SEFI Journal of Engineering Education Advancement
Vol. 2, No. 1, 2025, pp. 142-180, ISSN 3006-6301
DOI : 10.62492/sefijeea.v2i1.35

Utilizing a Knowledge Based System with Design Heuristics for Sustainable Engineering Education

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ABSTRACT

This paper explores the integration of a Knowledge-Based Engineering System (KBES) for design heuristics to enhance sustainable engineering education. The primary goal is to equip students with the skills needed to develop sustainable products while comprehending the complexities and multifaceted nature of sustainability. As sustainability is highly context-dependent, the importance of utilizing context-specific knowledge in product development is emphasized. A key question addressed in this study is how digital tools can effectively provide and facilitate the sharing of knowledge critical for sustainability-oriented design. The paper also examines how to build competency in sustainability using design heuristics, which are easy to understand and apply, offering students a practical approach to sustainable problem-solving. By integrating KBE systems with these heuristics, this paper proposes a framework for engineering education that fosters a deeper understanding and actionable skills for developing sustainable products. This approach aims to empower future engineers to create solutions that are not only innovative but also responsible and adaptive to the complex demands of sustainability.

KEYWORDS

Sustainable Engineering Education, Knowledge Based Engineering Systems, Design Heuristics, Product Development, Knowledge Management

PUBLICATION

Submitted:
5th April 2025

Accepted after revision:
2nd June 2025

1. Motivation

Sustainability has become a defining challenge of the 21st century, requiring innovative approaches in engineering education to equip students with the knowledge to address complex environmental, societal and economic issues (Kamp, 2006; Lozano et al., 2017). Engineers play a central role in sustainable development, designing products and systems that minimize resource use and environmental impact while maximizing efficiency and social value (Mulder, 2006). However, integrating sustainability into engineering curricula remains a challenge, particularly when teaching students to navigate the multi-dimensional and context-specific nature of sustainable design (Lambrechts et al., 2013).

Current engineering education frameworks often fall short in providing students with methods to internalize sustainability principles and translate them into actionable design decisions (Byrne et al.,

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2013). Addressing this gap requires not only the inclusion of sustainability topics in curricula but also the development of digital tools that support knowledge organization, transfer, and application (Gutierrez-Bucheli et al., 2022). This paper focuses on the potential of Knowledge-Based Engineering Systems (KBES) utilizing design heuristics to meet these needs, offering a structured yet flexible framework to provide easy to understand knowledge to students while building sustainability competencies.

Problem Definition

The primary challenge in sustainable engineering education lies in enabling students to make well-informed design decisions amidst complex, context-dependent scenarios. Sustainable design requires the integration of diverse knowledge types, ranging from explicit guidelines to tacit insights gained through experience (Nonaka et al., 2000). Traditional education methods in engineering design focus on established explicit knowledge derived from research and providing it in lectures. Still this focus leaves gaps in students' abilities to apply sustainability principles in practice, as this practical knowledge on how to achieve sustainability goals is often strongly context dependent and not possible to (Chandrasegaran et al., 2013). In recent years a shift has been underway in engineering education, in which the curriculum included project-based learning approaches.

Lectures combined with project-based learnings showed better results in building competences of students. However, the knowledge provided to the students in these settings mostly did not focus on practical knowledge for achieving desired goals in product development but were rather general knowledge about tool usage or sustainability principles.

Digital tools, such as KBES, which are used in engineering practice, have the potential to address these challenges by organizing and providing access to structured practical knowledge that supports sustainable decision-making. These systems often leverage symbolic artificial intelligence methods to codify design rules, principles, and heuristics, allowing its users to apply them in real-world scenarios (Wang et al., 2022). It has already been investigated that the usage of KBES including design heuristics, experience-based rules of thumb, have positive effects on achieving sustainability goals (Kremer, Peters, & Stark, 2023). Moreover, fostering competency development in sustainability also requires mechanisms for capturing and sharing experiential knowledge. Design heuristics are particularly useful in this regard, as they are intuitive, adaptable, and aligned with natural reasoning processes (Yilmaz et al., 2016). However, while KBES are widely used in professional engineering contexts, their integration into educational settings remains underexplored (Narong & Hallinger, 2024).

