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ASSESSING COMPETENCIES FOR SUSTAINABILITY IN ENGINEERING EDUCATION – A CASE STUDY

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ABSTRACT
Achieving a sustainable and climate-neutral world is a social and complex technological task. Engineering designers therefore play a vital role as their technological developments may require the use of resources on a large scale. However, these developments are also driving factors for the transformation towards a more sustainable future.
This transformation requires capable, specifically trained engineers who are able to take sustainable aspects during the product development process into account. This in turn requires basic knowledge in the field of sustainability, which students should be introduced to in engineering education.
In this paper we examine competency models for sustainability described in the literature and which can be directly adapted for engineering education. Using the example of the course "Sustainable material selection and product development" at the University of Rostock, Germany, we present a way to assess competencies of sustainability in engineering education to evaluate the impact of our course design.

Keywords: Engineering education, product design, sustainability, core competencies, competence models

1 INTRODUCTION
The global population is projected to exceed 9.7 billion by 2050 [1], contributing to a steady increase in the extraction of raw materials, which could surpass 100 billion tonnes annually by 2030 if the current trend persists [2]. This unsustainable resource consumption, coupled with a lack of recovery frameworks, is exacerbating the scarcity of resources and putting an immense burden on global ecosystems [3].
Engineers have a critical role to play in the transition towards a circular economy, given that the technologies they design consume resources on a large scale and drive social change [4]. Consequently, they bear a responsibility to consider the ethical and sustainable dimensions of their work from the outset of product and process development. Despite this, prospective product designers often receive inadequate training on sustainability issues, as studies reveal that only a small number of engineering programmes in Germany incorporate such topics into their curricula [5]. To address this gap, the authors developed a course at a German university, described in a previous paper [6]. The course deals with various topics and techniques along the product life cycle and combines different, mostly interactive, teaching approaches. The examination performance is a semester project in which the students develop a sustainable solution for an engineering problem. The goal is to equip students with relevant skills and mindsets to actively contribute to a more sustainable future.
The aim of the present study is to evaluate the effectiveness of the developed course and analyze the competency areas where it has the highest impact.
This leads to the following research question:
- Q1: What are the competency areas where we have the most significant impact?

For which we must first answer the following two questions:
- Q2: What are the available competency models that categorize relevant competency areas for sustainability in engineering education?
- Q3: How can we assess the improvement in competency areas?

1.1 Competency Models for Sustainability in Engineering Education

Starting from the question of whether the module serves its purpose, we searched the literature for competency models in the field of sustainability for engineering education.

Desha et al. [7] present a view of global organisations such as the International Engineering Alliance (IEA), which is developing universal sustainability standards for engineering education. The authors also draw on examples from the US and Australia to illustrate how these standards are put into practice at the national level. However, implementation remains vague or is limited to certain engineering disciplines. Looking at Germany, there is also no comprehensive regulatory framework for the integration of sustainability topics in engineering education and even well-respected accreditation agencies like the "Accreditation Agency for Study Programmes in Engineering, Informatics, Natural Sciences and Mathematics" (ASIIN e.V.) have yet to provide specific guidelines on this matter [8].

It is becoming apparent that the development of competency models for sustainability in engineering education is an ongoing process, and various scientific studies have been conducted to understand the competencies required for sustainable engineering practice, including those by Svanström et al. [9], Segalàs [10], Quelhas et al. [11] and Beagon et al. [12]. The reviewed papers provide valuable insights into the competencies, highlighting the complexity of the field and the need for multiple perspectives. However, despite some overlap, discrepancies exist in the competencies found in the reviewed literature, including differences in the number of competency areas identified and variations in the terminology and descriptions used.

It is evident that although efforts have been made to develop competency models for sustainability in engineering education, there is currently no widely adopted or universally recognized model for this field. Furthermore, the question remains of how the identified competencies can be assessed in our course.

