21^{ST} INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

TEACHING SYSTEMIC DESIGN FOR SUSTAINABILITY IN ENGINEERING BY BUILDING ECO SKIS

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Abstract

Resource limitations are drivers for engaging in sustainability. Systemic design approaches to address complex sustainability challenges need to be implemented more in education curricula, especially in design and engineering programs. Innovative and adequate didactic concepts should be effective in the long-term learning outcomes, and motivate students to engage in systemic design thinking and practice. The main objective of this paper is to deliver and evaluate an innovative format for teaching systemic design in an engineering program at the ETH Zurich, that is effective both in direct learning outcomes and long-term motivation to embrace and apply its theory and practice. We evaluate the effectiveness of the course with self-reflective material and process matrices, and with a final questionnaire. The combination of lectures and a ski-building workshop led to highly engaged and motivated students who experienced simplifications to complexity and trustable, aesthetic eco-design solutions to incorporate in their skis. The majority wished to study further in systemic design and to apply such practice more in their engineering design work.

Keywords: Complexity, Ecodesign, Human behaviour in design, Sustainability, Circular economy

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21^{st} International Conference on Engineering Design (ICED17), Vol. 1: Resource-Sensitive Design | Design Research Applications and Case Studies, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

Resource limitations and their overuse beyond the planetary boundaries require the transition to a more sustainable society. Concerted efforts of participation and communication are required for this sustainability transition, and despite its overuse and normative character, the term sustainability entails a conceptual framework with critical guidance (Luthe and Kutzschenbach, 2016). With the global adoption of the Sustainable Development Goals (SDG), sustainability as a binding concept of development has become mainstream (United Nations, 2016). The globalized world is continuously gaining in complexity. Challenges such as climate change are complex to understand and to tackle. Complex problems are no longer only decomposed in their fragments and re-assembled after their analyses, but the systemic interactions within coupled social-ecological systems (SES, Fischer et al., 2015) and with the technical sphere need to be looked at with adequate methods. This requires new inter- and transdisciplinary partnerships between the natural and the social sciences, with designers and engineers, policy makers and entrepreneurs. Solutions require a systemic design approach that applies a combination of systems thinking, design thinking and practice to innovate for sustainability in a resource-sensitive way (Byggeth and Hochschorner, 2006). Engineering design is at the forefront when it comes to leverage and responsibility in innovation. Developing adequate teaching concepts and methods in engineering programs to embrace resource-sensitivity is the motivation and main focus of this paper. Systemic design thinking for sustainability needs to be taught to students as future opinion leaders in a motivating way so it may become part of a timely lifestyle.

