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Sustainability *by design*: a holistic approach to integrating sustainability into structural engineering education

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Abstract

This paper presents a holistic teaching approach to include sustainability *by design* in structural engineering education; it discusses teaching methods and learning objectives which are later applied to a design studio for engineering students at HafenCity University to evaluate outcomes of the proposed teaching method. For a holistic integration of sustainability in structural engineering education, students need to develop and apply societal and ethical values, which reflect their attitude towards the ecological, economic and social implications of structural design. This reflection is based on theoretical knowledge and facilitated by practical means to evaluate sustainability. Within the practical means, an open-source parametric carbon optimisation tool for Rhino/Grasshopper is presented, which helps students to understand and evaluate the ecological constrains of their design projects.

Keywords: Sustainability, structural education, education for sustainable development, life-cycle-assessment, parametric design

1. Introduction

1.1. Motivation

Given the construction sector's substantial consumption of energy and resources (UNEP [1]), building professionals play a central role in combating climate change. To achieve climate-neutrality by 2050 the construction sector must undergo significant changes in the way we think, design, construct and use buildings and infrastructure. This responsibility extends not only to the industry but also to higher education institutions, which need to promote innovative solutions in research and emphasize on the importance of sustainability in teaching (Farag [2]). The sustainable agenda states sustainable development goal SDG4 *Quality education* not only as a primary goal, but also as a key enabler to achieve the remaining SDGs. Education is portrayed as an engine for change, necessitating higher education institutions to adapt their teaching accordingly (United Nations [3]).

Currently, sustainability is mostly taught as a parallel unit or an elective course and "added" to the curriculum rather than integrated within the core of education (Buchanan [4]). However, Van der Ryn and Cowan explain that the "environmental crisis is a design crisis" because we have "designed cleverly in the service of narrowly defined human interests but have neglected its relationship with our fellow creatures" (Van der Ryn and Cowan [6]). Thus, to change the way we design, we need to start with innovation in design education; we need to integrate sustainability concerns in students design thinking, rather than simply adding a new subject to the curriculum. This paper outlines an approach to include sustainability *by design* at the core of structural education. Within a studio-based environment, methods for solving complex problems are applied by encouraging 'design thinking' with a focus on sustainable design.

Therefore, a theoretical approach is described, by outlining its learning objectives and teaching methods. Within this approach, an opensource tool for parametric carbon optimization is introduced, to include sustainability in students design projects. Later, this is transferred into praxis by supplying a Masters' studies design studio at HafenCity University in Hamburg. The studio is critically discussed and reflected upon at the end.

1.2. Principles of sustainability

The term 'sustainability' is currently often used in the context of ecological concerns. However, the term sustainability, which the *United Nations (UN)* played a decisive role in developing, describes far more than that: Sustainability means considering ecological, economic, and socio-cultural aspects equally, to leave an intact environment and equal conditions for future generations (Braham and Casillas, [5]). Here ecological, economic, and socio-cultural aspects are often described as the 'Three pillars of sustainability' (Pfeiffer et al. [7]). To achieve the above mentioned holistic goal, the UN has defined 17 ***Sustainable Development Goals*** **(SDGs)** in its '2030 Agenda for Sustainable Development', which adress the global challenges we face as an urgent call for action for all countries. Among the SDGs are goals for ending poverty, improving health and education, reducing inequality and spuring economic growth as well as achieving peace and justice, while combating climate change and working to preserve biodiversity on land and below water (United Nations [3]). The built environment influences each one of these goals, because it shapes communities, cities and countries through the buildings and infrastructure that is needed, perceived, and used in everyday life. At the same time, these buildings and infrastructure consume energy and resources from construction phase to end of life. For example, the choice of materials for a residential building affects not only biodiversity and resources during construction phase and demolition, but also energy consumption and thus costs during the usage. Furthermore, different materials lead to different indoor climates, affecting people's health and hence causing inequal living standards. The impact of the construction industry on all SDGs represents a unique opportunity as well as responsibility to help sustainable development by transforming the construction sector towards sustainability.