This paper investigates how KBES utilizing design heuristics can be used to overcome these limitations, providing an educational framework that nudges students to use and internalize knowledge for sustainable product development. Specifically, it addresses the following research questions:

- How should design heuristics be modelled to enhance comprehension?
- How can students capture and share their experiential knowledge effectively though a KBES?
- Does integrating such a tool improve students' perceived competence in sustainable product design?

By exploring these questions, this study aims to contribute to both engineering education and sustainability research, offering insights into how digital tools can enhance engineering knowledge organization, transfer, and application.

Research Framework

The research paper addresses the need to provide students with easily understandable design knowledge to support sustainable product development, as highlighted in the introduction. Additionally, the study seeks methods for students to share their own expertise. Ultimately the study aims to assess whether the usage of a KBES will lead to higher perceived competences in the field of sustainable product development. The structure of the paper and the research framework can be found in Figure 1.

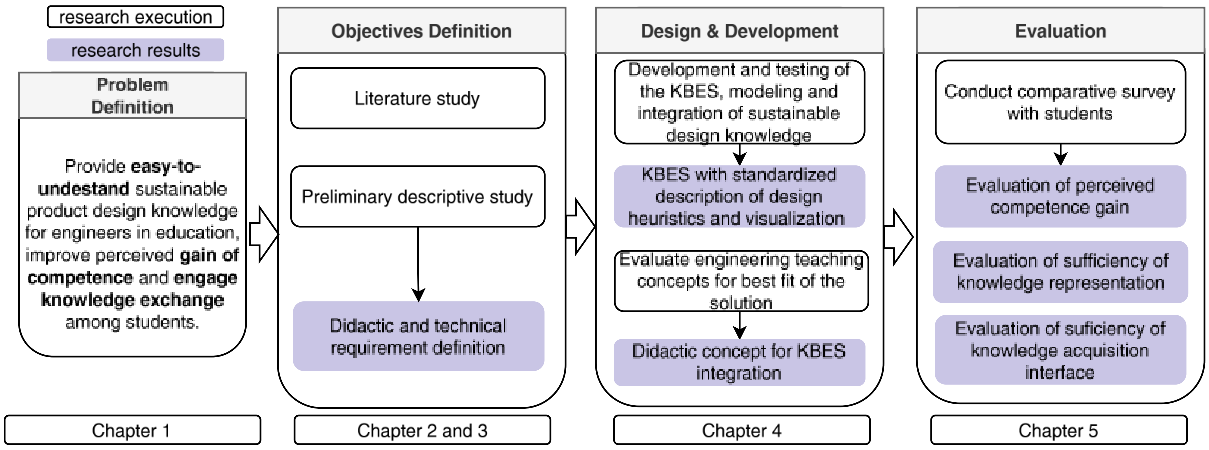

Figure 1: Depiction of the Research Framework and Corresponding Outline of the Paper

The research problem identified as the need for providing practical design knowledge on sustainable product development for students is introduced in chapter one. Chapter two provides the relevant technical background and current related scientific works, providing an overview of other researchers' efforts in sustainable product development, engineering education and knowledge-based systems.

In the third chapter, the requirements for the KBES are described based on insights gathered from interviews with product developers and engineering education staff. These interviews identify both technical and didactic requirements for the KBES and its integration into an educational framework. Additionally, requirements derived from other research are discussed, helping to contextualise the KBES within existing literature and practices. This section serves as a foundational step in defining the scope and direction of the developed tool.

Chapter four outlines the development steps leading to the creation of the KBES and an engineering teaching concept. It begins with a summary of the design and development phases. The chapter then presents the developed tool, and the didactic concept tailored for student engagement and learning.