2 THEORETICAL BACKGROUND AND CONCEPTS

Design thinking is becoming increasingly important for solving sustainability problems (e.g. Fischer, 2015). The complexity of interrelated social and ecological systems and changes demands design solutions from a whole systems design perspective**,** while systemic design or “whole systems design”, as discussed in Blizzard and Klotz (2012), is a rather young, interdisciplinary field. Their conceptual design framework entails systemic design processes, principles and methods. Systems thinking is a central design principle that builds on methods of life cycle analysis (LCA) and cradle-to-cradle or circular design as of re-thinking waste. Existing approaches and tools for the inclusion of ecological aspects in product design and engineering, such as eco-design, sometimes lack the integration of strategic sustainability aspects (Byggeth and Hochschorner, 2006), decision orientation (Mattila et al., 2012), or the connection to the technical product development process (Luthe et al., 2013). On the illustrative case of skis, Luthe et al. (2013) propose a Systems Approach to Sustainable Technical Product Design (SASTPD), where the systemic design process is based on environmental and social life cycle assessment and its integration with human behavioural considerations and technical product engineering design. The SASTPD integrates environmental and social LCA in a sustainability assessment process and combines them with an engineering and CAD module early in the planning phase of the product life cycle (PLC). It is a conceptual baseline for the systemic design of technical products. For the specific case of skis, LCA data provided by Luthe et al. (2013) suggests the use of low-impact materials, such as sandwich construction-supporting fibres from volcanic basalt rock or natural flax fibres in exchange for conventionally used glass and carbon fibres, regionally sourced hard wood and wooden veneer from sustainably managed forests for cores, sidewalls and top sheets, glues based on industrial waste streams, recycled Polyethylen (PE) as ski base and the ban of polymers like Acrylonitrile butadiene styrene (ABS) as used for conventional sidewalls and top sheets. From a human behavioural and consumption perspective, Luthe et al. (2013) argue to embrace simplicity in the visual design; carefully selected and oiled wooden top sheets deliver individual aesthetics independent from annual fashions and the perceived obligation to follow them in one’s consumption behaviour. An “Allmountain” dimension setup allows for the functional use of the skis in most conditions, replacing more specific skis for different usage scenarios. The question how to teach systemic design that is elegant, simple, effective and efficient is still an open one (e.g. Nix et al., 2016; Waldo, 2006). Effective methods and curricula to teach design for sustainability, eco-social design, responsible design, or systemic design, as we coin it in this paper, is still limited (e.g. Jones, 2014). As part of teaching and learning systemic design, coping with complexity while seeking for simplified solutions, and dealing with uncertainties in human behaviour in design and consumption are of critical relevance. Didactic settings for teaching sustainability (in general, not only in design or engineering) entail experiential, hands-on, self-reflective and mutual learning environments; competences are drawn from instrumental (e.g. systems thinking), technical or professional (e.g. material life-cycle assessment) and mental or social (e.g. team work) skills (Wiek et al., 2011). Within the design disciplines, engineering design is most based in science and covers a large array of topics from heat transfer to eco-design. Its approach to teaching needs to address such complexity. More hands on didactical settings have shown to be beneficial for developing engineering design skillsets beyond the text book (Nix et al., 2016). In the following chapters we describe and evaluate a teaching case in systemic design where theory lectures incubate and wrap around a practical ski-building seminar in the Mechanical and Process Engineering third and final year Bachelor program at the EDAC (Engineering Design and Computing Laboratory) at ETH Zurich. One motivation for offering this course as a didactical experiment was to complement existing “applied theory” courses at EDAC, such as in design methods.

3 METHODS

The teaching case is developed according to the conceptual framework of systemic design, sustainable technical product development, and didactics of sustainability education as introduced above. Prior to the actual ski-building workshop, students received a specific lecture on systemic design for sustainability, providing them with the fundamental instrumental and technical knowledge on material life cycle data and further relevant eco-design and health considerations in engineering design.

We evaluate the effectiveness of the course and its learning outcomes in a two-fold process. First, students were asked to fill out two matrices, one for their design and materials selection for the skis, and one for the processes, reflections, learnings and possible decision-making changes during the workshop. Both matrices contain descriptive information on technical, aesthetical, functional and ecological life cycle data, on the detailed building process steps, including space for self-reflections during their learning process. The matrices accompanied students during the whole building workshop, while the course instructors controlled their continuous updating. Due to the experiential setting, many individual discussions and feedback on design compromises and processes between students and instructors took place and enriched this continuous course evaluation. These matrices serve as the main source for evaluating the reflective learning process of the students.

Second, an online questionnaire was circulated to the eight students after the last workshop day when the skis had been finished; it was used to round up the self-reflections and provide a separate, quantitative analysis of the course’s effectiveness. The ten questions looked at the learning progress specific on knowledge and awareness in sustainability and systems thinking (addressing complexity) before, during and after the workshop. Students were asked for self-reflections on their learning progress, their motivation, their satisfaction with the process and the outcomes, and their future interest in systemic design for sustainability.