This means holistic planning, construction, operation, maintenance, and dismantling, while being economically efficient, value-preserving in the long term, environmentally friendly and appropriate for use (Pfeiffer et al. [7]). The desired transformation can be achieved by following the 'strategies for sustainability': efficiency, sufficiency, and consistency. **Efficiency** describes the productive use of material and energy. For the built environment this implies among others a reduced use of materials, as well as planning buildings with minimized energy consumption throughout their operation phase. **Consistency** refers to the use of energy-efficient and environmentally friendly technologies, so that nature is aligned with technology. This would include building with renewable resources, which can continue to be used to a high standard beyond the life cycle of a building, provided that the construction is recyclable. **Sufficiency** aims at reducing the consumption of resources by reducing the demand for resources. It addresses the lifestyle of individuals by raising questions like 'How much space does one person need?', 'Build new or preserve existing?' (Behrendt et al. [8]).

2. Teaching approach to framing sustainability in structural education

2.1. Learning objectives

As shown above, sustainability is multidimensional and consists of ecological, economical, and social values, all of which overlap with the construction industry. Despite this interconnectedness, in reality the emphasis within structural design education and practice predominantly revolves around economic factors. Consequently, achieving the desired and necessary shift towards sustainability demands a fundamental (re)definition of our design attitude.

To achieve a comprehensive integration of sustainability in structural design education, the aim of the proposed teaching strategy is to introduce a design mindset focused on sustainability principles. Students will apply this throughout the course. Thereby, the design-attitude focuses on the ecological aspects of structural design. This is motivated by the long-term neglection of ecological over economical values, resulting in a tremendous, constantly rising consumption of energy and resources.

The proposed design-attitude primarily comprises two core values intended to be deeply embedded in students' design thinking:

1 **Prioritize sustainability:** Emphasizing the importance of considering environmental, economic, and social impacts when making design decisions, with a commitment to minimizing negative effects on the planet and its inhabitants. To achieve this objective, it's imperative to develop a mindset that actively explores alternative approaches across all three dimensions of sustainability.

2 **Design with awareness:** Encouraging thoughtful and deliberate design choices that take into account the long-term consequences and broader implications of structural solutions, promoting responsible and ethical design practices. Therefore, it is crucial that structural engineers engage with design in engineering in the first place (Bögle, [9]).

Designing sustainably presents a multifaceted challenge. In our approach, we aim to facilitate students' entry into sustainable design, fostering their interest and passion for the topic. To this end, we offer students accessible tools to seamlessly integrate ecological considerations into their designs. Throughout the course, students are encouraged to utilize the 'LCA-Booklet' provided by the *Attitude Building Collective e.V.* (ABC e.V., [10]), offering a comprehensive introduction to life-cycle assessment and ecological structural design fundamentals. Additionally, we introduce an open-source parametric carbon optimization algorithm for Rhino/Grasshopper, which enables students to effortlessly compare design alternatives based on their carbon emissions.

2.2. Teaching methods and strategies

(Re)defining the attitude of engineering students towards sustainable design is a nuanced task, one that varies among individuals and can only be accomplished by igniting intrinsic interest and motivation in each student. In addition, as sustainable construction has many aspects and touches on various disciplines, a multi-disciplinary approach should be chosen that requires students to adopt different perspectives within the learning process. This personal, multi-disciplinary learning can best be achieved by the method of 'design thinking' within a studio-based environment. **'Design thinking'** describes the dynamic interplay between defining and understanding the task at hand, and the iterative development of potential solutions through a multidisciplinary approach (Bögle and Popova, [11]). Consequently, it offers a means to personalized learning experiences, engaging students through work that holds personal significance. Therefore, we choose to integrate the topic of sustainability within the task of a parametric design for a lightweight pavilion (see chapter 4.). In the design process, students shall integrate qualitative principles of sustainable design (see chapter 1.2.) as well as quantitative measures i.e. parametric carbon optimization (chapter 3.).