The evaluation phase of the research is documented in chapter five. A comparative survey with students from different semesters, one in which the KBES is used and one in which it is not used, is conducted to assess the perceived gain in competence, the sufficiency of knowledge representation, and the usability of the KBES interface for knowledge capturing. The results are presented in relation to findings from other studies, offering insights into the system's effectiveness and relevance. This chapter also discusses derived insights, providing a detailed analysis of the study's outcomes in the broader context of knowledge provision for sustainable product development and education.

The paper concludes by summarising the findings and highlighting their implications for future research and practical applications in chapter 6. It also identifies potential ways to further enhance sustainable design education and support knowledge sharing within engineering practice. This final chapter aims to offer valuable insights not only for academic research but also for practitioners looking to implement similar tools in industry.

2. Theoretical Background and Related Works

In the following chapters the key concepts for the theoretical background are introduced as well as relevant related works of other researchers. The chapter starts with fundamentals about sustainability in engineering education. It will then present the importance of knowledge provision in product development as well as types of linguistic knowledge. This will form the basis for the final subchapter, in which the concept of KBES is introduced, together with a classification of different types of knowledge modelling within KBES and examples for sustainability focussed KBES of other researchers.

Sustainability in Engineering Education

In recent years, the integration of sustainability into engineering education has become a key focus to face the challenges of the modern world. Engineering is a discipline that sits at the interface between the needs of society and scientific knowledge and therefore plays a crucial role in promoting sustainable development. However, the incorporation of sustainability principles into engineering curricula is still evolving and in some cases in its infancy, with success varying by university and region.

A comprehensive overview of the research landscape between 1991 and 2022 highlights several key issues. One of the main needs is to reform engineering education to bring it more in line with sustainability goals. This includes defining precise competencies and ensuring that curricula meet industry standards and accreditation requirements. In addition, the study highlights the growing importance of including Industry 4.0 technologies as part of the sustainability agenda in engineering education (Narong & Hallinger, 2024; Hagedorn & Stark, 2025).

Another study looks at the role of engineering faculty and students and shows that while many students are aware of the challenges of sustainability, they often lack a holistic understanding of how these can be addressed in the broader context of societal and environmental needs. The study highlights the importance of developing in students a sense of personal responsibility for sustainability issues, particularly in areas such as sustainable energy and waste management. Engineering programs therefore need to foster not only technical skills but also an understanding of social and environmental responsibility (Wilson, 2019).

Further research on sustainability-focused curricula has also explored specific teaching methods, such as problem-based learning (PBL), to bridge the gap between theory and practical application. These methods encourage students to engage in interdisciplinary collaboration, creative problem solving, and ethical decision making - skills that are critical for tackling complex sustainability problems (Gutierrez-Bucheli et al., 2022).

Engineers play a central role in promoting sustainability as they are directly involved in the design, planning and implementation of technologies and infrastructures that optimize resource consumption and reduce environmental impact. Their responsibility goes beyond technical solutions and includes consideration of social, environmental and economic factors. Research emphasizes that engineers play a key role in promoting sustainable developments in various areas, such as the design of energy-efficient buildings, waste treatment and the management of water resources (Acero & Ramírez Cajiao, 2023; Gillings & Hagan-Lawson, 2014; Murphy et al., 2015).

Engineers also play an important role in the implementation of the UN Sustainable Development Goals (SDGs) by using technological innovations to reduce pollution, provide clean water and promote renewable energy (Kuhn, 2018)

In essence, engineers are not only technical problem solvers, but also important players in promoting sustainable change in society. They must therefore be prepared in their education to tackle complex sustainability challenges, which requires a deeper integration of sustainability topics into engineering education. While the integration of sustainability into engineering education has already gained momentum, much remains to be done. Educational institutions need to prioritize curricular reforms and pedagogical strategies that empower future engineers to take a leadership role in sustainable development by ensuring that they not only have technical expertise, but also a deep commitment to the social and environmental dimensions of their work.