4 CASE STUDY: THE ETH SKI BUILDING COURSE

4.1 Course description

4.1.1 Learning goals

The overall goal of the EDAC course "Integrative Ski Design and Fabrication Workshop" is to combine engineering knowledge and (eco-)design thinking and practice in a hands-on project that allows students to learn systemic design in the whole product design process. The experiential setting is chosen to increase motivation and effectiveness of the course, and ultimately to embrace systemic design thinking as part of the students’ work routine. At the beginning the students learn to distinguish between the different aspects of product design. By first defining the use case, the user and the core behaviours and features, they experience the influence of basic design decisions on the final product. A detailed analysis of the key factors allows for a distinguished specification of both formal and functional design parameters. A simplified analytical calculation of the bending stiffness of the ski shows how relatively simple engineering tools can already provide a useful insight into the relation and interaction between behaviour design, materials and mechanical behaviour of the product. Students learn to combine knowledge of different fields (classic mechanics, fibre composites) in an interdisciplinary approach. Building the self-designed and analysed ski in the workshop provides an insight into different manufacturing techniques, difficulties and advantages with different materials. Team-working skills are trained and the students learn to understand the importance of including workers' capabilities in the design of the product. Balancing partly opposing design goals requires a systems thinking approach from early on.

4.1.2 Prerequisites

The course is offered to Bachelor students in the third and final year, so only basic skills in mechanics and design are expected, and no workshop experience is required. Some of the students had already experience in woodwork, fibre composites and with tools whereas others had no experience at all. These factors were taken into account in the design of the course structure: the instructors introduced basic concepts and tools and assisted in their application (e.g. working with fibre composites) or support was fully provided (e.g. complex CAD model of a ski). A workshop room, basic tools (jigsaw, circular saw, belt grinder, drilling machine etc.) were provided by EDAC laboratory at ETH. Basic materials like glass fibres and consumables like foils, gloves etc. were purchased at common commercial stores. Basalt and natural flax fibres, hardwood, wood veneers and resin based on industrial waste streams were obtained from the manufacturers or direct via the Grown Outdoor Creativity Lab[1]. For curing the laminate, an autoclave was available at the Laboratory of Composite Materials and Adaptive Structures at ETH. All costs, i.e. for material, tools, consumables and processes, were covered by the EDAC laboratory, which allowed all students, independent of their financial situation, to participate in the course. The overall material costs per pair of finished skis account for about 280€.

4.1.3 Course structure

The "Integrative Ski Design and Fabrication Workshop" is connected to the lecture series "Grand Challenges in Engineering Design" at ETH Zurich, featuring presentations about *General Ski Design*, *Ski-Testing*, *Mechanics of Skis*, *Design by Intuition*, *Bio-mechanic Aspects of Skiing*, *Ski Design for Sustainability*, *Ski Manufacturing*, *Mechatronic Ski Binding Design* and *Ski Simulation and Testing*. The lecture on *Ski Design for Sustainability* introduced basic concepts of systemic design and especially sustainability in ski design as a starting point for the workshop. The workshop was scheduled for six weeks with one four-hour-class every week (Table 1).

Table 1. Overview of the course structure

	Goals	Tasks
Week 1	Formal definition of behaviours and requirements of skis. Understanding of influence of different laminates, geometries and materials on mechanical properties. Visual design.	Define type of ski; identify critical geometric parameters and define geometry of ski. Calculate bending/torsional stiffness with simplified model; design laminate and estimate overall mechanical behaviour. Define visual design of ski.
Week 2	CAD-model of the ski including mold-shape and protectors.	Adapt template of CAD-ski model to match chosen geometry.
Week 3	Base sheet with individual geometry. Mold Ski edges glued to base sheet	Laser cut base sheet material to match geometry. Prepare mold with chosen geometry. Bend edges s o that they match chosen geometry; glue edges to base sheet.
Week 4	Wood core and sidewalls with individual geometry.	Trim core so that it matches chosen geometry. Glue sidewalls to core. Work core so that it matches chosen thickness profile.
Week 5	Assembly of all components	Cut fibres and top sheet. Join all components with epoxy resin (laminating).
Week 6	Final ski	Remove unnecessary material. Sand sidewalls. Oil top sheet (if applicable).