At the same time, a theoretical framework is needed to understand the design process and to make the "right" decisions (in relation to the goal of sustainable design) when iterating different solutions within the design thinking. Any theory guiding our actions to achieve specific outcomes inherently relies on an underlying understanding of the world and its response to our interventions (Hillier [12]). It may be concluded, that for the desired shift in students' mindsets a combination of theoretical knowledge, and experiential knowledge (design thinking) is needed, as illustrated in Figure 1.

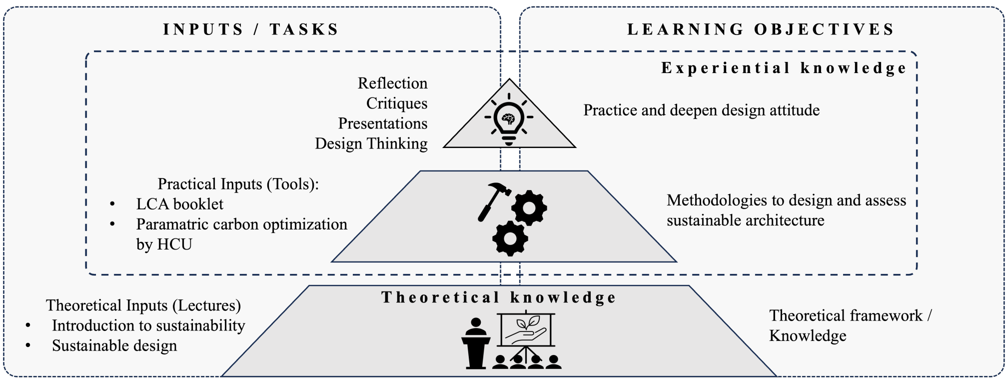

Figure 1: Summary of the proposed teaching approach

Hence, the teaching approach is divided into the following methods:

1 **Theoretical input:** Lectures on the principles of sustainability and sustainable design, as well as lectures on (parametric) design and optimization were held, to create a theoretical framework for the following design tasks. As the course takes place in the first semester of the masters degree, the basics of structural design (see chapter 4.1.) can be assumed.
2 **Practical input:** Provision of tools for sustainable design, which are used by the students throughout the design process. Students are advised to use the 'LCA-booklet' (ABC e.V., [10]) on the quantification and reduction of greenhouse gas emissions. Furthermore a parametric carbon optimisation tool (see chapter 3.) is provided.
3 **Design thinking:** Each student designs a pavilion on its own, following the principles of sustainable design.
4 **Presentations:** Every month the students have to prepare interim presentations on the current stage of their design. In the end of the course a final presentation is held, summarizing the final design.
5 **Critique:** The presentations are followed by critiques, to reflect on the students work. Two forms of critiques are applied:
   a. Peer reviewing: Critique given by the students
   b. Consultation: Feedback given by the teachers
6 **Reflection:** Part of the task is to reflect on one's own design with regard to sustainability criteria. The reflection is intended to deepen the design attitude.

3. Parametric carbon optimization as a tool for sustainable design education

3.1. Parametric Design and sustainability

Parametric design is a powerful tool for conscious and careful design because it allows the designer to think in many alternatives. Therefore, it offers immense potential also for sustainable architecture by enabling designers to create more efficient and environmentally friendly structures. Substantially, parametric design relies on the interdependency of predefined parameters and may be used in a digital or analogous environment. This paper focuses on digital parametric design using *Rhino/Grasshopper*, where the relationship of the parameters is described through mathematical or logical definitions, which are implemented in an algorithm. The algorithm comprises three main parts: (1) the input parameters, which are modified within (2) the algorithm, creating the design instance as (3) output.

