental performance of buildings. Part B, LCAByg, is a free software tool developed by BUILD, part of Aalborg University. LCAByg is used to calculate LCA for buildings and is adapted to Danish national legislation and practice for LCA calculations. Although there are several tools for LCA calculation, each with varying complexity, LCAByg was chosen primarily based on previous teaching experience. Its ease of use, especially for beginners, became apparent through interactions with students, which is a crucial aspect due to the limited time the students had to learn and use the software as part of the assignment. The software is also not fully automated, requiring users to understand the LCA process and enter variables such as quantities, environmental data and material selection. This semi-manual approach encourages a better understanding and reflection on the LCA methodology.

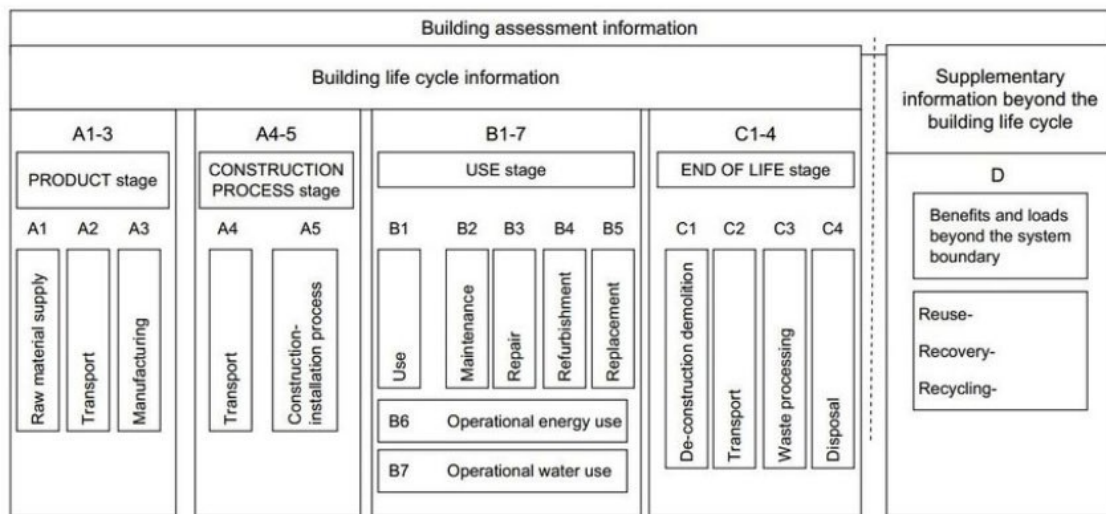


Figure 4: Building's LCA stages according to EN 15978. Source: (DS/EN 15978:2012. Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (2012).)

The workshop content was presented through a dynamic interaction that combined several short presentations (approx. 10-15 minutes) of the first part (A) with hands-on engagement using LCAByg. In addition, small group discussions on the presented content and dilemmas were also facilitated, e.g., concerning the impact of different 'energy futures' for Denmark. This teaching approach accommodates different learning styles with inspiration from Kolb (1983) and Illeris (2015), emphasizing the importance of an active learner to support the learning process. As an educator, it is almost impossible to know each student's preferred learning style, and therefore, the presentation strategy was aimed at creating learning activities that could provide different learning preferences according to the theory of learning styles (Kolb 1983; Illeris 2015).

2.5. Pre and post evaluation

Pre- and post-evaluations were conducted via digital questionnaires and focus group interviews before and after the course. During the pre-course focus interview, it came forth that the students placed more emphasis on biodiversity than the course planners had anticipated, and 4 hours of consultancy concerning biodiversity impacts from design proposals were integrated into the final course planning. Many wanted to learn about LCA, and though 60% had never worked with it before, the post-evaluation showed that 100% could conduct a simple LCA. According to the post-evaluations, many wanted to learn about energy and indoor climate but did not learn it to the same extent.

A majority in the pre-evaluations described their motivation for taking the course as driven by ethics, but this changed in the post-evaluations, showing that more people moved towards the course design processes and the goal of planetary boundaries could lead to an exciting working life, and this could be a 'driver'. In the final evaluation, only 10% saw ethics as a central 'driver' compared to 58% before the course started, the pre-evaluation. It could be interpreted in that way that the course gave the students concrete tools and methods that made it operational to design buildings that would stay within the planetary boundaries. In this sense, a new design practice was outlined. In the final evaluation, 70% rated 'changing people's mindset' as the most important element in reaching the goal of staying within planetary boundaries, compared to 73% in the pre-evaluation. So, this aspect did not move during the course.

CONCLUSION

Staying within the planetary boundaries

Despite the availability of cutting-edge design processes and matching software, it is very difficult to establish processes that lead to construction within planetary boundaries. The students' projects came close to reaching the goal, but no one could meet the target of staying within the planetary boundaries in their design for a dwelling for 2 adults and two children. There are two factors responsible for this: firstly, the Danish rules for LCA in construction dictate that biogenic building materials must be calculated to be incinerated after 50 years, though a large number of historical buildings demonstrate that this will not actually be the case for biogenic materials in the interior (Andersen, Jensen, and Ryberg 2022).

Secondly, the students were very concerned with designing solutions with broad appeal. They deliberately sought a 'common' expression that would be acceptable to many. There was an ethical choice in this, informed by numbers that illustrate the scale and speed of the total transformation needed to adequately address the biodiversity and climate crisis. In addition, the interdisciplinary aspect of the groups and the appeal of influential keynote speakers also meant that the projects were not as extreme in terms of design as the situation might require. It could be seen as a result that even if the dwelling is based on reuse and transformation with only very little added new (and biogenic) material, with a maximum effort for reducing energy use, it is not possible in a Danish context to match familiar imagery of what a family home should look like in size and form. The closest project had a smaller amount of m² (a third of what is usually allocated in Denmark), and included radical proposals concerning sharing and inside-outside climate boundaries.

The radical educational choice to use so much of the time to establish a truly interdisciplinary common ground was a surprising success. No students complained of low learning on the days when 'their' discipline was taught to the others. On the contrary, the evaluations emphasized that new perspectives on their discipline were necessary. According to the pre-evaluations, LCA is central and a significant motivation for taking the course. That wish was fulfilled. Two surprises emerged when comparing pre- and post-evaluations: the primarily ethical motivation during the course was replaced by a realization that working with planetary boundaries can lead to an exciting working life. This was probably due to the support from the industry that participated in the critics, but also because reaching the planetary boundaries went from being abstract to being given a path and software to document the distance from the goals. Surprisingly, there was no move during the course to consider a 'change in general mindset' to be more important than 'quantifying environmental impact'. It stayed the same.

Next iteration and afterthoughts

As mentioned, the course was the first iteration. In further development, some feedback the students gave in the evaluations will be integrated, e.g., the professional common ground can be more precise if there is a daily upload of exercise material and design material. The architectural workshop can be developed with precise and specific 1-hour 'exercises' that get team members to explore the design strategies both individually and as a team, and it must be made clear earlier how radically different the space of solution must be. In other words, it is not what looks like known, that leads to the goal. Integrating biodiversity regeneration in a quantifiable way, not just as a reflection, is also a concern, and direct reuse of existing structures is a priority.

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