4.1.4 Ski Design and Fabrication Parameters

Figure 1 shows a schematic of a ski's cross-section. The base sheet is in contact with the snow and accounts for the reduced friction between snow and ski. The steel edges provide grip on hard packed

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[1] http://www.grown.ch

snow and are used to initiate turns and steer the ski. The fibre composite layers above and below the core provide bending and torsional stiffness, and influence vibration and damping characteristics. The core separates the fibre layers to increase stiffness and is used for damping the ski. The sidewalls protect the inside of the ski against mechanical and environmental impacts like humidity. The top sheet also protects the inside of the ski. Protectors at the tip and the tail of the ski buffer impacts from the front (e.g. skiing into an obstacle like a rock) and the back (e.g. pushing the skis into the snow to stand upright). The students could choose between several materials and designs for each component except for the steel edges and the core, where only one option was available. Table 2 shows all components and the possible options.

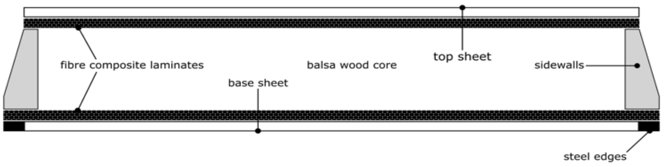

Figure 1. Ski cross section

For the design of the laminates in the skis, students were provided with four different materials to choose from, i.e. carbon fibres, glass fibres, basalt fibres and flax fibres. To achieve both desired bending and torsional stiffness, a mix of unidirectional (UD) fibres with a ply angle of 0° with respect to the ski's longitudinal direction and a weave of fibres with angles of +/-45° respectively need to be combined. UD fibre mats were provided from carbon, glass and basalt, whereas +/-45° glass and flax weave were provided. The Young's modulus of laminates with carbon fibres is usually many times higher than the moduli of laminates with all other materials provided, yielding high bending stiffness at low weight. Basalt and glass laminates show similar stiffness in terms of bending. For the torsion stiffness of the ski, the shear modulus of the laminate is the relevant parameter. Both glass and flax fibre laminates exhibit similar shear moduli, but flax is thicker, thus increasing the thickness of the laminated ski. From an ecological point of view, the natural flax fibres and basalt made from 100% volcanic rock are more sustainable than glass and carbon fibres. Their main ecological constraints are their high amount of embodied grey energy and the additives so they cannot be recycled. Glass has a human toxicity about forty times higher than flax, its greenhouse gas emissions are about three times higher (Deng and Tian, 2015). Natural fibres are barely used by big manufacturers, as there exists limited experience with these materials and due to their higher costs. For the sidewalls, durable hardwood from European, FSC[2] certified forest management (chestnut) as well as ABS (acrylonitrile butadiene styrene) with different colours were offered. At higher temperatures (400 °C) ABS can decompose into its constituents: butadiene (carcinogenic to humans), acrylonitrile (possibly carcinogenic to humans), and styrene. Concerns have been raised regarding airborne ultrafine particle (UFP) concentrations generated while printing with ABS, as UFPs have been linked with adverse health effects (Plasticseurope, 2016). The production of ABS, especially the pre-chain, leads to a high environmental footprint, whereas wood has a net-positive carbon balance and is renewable. The ski protectors can be 3D-printed from ABS, manually manufactured from wood or completely left out.

Table 2. Ski components and available material/design options

Component	**Material/Design options**
Base sheet	ABS black, ABS white
Edges	Steel
Fibre composites	Carbon (UD), glass (UD, +/-45°), basalt (UD), flax (+/-45°)
Core	Balsa wood with vertically laminated flax fibres
Sidewalls	ABS (orange, green, blue …), wood (chestnut)
Top sheet	Wood (walnut, cherry), transparent PVC with paper print below
Protectors	3D-printed ABS, wood (chestnut)

For the top sheet, both wood and plastic (PVC) were offered. While the transparent PVC allows for customization with a printed graphic below the sheet, the wooden top sheets can be worked with a laser cutter to burn images or text into the material or cut out and insert parts like inlays. PVC is known to

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[2] Forest Stewardship Council, a leading sustainable forest management certification scheme

release potentially harmful emissions of phthalates (e.g. Afshari et al., 2004) and during its entire life cycle PVC leads to the formation and environmental discharge of organochlorines and other hazardous substances (Thornton, 2002). The two different options for the base sheet only differ in color, the function and environmental properties are the same.