Variation of the parameters changes the geometry and characteristics of a design, allowing the designer to explore (and evaluate) various design solutions. The output is not only a geometrical configuration, but also possesses structural and formal characteristics, which are quantifiable. This allows for a process called optimization, which describes a design loop, where the output dynamically changes the input parameters, to find the best performing solutions within a design space (Bögle and Schramme [13]).

The optimization loop relies on the evaluation of quantifiable characteristics of the output geometry, which modify the input to create new solutions. Thus, for sustainable design quantifiable characteristics are needed within the algorithm, which can be included considering **life cycle assessment (LCA)** in the design process. LCA describes a method to quantify and evaluate the environmental impact of a product or service throughout its lifecycle (Braham and Casillas [5]). Solvers can thus aid in finding optimal solutions to minimize the carbon footprint of a design.

Through its ability to iteratively test and optimize designs based on various parameters, parametric design can minimize resource consumption, reduce waste, and enhance energy efficiency in buildings. For example, parametric design creates more efficient structures by continually testing different forms and materials to find those that use fewer resources while maintaining structural integrity. Furthermore, parametric carbon optimization can be used to prioritise sustainability by generating different solutions for a structure that cause the least CO_2 emissions. The designer can compare these alternatives and reflect on them considering other criteria. This way, sustainability can be considered and prioritised at the beginning of the design process.

3.2. Review of existing tools

Within the proposed teaching approach, parametric carbon optimization shall be used by the students to reflect on different design variants considering their environmental impact. Therefore, a tool is needed, that can be used within the *Rhino/Grasshopper* environment and allows for:

a) Embodied carbon: calculation and evaluation of the embodied carbon of a structure
b) Optimization Process: Reflection of the calculated result (output) by changing the input parameters

Six LCA-tools are available for download as grasshopper plug-ins on food4rhino.com. In the following, the most widely used plugins are evaluated with respect to the above mentioned characteristics, that are needed for the proposed approach.

The LCA-Plugin that has been downloaded the most is “Bombyx”, which was developed by the Chair of Sustainable Construction at ETH Zurich (Basic et al. [14]). Bombyx offers comprehensive functionality for LCA, including the calculation of operational energy. Yet, the material database used by the plugin is limited to Swiss data and does not allow for the use of other material data.

Another available plugin on food4rhino.com is the “Oneclick LCA”-Plugin, which was developed in cooperation by Bollinger+Grohmann Ingenieure GmbH and Bionova Ltd. (Apellaniz et al. [15]). The plugin allows for holistic parametric lifecycle assessment, by combining the database of *OneClick LCA* with an object-oriented structure. Unfortunately, a license is needed and the educational license only provides the API to export from Rhino/Grasshopper to the web-application of OneClick LCA, but not vise versa. Following this, within the parametric context only the output is created, but cannot be imported back to grasshopper, providing no option for optimization. The same accounts for the Plug-In “CAALA” (Hollberg [16]), which provides a user-friendly and flexible web platform for LCA, but the grasshopper Plug-In is limited to the export of material quantities to the web service.

The last widely used plugin, which can be downloaded on food4rhino.com, is “Tortuga” which offers an intuitive interface and the input of a user-defined material database. The plugin can be used free of license and seems very promising. However, it was last updated in 2016 and does not seem to be fully compatible with Rhino 7.

3.3. Open-source parametric carbon optimization by HCU

The presented tool aims to incorporate life cycle assessment methodology into educational practices focusing an interactive design process. Its primary goal is to foster a comprehensive understanding of this methodology among students, emphasizing the importance of correct application. Active engagement and reflective practice are essential for students to not only grasp the methodology but also to critically evaluate it. The tool's algorithm is designed to prevent the simplistic use of life cycle assessment as a black box, where the LCA result is accepted as a mere number to be fulfilled. To achieve this, the algorithm ensures that users comprehend the underlying principles, such as the data sources for materials and the life cycle phases under consideration. To aid comprehension, the algorithm is divided into three main components, as shown in Figure 2. These components will be explained in the following sections.