As the development of competencies for sustainability in engineering education is still in its early stages, there is currently no prevalent or universally accepted competency model for this domain. As a result, we consulted general competency models for sustainability, with the model by Wiek et al. [13] being particularly well-regarded and highly influential [14]. This model identifies five competency areas, including

- *Systems-thinking competence* (Evaluate a sustainability challenge holistically.)
- *Anticipatory competence* (Generate potential scenarios for how the problem might evolve in the future.)
- *Normative competence* (Thoroughly evaluate a sustainability-related issue and its surrounding context.)
- *Strategic competence* (Develop intervention tactics aimed at preventing unfavourable outcomes and achieving sustainable goals.)
- *Interpersonal competence* (Foster collaboration with researchers from other disciplines, along with key stakeholders in government, corporate, and civil sectors.)

1.2 Assessment of Competencies

As described in section 1.1, there is no universally accepted competency model for sustainability in engineering education. Therefore, we searched for literature on how competencies in the field of sustainability can be measured in general. Redman et al. [15] published a comprehensive literature review "Current practice of assessing students' sustainability competencies" in 2021. Due to its recognition, Wiek et al.'s competency model served as a basis. In their work, the authors differentiate eight different types of assessment tools from a total of 75 studies, namely scaled self-assessment, reflective writing, focus group/interview, performance observation, regular course work, concept mapping, scenario/case test, scenario/case test and conventional test. The review of the advantages and disadvantages of each tool by Redman et al. [15] showed that the scaled self-assessment was the most common method. In the review, the scaled self-assessment by Savage et al. [16] was chosen as a representative example with a precise description, whose paper also includes the complete questionnaire based on the competency model by Wiek et al. [13].

2 RESEARCH APPROACH

2.1 Study Design

This study investigates the development of students' sustainability competencies in the course "Sustainable material selection and product development". This course is part of the engineering education at the bachelor level, but can also be attended by master students. As shown in the previous sections, there is currently no model for sustainability competencies that is tailored to engineering education. For this reason, we utilized the widely recognized competency model by Wiek et al. [13].
For our survey, we used a multi-part self-assessment procedure where the students rate their agreement to pre-defined competencies statements. We choose this tool because it produces quantitative data which we can analyze and it is easy to administrate and scale if needed.

2.2 Test Procedure

For this survey, we chose the scaled self-assessment tool developed by Savage et al. [16]. The survey tests the students' self-assessment and competence to perform an action in the five areas provided by Wiek et al. [13]. To detect the changes over the semester we conducted a pre-test on the first day of the module and a post-test about 12 weeks later at the end of the term. The post- test contains an additional second part, where the students can state, why they rated a question differently or the same as in the pre-test. It is a pen and paper test consisting of 15 Questions which were translated into German - three questions each on the five sustainable competence areas. One of the questions (original question 5 - see Figure 1 b) was too broad for our purposes, so we removed it. Additionally, we slightly adapt the questions to subjects that are addressed in our course, as proposed by Redman et al. [15]. For reasons of space, we are not able to display our entire questionnaire. But this can be requested from one of the authors if necessary. Another adjustment was made to the Likert-scale. We increased this to a scale range of 5, with 0 (disagree) and 5 (agree) to allow students to take a neutral standpoint. Excerpts from the questionnaire are shown in the Figure 1 below.

a)

I feel confident and competent to: 1= Disagree 2=partially agree 3=neutral 4 partially agree 5= agree	disagree	Partially disagree	neutral	Partially agree	agree
1. Articulate a vision of a just and sustainable society					
2. Account for individual and cumulative social, environmental, and economic implications of a decision or process.					
3. Analyze complex problems drawing from multiple discipline					
4. Assess the resources available and necessary for an action					

b)

I feel confident and competent to: 1 = Disagree 2 = Partially Disagree 3 = Partially Agree 4 = Agree	Response 1st	 2nd	1. Explain why your responses did or did not change.	2. Do the questions represent each competency for you? Are they good indicators? Explain.
Normative				
1. Articulate a vision of a just and sustainable society				
14. Understand your own strengths and weaknesses as a sustainability leader				
5. Collectively assess the current and future states of social-ecological systems				
Interpersonal				
9. Motivate positive change in others				
11. Pursue collaborative approaches to problem-solving				

Figure 1. Excerpts from the questionnaire by Savage et al. [16]: a) pre- and post-test; b) second part of the post-test

Figure 1 a) shows the structure of the pre-test and post-test with the mixed individual questions. The right section shows the structure of the second part of the post-test. Here the tasks are sorted by competencies. The students enter their scores and give a self-assessment for possible changes. Additionally, they could state their most significant learning in the course. There was no time limit for the test performance, neither in the pre- or post-test. The students were given verbal instructions and then a printed questionnaire on which the answers were recorded. A randomly generated 3-digit participant number was used to assign pre and post-tests. Immediately after the post-test, students were again given the results of their pretest and completed the second part of the post-test based on the difference in scores (Figure 1b).
Participation was voluntary and did not influence the course evaluation. At any time, the participants could stop the test or withdraw their consent.