4.1.5 Realization, Possibilities and Limitations

In the first step in week one, the students developed the requirements and behavioural design of their skis. Depending on the type of the ski, a desired bending and torsional stiffness was determined. To estimate the required core thickness and fibre layout for the specified stiffness, the ski construction was simplified by assuming a sandwich beam construction, the laminates below and on top of the core being the face sheets. This allows for the use of the Euler-Bernoulli-equation for a beam with linear variable cross-section to determine the deflection (and hence the stiffness) of the beam for a given load and cross-section. For the estimation of the effective Young's modulus of the laminate, we used AlfaLam Version 1.3[3] from the Technische Universität Darmstadt, an Excel-based tool to calculate laminate properties based on the classic laminate theory (CLT). Students were provided with a CAD-model of a ski as a template to adapt according to their own ski design. Tip and tail protectors were also included and were 3D-printed out of ABS later, if the students' designs included some.

Unlike professional ski manufacturing, the workshop was carried out with only basic tools, e.g. jigsaw, circular saw, belt grinder. The restriction to simple tools, e.g. jigsaw, circular saw, belt grinder, necessitated primarily more and precise manual work of the students, like sawing, milling and sanding in many of the steps. The manual approach is limited when it comes to assembling all subcomponents and laminating the ski, as the metal base plate of the mold can't provide exactly the desired shape of the ski. The most common error encountered in the course was a misalignment of the base sheet, the core and the top sheet. The lower, non-uniform pressure of vacuum sacks results in lower fibre volume ratios and may cause wrinkles and bubbles, thus leading to increased weight at lower stiffness and lower surface quality. The autoclave was only used to heat cure the ski at 75°C without additional pressure, reducing curing time to one hour instead of approximately seven hours. Within the scope of this course the disadvantages were acceptable since the influence on the overall performance of the final ski is little and the additional costs for a pressurized mold combined with the loss of the possibilities of creating individual ski geometries make the chosen process the best choice. Figure 2 shows the main steps in the manufacturing process.

4.2 Description and analysis of course results

4.2.1 Eco-design in the material selection and the ski building process

Students had little or almost no knowledge of eco-design aspects prior to the first systemic design lecture. In this lecture, life cycle analysis (LCA) data of relevant materials used in skis was clarified as the ecological basis for this course. However, students were free in their material and design choices and were explicitly not obliged to choose the most eco-friendly alternative.

For the fibre composite laminate, all students chose basalt fibres in the longitudinal direction over the other materials, and all named the ecological aspect and that Grown also uses basalt fibres for their skis as the main drivers for their decision. For the torsional stiffness, half of the students chose flax and half glass fibres. The students who decided for flax fibres named again the ecological aspect the most important for their decision, whereas the others referred to the experience of ski manufacturers with glass fibres and a lack of trust in the seldom-used natural flax fibres: The uncertainty about both long-term effects and general suitability of flax fibres for the use in skis made them chose well-established glass fibres, despite their higher ecological footprint. One student initially decided for glass fibres, but changed his mind after having seen the flax fibres. Handling the material helped to overcome prejudices and convinced the student of the material's high quality and manufacturing standards. Generally, it was hard to convince students to choose an eco-friendly material over a conventional one if there were little experience or reference skis in which these materials were already successfully used. They were willing to consider ecological aspects, but not at the price of reduced or uncertain mechanical properties. Increased weight and thickness of the skis however did not affect the decision. For the sidewalls materials, everyone chose wooden sidewalls except for one student. Even though the ecological

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[3] http://www.klub.tu-darmstadt.de/forschung_klub/download/index.de.jsp (09.11.2016)

friendliness of wood was always clarified, the overall visual design of the ski was the most important argument for all wooden sidewalls. The functional disadvantage that wood might need some treatment (sanding, oiling) after some time was not important. The main reason for choosing ABS sidewalls by one student was visual - the contrasting colours. During the building process, students experienced that ABS is less convenient to work with; the smell of the heated plastic and the clogging up of power tools left a negative impression on choosing this material again in favour for wood, mostly for health reasons (Figure 2 picture 6).