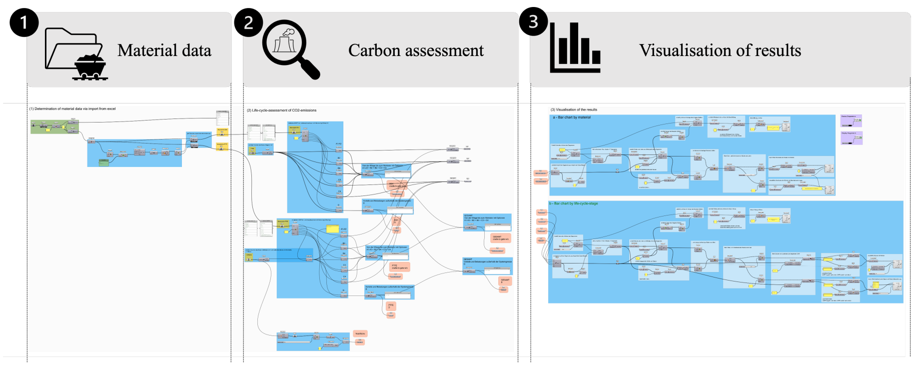

Figure 2: Workflow diagram of the LCA algorithm

Step 1) Material data

The first part of the algorithm focuses on gathering material data essential for calculating the global warming potential of the structure. Users are prompted to create a personalized material database in the form of a .csv-file, encouraging awareness of data sources and the specific information considered. In Germany, this process involves compiling global warming potentials for each life cycle phase from the German database "Ökobaudat". In the next step, this .csv-file is imported into grasshopper and prepared for further use. Here, users may select materials, which are then filtered from the material database.

Step 2) Carbon assessment

Now that the material data is available in Grasshopper, the volumes, areas and/or masses of the components are calculated as required according to the consideration in the material database and multiplied by the Global Warming Potentials. The results are presented by component group or life cycle phase. This has the advantage that the subsequent visualisation can be done differently: for example, by life cycle stage, material or by component group. Furthermore, these results, as quantifiable characteristics for the ecological influences of the structure, can now be considered the starting point and optimization target of the optimization process.

Step 3) Visualisation of results

The third part of the algorithm is the visualisation of results. Here, bar charts are created that show the global warming potential of the construction by material and by life cycle stage. These diagrams can be used by the students to evaluate their designs and to visualise the ecological impact in their presentations.

4. Case study: Computational Design at HafenCity University Hamburg

4.1. About the course

The course "Computational Design" is taught in the first semester of the master's degree of architectural engineering at HafenCity University Hamburg and combines the ideas of lightweight and parametric design. From their respective bachelor's degree, the students have prior knowledge in statics, mechanics, Computer Aided Design (CAD), Finite Element Analysis (FEA) and informatics. Throughout this course, they are guided with lectures and exercises to apply their existing and newly acquired knowledge and skills to design a lightweight pavilion for a given topic.

The pavilion design is an individual project, which is organized into separate tasks, following the progress of the course. All of which are graded individually and make up the final grade. First, the students develop the (geometric) FORM of the pavilion based on the definition of a set of parameters. Secondly, they translate the respective form into a dissolved STRUCTURE, which will be dimensioned with the help of *Karamba3D*. To understand the correct modelling of the structure and its boundary conditions, the results from Karamba3D will be compared to conventional FEA-software. Next, students describe the structural behaviour and identify the weaknesses of their structure in order to optimize form and structure within the next task OPTIMIZATION, using a generative solver. The process is accompanied by the task "physical model", which underlies the idea of rapid prototyping and assigns the students to 3d-print a physical model of their design as well as discuss / estimate the grade of abstraction of their initial idea. The final task is the documentation of the algorithm in grasshopper, which is done within the interface of *Grasshopper*. Comments and annotations shall be written into the grasshopper canvas, and a colour-code must be applied to make the algorithm understandable for future users. Furthermore, a five-minute screen-video-presentation of the algorithm is expected, to explain the parametric idea throughout the whole project. Each of the main tasks FORM, STRUCTURE and OPTIMIZATION is presented on a poster in an "interim presentation", which is held as a mixture of "silent presentation" (Bögle and Popova [11]) and peer review, so that the drafts must be presented in a self-explanatory manner and then commented on by fellow students. On the last day of the semester, the final design shall be presented within the "Final presentations".