3 RESULTS

The course was composed of ten students (five bachelor and five master students). It was made up of different disciplines mainly mechanical engineering but also biomedical and civil engineering. One student only participated in the pre-test and one student did not answer all questions resulting in a final sample size of n=8.

Below are presented the results, clustered by competency area according to Wiek et al. [13]. In Figure *2*, the light green bars represent the average self-assessment of the students on the Likert-scale for each question in the pre-test. The light blue bars show the corresponding result in the post-test. The dark grey bars show the difference between the average points of pre- and post-test with corresponding numerical values. These values represent the increase in self-confidence of the students ans therefor our courses impact regarding the competencies.

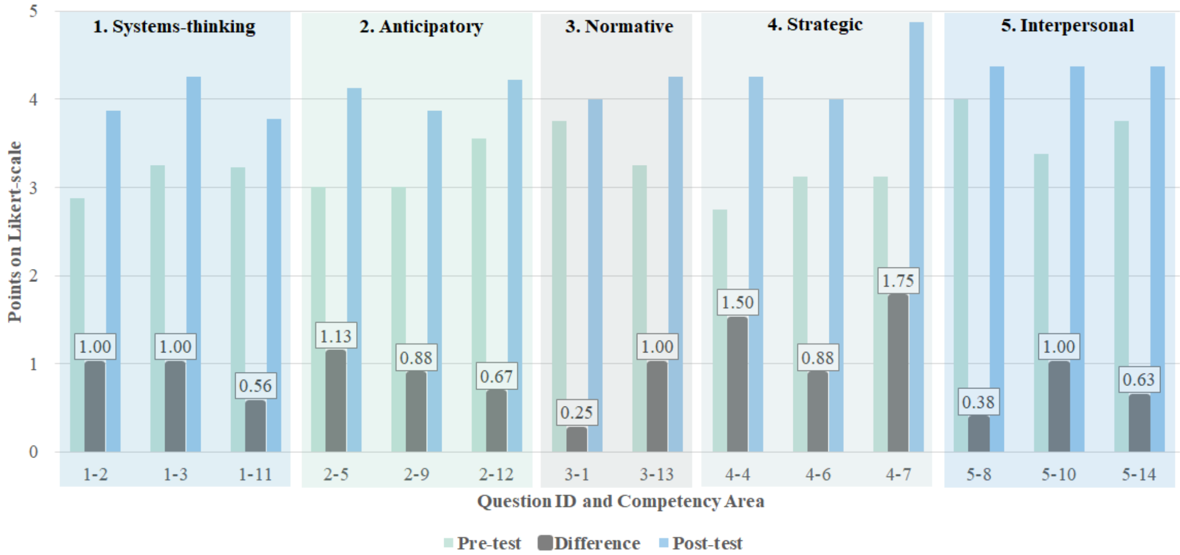

Figure 2. Point distribution in pre-and post-test and average differences between results

Within the individual competence areas, certain variations in the difference are evident, although the initial levels are relatively high for all questions. It also gets obvious that the students' self-assessment of their respective competence has increased on average throughout. When the competency areas are combined as shown in Figure 3, the following additional trends can be observed:

In the area of normative and interpersonal competence, the students' self-assessment at the beginning is relatively high. The lowest is in the area of strategic competence. Systems-thinking and anticipatory competence fall in between. In contrast, it is noteworthy that self-assessment regarding strategic competence in the post-test not only increased to a similar level as the other areas, with a maximum difference of Δ=1.38 points on average. It is now rated as confidently as interpersonal competence, with an average assessment of pre4 = 4.38 points.