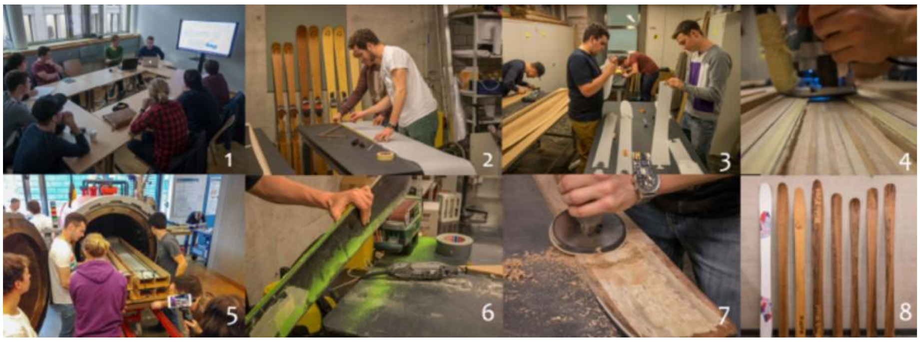

Figure 2. Pictures from the ski-building process: 1. Behavioral design and CAD, 2. Workshop setup, 3. Cutting ski bases, 4. Routing the wood cores, 5. Curing in an Autoclave, 6. Sanding ABS sidewalls, 7. Sanding wooden top sheet with logo inlays, 8. Final skis

Five students decided for a 3D-printed ABS-tail protector, whereas only one tip protector made out of wood was chosen. The function of the protector was the most important argument for their usage, even though all students rated the impact of adding protectors to the design slightly negative. The plastic part was perceived as a change in style in combination with the other wooden components. All of the students who refused to use protectors also named the visual design as the main factor for their decision. It became clear that for smaller parts which are non-critical for the overall behaviour of the ski, both functional and design aspects were considered very important by the students, whereas environmental aspects in this case didn't contribute to design decisions at all**.** Half of the students decided to design an individual top sheet, either by adding wooden inlays to a veneer sheet or a PVC top sheet covering graphics. The most used material for the top sheet and the sidewalls was wood (walnut or cherry veneer for the top sheet, chestnut (Castanea *sativa*) for the sidewalls), only two students decided for PVC or ABS. Aesthetic design aspects were the main drivers for the material choices - both environmental and functional aspects were no major influence factors for the top sheets design. Table 3 provides an overview of all eight resulting ski pairs, including type, material choices and overall weight. The final weights of the skis are similar to comparable commercially available skis.

Table 3. Overview of the final eight pairs of skis and their characteristics

Ski #	Type	Top sheet design	Materials				Weight [kg]	Length [m]	Shovel/ Waist/Tail width [mm]
			Top sheet	Sidewalls	Tip/Tail Protector	Laminate			
1	Freeride	Graphics	PVC	Wood	-/-	Basalt, Glass	1.93	1.84	138/114/130
2	Freeride/ Tour	-	Wood	Wood	-/ABS	Basalt, Glass	1.66	1.85	135/100/120
3	Freeride	Logo	Wood	Wood	Wood/ ABS	Basalt, Flax	1.65	1.80	135/98/120
4	Freeride	Logo	Wood	Wood	-/ABS	Basalt, Glass	1.71	1.88	146/114/130
5	Allmtn	-	Wood	ABS	-/-	Basalt, Flax	1.83	1.74	121/99/124
6	Racing	-	Wood	Wood	-/ABS	Basalt, Glass	1.38	1.68	125/68/109
7	Tour	-	Wood	Wood	-/-	Basalt, Flax	1.81	1.80	130/100/115
8	Allmtn	Logo	Wood	Wood	-/ABS	Basalt, Glass	1.57	1.85	130/93/122

4.2.2 Making design choices

In the design of skis, eco-design aspects needed to be balanced with individual design aesthetics, functional properties, feasibility and time, which is a complex decision making process where systems thinking helps to identify tangible and simplified solutions. The required time for each step of the course is one such decision factor. Figure 3 shows the mean values and standard deviations, based on the students' data from the processes-matrices. Design aesthetics, which are mostly the design of the top sheet and its fabrication, are highly individual, and thus listed separately. Manufacturing the base sheet and preparing the edges are listed separately, as these two steps comprise two different manufacturing processes. The most time-consuming part of the process was the preparation of the wood core and the sidewalls. These steps consisted of manually working the core with saws and belt sanders to fit the required shape and thus involving a lot of checking and reworking. For cutting the base sheet, a laser cutter was used, which reduced the working time drastically, as the complex shape was directly obtained and only little additional rework was necessary.