Throughout the course, the focus is on a consequent and reflective argumentation starting with an idea, developing and optimizing form and structure. Thus, students justify, argue and reflect on their own design decisions and understand the interactive and nonlinear process of designing.

4.2. Integration of sustainability within the course

Based on the conviction that engineering must take responsibility not only for structural performance this course conveys a holistic attitude. Thus, students do not only learn and apply parametric design, but also develop an attitude of sustainability with which they approach and evaluate their design. By prioritising sustainability and reflecting on individual design decisions, the pavilion will be developed against the background of 'sustainable architecture'.

To lay the foundation for the development of the design attitude, in accordance with Figure 1, theoretical input on parametric design and sustainable construction is provided at the beginning of the course. Next, the algorithm for parametric carbon optimisation is presented in the form of exercises. Furthermore, the LCA booklet from the *Attitude Building Collective e.V.* (ABC e.V., [10]) is provided as a tool for individual research outside the lectures. Based on that, students individually apply this knowledge to their design and reflect on their own design in terms of sustainability as part of the interim and final presentations.

4.3. Examples of students works

The theme of this year's course was "Shelter capsule: everyday breaks". The students were asked to design a pavilion that provides rest from the stresses of everyday life. The interpretations of the theme were quite diverse, with many designs being inspired by nature. This was very helpful for the development of the design approach, as the transfer to sustainability, especially in its ecological dimension, was inherent. In the following, two examples of student works are presented, that approached the topic of sustainability in different ways.

Consistency through form and function

In his project "ShroomShelter" Hagen Daub follows the strategy of 'consistency' by taking up aspects of sustainability in both structure and function. To create a place where people can spend the small breaks of everyday life with a high quality of relaxation, the design utilises the organic diversity of nature, which has a calming and relaxing effect on many people. Within this design the mushroom is intended to represent a place of peace and protection in the open air. The organic wood structure is intended to emphasise the form and promote a sustainable character in keeping with nature. The shape of the roof is one of the chosen design parameters. After parameter variation (Figure 3), a funnel shape is chosen for the roof, which offers plenty of space for intensive green roofs. This functions as a rainwater reservoir and evaporation surface. Although this shape resembles the original shape of the mushroom less, it was deliberately chosen to accommodate a function, which is consistent with the attitude of sustainability, demonstrating how the student prioritises sustainability within his design (Figure 4). Furthermore, the connections of the timber trusses are designed so that they can be dismantled and recycled or reused. In the further course of the design, the shape was optimised using the algorithm presented in the course, with the aim of minimising the CO_2 footprint by exploring different materials and aiming for structural efficiency.

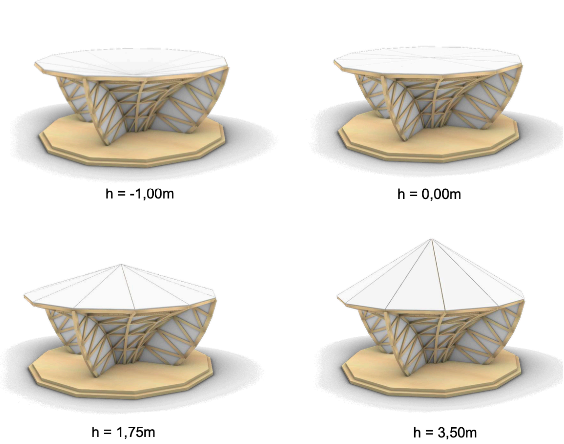

Figure 3: Parameter variation of the roof shape, chosen parameter: -1,00m (upper left) ["ShroomShelter" by Hagen Daub]