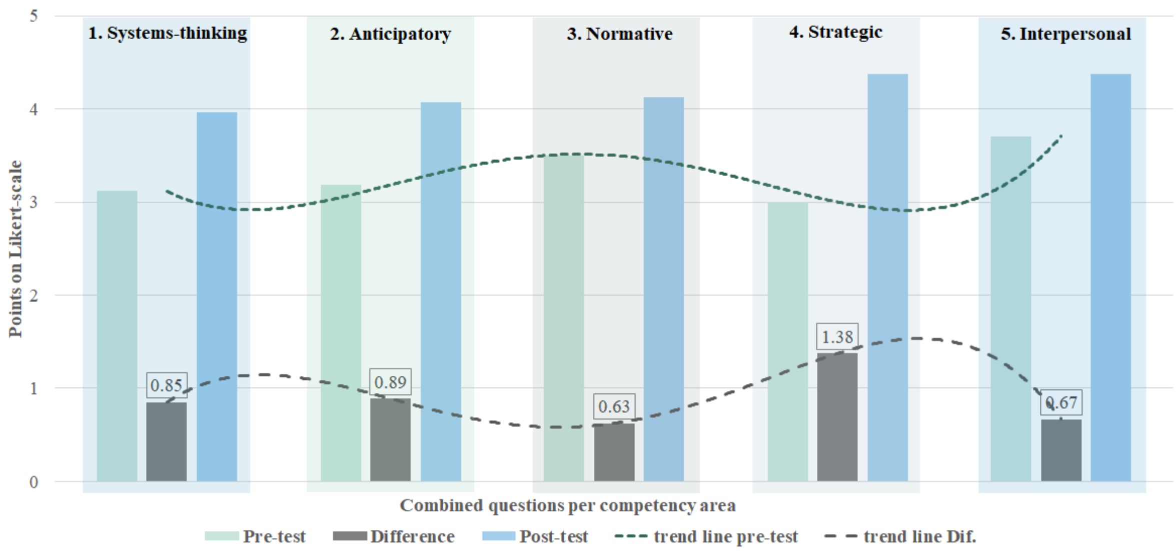

Figure 3. Point distribution per competency area in pre-test (including trend line) and post-test including differences between results (including trend line)

In the post-test statements regarding the most important learning outcome, the following points were particularly highlighted by the students: Practical tools for assessing the sustainability of solutions in product development, not only qualitatively but also quantitatively; a combined approach from the perspective of different disciplines; and most notably, the hands-on application of the learned material in their semester projects.

4 DISCUSSION AND CONCLUSION

The study showed that we have achieved a general increase in self-confidence in all areas of competence with our course. The basic effectiveness has thus already been proven.

Furthermore, it was noticeable that the participants were particularly self-confident in the areas Normative (pre3=3.50) and Interpersonal (pre5=3.71) and the areas System-thinking (pre1=3.12) and Strategic (pre4=3.00) were in last place. We achieved the greatest improvement (Δ= 1.38) for this competence area "strategic" with the worst starting position. Of course, we expected the greatest development potential in the lowest areas but we even managed to rise above the other competence areas with a final self-confidence level of post4=4.38.

This corresponds to the contents of our course. It has an informative character and is intended on the one hand to establish systems thinking and on the other hand to provide tools for application in different problems and tasks along the product development process. With these tools, students are enabled to achieve self-set sustainable goals for their design and to evaluate design decisions in terms of sustainable impacts.

So, the results of the study show that we have the biggest impact in the area of the learning objectives of our course. If we include the verbal explanations of the participants, it becomes clear once again that the practical application of the various tools in the different design phases has contributed to this.

The multi-self-assessment test with the basic questionnaire provided by Savage et al. is easy to use and to adapt but of course still subjective. An additional limitation is due to our small sample size.

5 OUTLOOK

We plan to continue the study in future runs of the course. Additionally, part of the data has not yet been analyzed. For instance, an examination of the individual self-assessment regarding changes in the students' pre- and post-test in the context of the competency areas could lead to further adaptability of questions in our course. Additionally, we propose an expansion of the analysis to additionally include a more objective method as proposed by Redman et al. [15]. This is important to ensure the reliability and validity of the results, as well as to provide a more comprehensive understanding of the studied phenomena.

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