The top sheet design is an example for balancing time and aesthetics. Seven students chose a wooden top sheet, one student decided for a printed paper with a plastic top sheet. Three students chose to individually add a logo design to their wooden tops. The large standard deviation for the second column in Figure 3 depicts the complexity connected with an individually designed top sheet. While the preparation of the wood veneer top sheet took only about one hour, students spent up to almost twelve hours in the design and manufacturing of individual design parts, i.e. wooden inlay logos. Among the students who did not use a specific logo design, only one referred to the simplicity in design as a reason for the (non-) choice, whereas the others mentioned that the veneer top sheet already fits their design idea of the ski, since the provided cherry and walnut veneers were selected for differentiation in grain and colours. Consequently, the visual design aspect was rated very high by the students and almost all of them would not consider changing this part of the ski to reduce working time and simplify the building process.

For engineering the laminate layers, an analytical approach as described in section 4.1.5 was chosen to reduce the complexity of this design step. However, to fully describe the mechanical behaviour of the ski, a complex finite-element-model (FE-model) would be necessary (Wolfsperger et al., 2016). The simplification of the ski as a sandwich beam system neglects the influence of base and top sheet, edges and camber/rocker geometry. This produces only qualitatively useful results to compare different materials and core geometries, but can't generate quantitatively reliable values for the stiffness of the ski. However, by adding two different reference skis with known layer setup and tested stiffness, analytical calculations can support the layer engineering, as results can now be compared to real values and the effect of the error can be estimated. This systematic approach is only useful and feasible if knowledge already exists about the mechanical behaviour of different configurations, e.g. by building test skis with given layer setup. In the context of the course, this approach proved to be very useful, as it avoids the complexity of a FE-analysis of the ski, but at the same time provides the students with a tool to choose and validate their material and core geometry choices and helps them to understand the influence of their choice on the overall functional and mechanical properties.

Deciding under uncertainty and going for a “best fit” feeling is a lesson learned during this design step. Despite of access to the latest state of knowledge and data on i.e. technical properties, LCA data and health aspects, balancing these factors in the engineering design of skis showed to be a complex decision making process where much uncertainty remains, and where assumptions and individual aesthetics led to simplifications and necessary compromises.

4.3 Self-reflection and final evaluation

The following evaluation is mostly based on the questionnaire results. The numbers refer to the provided Likert response scale from 1 (very low) to 5 (very high), and depict the average of all students. Among all eight students, knowledge and awareness for systemic engineering design before the workshop were evenly little. As they barely had any contact with design for sustainability within their studies, knowledge and awareness were rated at an average of 2.6. After the introduction lecture on ski design for sustainability, especially the awareness for ecological aspects already increased to about 3.6. After having successfully completed the workshop, students rated their overall knowledge on systemic design about 3.9 and their awareness about 4.4. These results not only reflect many of the sustainability-related design decisions (wooden sidewalls and top sheet, basalt and flax fibres), but also a change in the students' mind-sets over the course. Overall, they were very satisfied with the final skis (4.0 on a scale from 1.0 to 4.0), none of them would use a plastic top sheet in the future (again), only one considered ABS sidewalls on a next ski due to design aesthetics.