Figure 4: Result of parameter variation: Sustainability through consistency in structure and function ["ShroomShelter" by Hagen Daub]

Structural efficiency

Vincent Stiehle shows in his design “Aeris Sanctum” how parametric design can lead to maximum structural efficiency and thus to a low ecological footprint. Following the motto "Lightweight construction in harmony with nature", the pavilion celebrates the idea of organic form and consciously sets itself apart from the clear lines of the anthropogenic space. The light structure, reminiscent of a bird rising from the air, appears to hover protectively over the people taking a break from everyday life.

During the form-finding phase of the current structural geometry, a physical simulation was employed to simulate a tension-loaded membrane spanning between four points. Later, this membrane was morphed into a monolithic shell-shaped structure, which was integrated into a preliminary structure in the subsequent phase (Figure 5). The objective of achieving a discretized load-bearing structure necessitates the transformation of the monolithic, continuous structure into a resolved load-bearing structure. This transformation is based on identifying main stress lines within the primary structure, which are modelled by catenary curves. By doing so, a supporting framework is established that retains the shell's fundamental form while facilitating optimal discretization for maximum material reduction. However, with continuous discretisation, the shell loses more and more of its original load-bearing effect and bending stresses arise in addition to the shell forces. The exact position of the beams on the moment lines should be found as part of the optimisation process. With the goal of minimising the carbon footprint, the material was to be further reduced by assuming a constant utilisation of all carriers of 70%. Furthermore, as part of a cross-section optimisation, the cross-section heights of the bars were adjusted over the course of the bars so that they achieve a uniform utilisation of 70%.

To emphasise the ecological responsibility of the construction industry, the construction is planned to be made of glulam with detachable plug-in screw connections so that it can be recycled or reused. The final design can be seen in Figure 6.

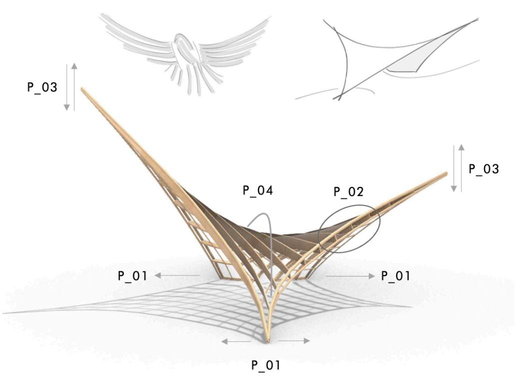

Figure 5: Variation of parameters within the initial formfinding
[“Aeris Sanctum” by Vincent Stiehle]

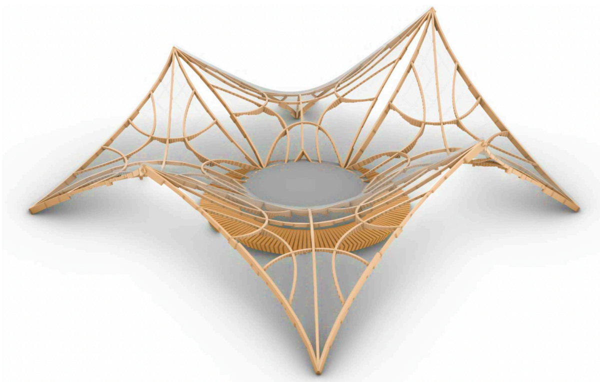

Figure 6: Final form - optimised arrangement of the beams and variation of the cross-section heights according to their load
[“Aeris Sanctum” by Vincent Stiehle]

To subsequently assess the extent to which the pavilion fulfils its goal of sustainable design, a life cycle assessment is carried out on the optimised form at the end using the tools demonstrated in the course, which is shown in Figure 7.