Integration of digital platforms, AI and educational theories to strengthen design heuristics in sustainable engineering education

The challenges of sustainability education in engineering can increasingly be addressed through digital technologies, artificial intelligence (AI) and sound didactic models. In recent years, a large number of studies have been published that examine these areas and provide valuable insights for practical, skills-orientated training.

Digital platforms offer a high degree of flexibility and accessibility for sustainability content. E-learning systems, Massive Open Online Courses (MOOCs), interactive modules and virtual reality environments promote the understanding of complex sustainability topics through immersive, adaptable learning formats (e.g. Moodle, Blackboard, MOOC) (Gavrus et al., 2025; Xu, 2024) Increasing emphasis is being placed on the didactically meaningful design of digital curricula (Tsaldari et al., 2024). Concepts such as sustainable digital transformation at universities, which take into account the ecological footprint of digital teaching, are also gaining in importance (Mohamed Hashim et al., 2022).

KBES on the other hand can support students in project-based product development processes. KBES can not only automate specific tasks during the development by applying integrated expert knowledge via rules but also explain its actions based on optional explanation modules and hence support the learning process of students (Plappert et al., 2020).

In terms of educational theory, the use of design heuristics can be justified in particular by constructivist and experience-based approaches (Milovanovic et al., 2021). Heuristics encourage active engagement with design problems and promote creative problem solving (Yilmaz et al., 2016). Within project- or challenge-based learning formats (PBL, CBL), they offer a low-threshold but effective way of teaching sustainable design principles in an action-orientated way (Jin et al., 2021). Modern didactic frameworks focus on hybrid learning scenarios, self-regulation and adaptive feedback, which are areas in which digital platforms and heuristic-oriented systems work in synergy (Stripe & Simpson-Bergel, 2023).

Overall, the literature shows that the combination of digital learning environments, AI-supported knowledge management and approaches based on learning psychology offer promising opportunities to systematically promote sustainable design skills in engineering. Future developments could lie in the combination of AI-supported personalization, adaptive provision of design heuristics and collaborative knowledge transfer.

Design Knowledge in Product Development

Design knowledge serves as a fundamental asset in engineering. The effective use of design knowledge within product development not only helps to create sustainable solutions. It also drives innovation and helps designers achieve goals when creating products, such as cost efficiency or better customer satisfaction.

In engineering and product development, knowledge is typically categorised as either explicit or tacit. Explicit knowledge is structured, codifiable, and easily transferable, often documented in formal models, blueprints, or engineering reports. In contrast, tacit knowledge is embedded in individual experience and intuition, making it difficult to document and transfer. This distinction is critical in product development, where tacit knowledge, such as lessons from previous projects, often informs design decisions and problem-solving approaches that cannot be captured by formal rules alone.

The SECI model, introduced by (Nonaka et al., 2000), provides a theoretical basis for understanding the transformation of tacit knowledge into explicit knowledge and vice versa, forming a dynamic "knowledge spiral", depicted in fig. 2 together with the core research fields of this study.