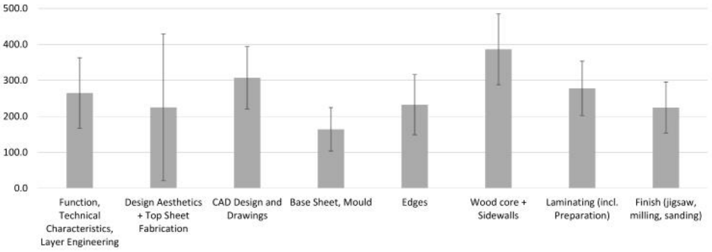

Figure 3. Mean value and standard deviation of time (in minutes) needed for different steps in building the skis. The data was obtained by evaluation of the processes-matrix

6 students would consider systemic design for sustainability more than before and 3 would be even interested in taking a specific course on this topic to further deepen their knowledge. Besides insights into the ecological impact of commonly known and used materials (e.g. ABS, glass fibres), discovering new ecological superior substitutes with almost the same mechanical properties for those materials (e.g. basalt fibres) was a major learning effect for the students. Even though some students were very sceptical at the beginning, especially towards flax fibres, the final results are convincing and help to establish trust in these materials. Students also improved their handcrafting skills (from 3.1 to 3.9), proving that the hands-on approach helps to raise awareness for the manufacturing itself and the related difficulties. The most difficult parts were the preparation of the core and the bending of the edges, which made students rethink their design critically in terms of simplification. As for ski number four, the bending of the edges required an above-average amount of time due to the small radii around the tip. Adapting this to a smaller radius would only influence visual design, but not the function, and thus was considered beneficial in terms of design for manufacturing by the students.

5 DISCUSSION AND SYNTHESIS

The course outcomes match the initial goals of providing a motivating, effective learning experience on systemic design for sustainability. As part of the rich data from the accompanying materials and process matrices, students came up with a couple of good ideas on how to improve and simplify the ski building process. Their motivation and learning progress in handcrafting and systems thinking was very high. Based on the lecture input on material LCA data and circular design thinking, eco-design aspects were incorporated in the final skis. The majority of students considered eco-friendly material alternatives in favour for classic design factors, but cognitive choices were primarily based on individual design aesthetics and functional aspects. When students experienced the differences in working with natural materials compared to ABS and PVC, especially while smelling heated ABS emissions during the sidewall milling process, this had an influence on stated material choices. What the theoretical input on eco-design did not achieve needed to be experienced during the building process. Since the sheer material costs per pair of skis per student summed up to around 280€, and since winter sports equipment cannot reach the majority of students as a motivational product to build, other and comparable products should be considered for building. The course structure followed the general process of building a ski, with an emphasis on the design and engineering parts. As it can be seen in Figure 3, these parts (first three columns) accounted for about a third of the total amount of time needed. Due to the specifics in the manufacturing process (i.e. only basic tools were available), a lot of time was spent on labour intensive steps (e.g. bending edges, wooden logo inlays). The overall average working time per pair of skis exceeded with about 34 hours by far the projected time of 24 hours (4 hours every week for 6 weeks). Hence, extra working time from the students was required to finish their skis on time, and due to the high intrinsic motivation to finish a personal pair of skis, this extra time was no problem. Improving the tools could reduce the manual workload. Even though the layer engineering for the laminates proved to be sufficient to roughly achieve the desired mechanical properties for the skis, a precise determination of related quantitative parameters and the required materials and geometries were still not possible. To give the students full control of the final mechanical properties of their skis, an improved model that takes these uncertainties into account would have to be established.

6 CONCLUSIONS

The ski-building seminar embedded in the lecture series was a success in that all students built functional and aesthetic skis in the available time, successfully manoeuvring the complex interplay of systemic design elements in their cognitive design choices. The theoretical input on circular design and LCA data needed the hands on experience in working with environmentally harmful materials like ABS and PVC to make students taking eco-design decisions in preference for solemnly functional and aesthetic reasons. Students improved their knowledge, awareness and motivation in systemic design during the course, and were satisfied with their built skis and their learning outcomes. Teaching systemic design for sustainability in an experiential setting where the necessary theoretical and systemic foundation is developed in traditional theory lectures and then experienced in actually executing an engineering design project has proven its success. Navigating in a complex systemic design process requires learning systems thinking and self-reflecting on simplifications and individual human behavioural priorities under uncertainty. Constraints in adopting eco-design are uncertainty, lack of knowledge, trust in alternative materials and experience. Successfully teaching eco-design should be based on theoretical LCA knowledge, but individual experiences, gaining trust and learning from good practice are required to embrace eco-design as a win-win habit.

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