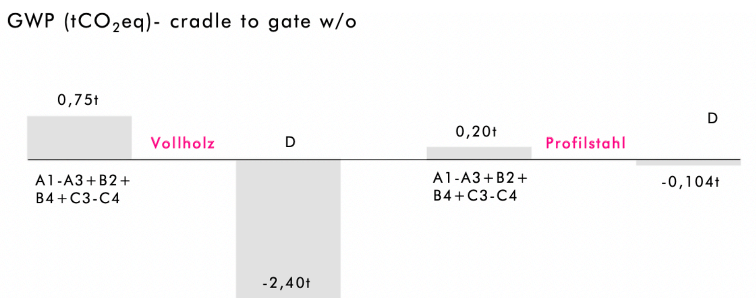

Figure 7: Life cycle assessment of the optimimized design – left: timber, right: steel connections
["Aeris Sanctum" by Vincent Stiehle]

4.4. Reflection on the student learnings

The above examples demonstrate that the proposed approach is suitable for (re)defining students' design attitudes, by showing two very different examples, which both achieved a sustainable design in their own way. They have presented the different facets of sustainable construction and how they can be integrated within an engineering design framework. In their designs, the students took different perspectives, ranging from form and function to materiality and connections, to optimisation towards a sustainable structure.

Furthermore, the diversity of designs shows that the open approach encourages personal interest among students, motivating them to follow their own individual path towards sustainable design based on their own interests. On the other hand, it was unfortunately evident that the importance of sustainability is not yet fully understood by all, with some students continuing to prioritise economic viability or "personal comfort" in terms of minimising effort during the design process.

The algorithm presented was found to be very helpful in the course for understanding the basics of LCA and prioritising sustainability within the optimisation process. However, it should be noted that the implementation of the algorithm is limited to students who already have a basic understanding of parametric design and Grasshopper. As there was no prior knowledge of LCA as a method, it was crucial to introduce it in the lecture and later to practice using the algorithm and LCA booklets (ABC e.V., [10]) in the exercises. It was also found that the algorithm is only useful if the global warming potential is used to compare different designs or later for optimisation. Otherwise, an LCA of the final design using, for example, Excel would be sufficient. Regardless of the method used, special emphasis should be placed on reflecting on the results and methodology of the LCA.

Overall, it was observed that the focus on sustainability in the designs has increased significantly compared to previous semesters, particularly due to the provision of the freely available algorithm as an accompanying tool for LCA. However, this approach needs to be based on a basic understanding of design, as well as design-experience by the students.

5. Conclusion

This paper presented a teaching approach to include sustainability *by design* at the core of structural design education, rather than simply adding it to the curriculum. This is achieved by (re)defining students' design attitude towards prioritising sustainability in thoughtful and deliberate design choices. Therefore, sustainability has been introduced within a studio-based environment, so that students embed these values deeply in their 'design thinking', by combining theoretical and experiential knowledge of sustainability. In addition to theoretical inputs on sustainable design, the students are supplied with tools, which should help them to prioritise sustainability in early design choices. These tools are the 'LCA booklet' (ABC e.V., [10]) for individual research and a Grasshopper-algorithm for parametric carbon optimization, that enables them to compare und evaluate different design alternatives in terms of sustainability. The key to changing design thinking is to understand the underlying principles of sustainable design, rather than simply accepting them as criteria to be met. Therefore, the LCA-based algorithm is designed so that the user understands LCA as a method and can reflect on both the method/results and their design.

The approach was applied to the Computational Design course at HafenCity University, where each student integrated sustainability into their design in a different way. The results show that the proposed methodology enables students to find a personal and individual approach to the topic, which will hopefully further guide their design thinking outside the course.

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