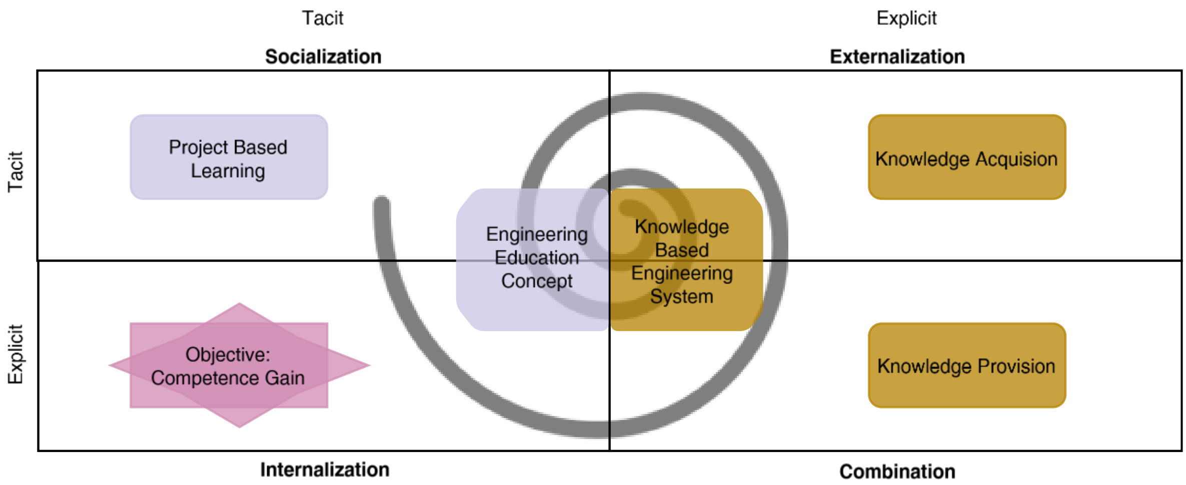

Figure 2: Own depiction of the knowledge spiral first introduced in (Nonaka & Takeuchi, 1995) including the role of this study's engineering education concept and technological support.

The SECI model (Socialization, Externalization, Combination, and Internalization) describes how organizations can foster knowledge creation through interactions and iterations. Socialization involves sharing tacit knowledge through direct interactions or in our case a project-based learning approach, while externalization captures this knowledge in a documented form. In our study we explore how this process can be supported through a knowledge acquisition module of a KBES. Combination integrates explicit knowledge from different sources, in our case lectures but also the existing knowledge integrated in a KBES, which is provided to the students. Internalization allows individuals to assimilate this knowledge, making it actionable in new situations, which is in our case the objective of gained of competence in the field of sustainable engineering. This iterative knowledge-sharing process is vital in both regular product development and engineering education, as it enables continuous improvement.

Recent studies have applied the SECI model specifically in sustainability-oriented engineering contexts and in education. For instance, (Liberona et al., 2024) explore how knowledge exchange processes change within a university that uses the SECI framework in education to address sustainability. This transformation allows sustainability practices to become embedded within an organization's culture, promoting a sustainable mindset across all levels of product development.

Additionally, (Klingenberg & Rothberg, 2022) highlight that fostering tacit knowledge sharing through the SECI model together with a cultivated "sustainability mindset" in a company improves sustainable outcomes in design decisions.

Nonetheless the concept of using a KBES for externalizing tacit knowledge of designers in engineering education to then provide it to new designers for them to combine and internalize the knowledge to gain new competences has not yet been investigated.

Linguistic Design Knowledge: Rules, Guidelines, Principles, and Heuristics

Design knowledge can be represented in different forms. It can be represented mathematically, which helps designers to optimize sustainability aspects of design and production as (Zamanloo & Mansour, 2023) explored in their research for sustainability optimized supply chains. Another form is the visual representation of knowledge, which is often used in the cases in which the knowledge receiver should be provided with knowledge fast and to spark creativity, as explored by (Ramanujan et al., 2017). Also, the physical representation of knowledge has been investigated by other researchers in engineering education. In this field (Sole et al., 2022) for instance explored whether the usage of physical prototypes and hence the additional use of resources could benefit the environment because students better understand sustainable product design knowledge.

This study on the other side will focus on linguistic knowledge. The linguistic form of knowledge, either written or spoken, requires the comprehension of its meaning. This means that to understand linguistic knowledge, the recipient needs to not only recognize letters and words but integrate its meanings in the context of their own already existing understanding of a situation f), which indicates that linguistic knowledge helps to internalize new knowledge (see the knowledge spiral). When formalized linguistically, knowledge is often described precisely to avoid misunderstandings between its users. At the same time studies emphasize the "underdetermination in linguistic communication", which results in the circumstance that linguistic knowledge needs to be interpreted and processed by its recipients individually which leads (Drożdżowicz, 2022) to suggesting that the usage of linguistic knowledge leads to the internal engagement with the topic and ultimately lead to creativity.

In product development externalized linguistic design knowledge is often differentiated in principles, guidelines, heuristics and rules (see fig. 3)

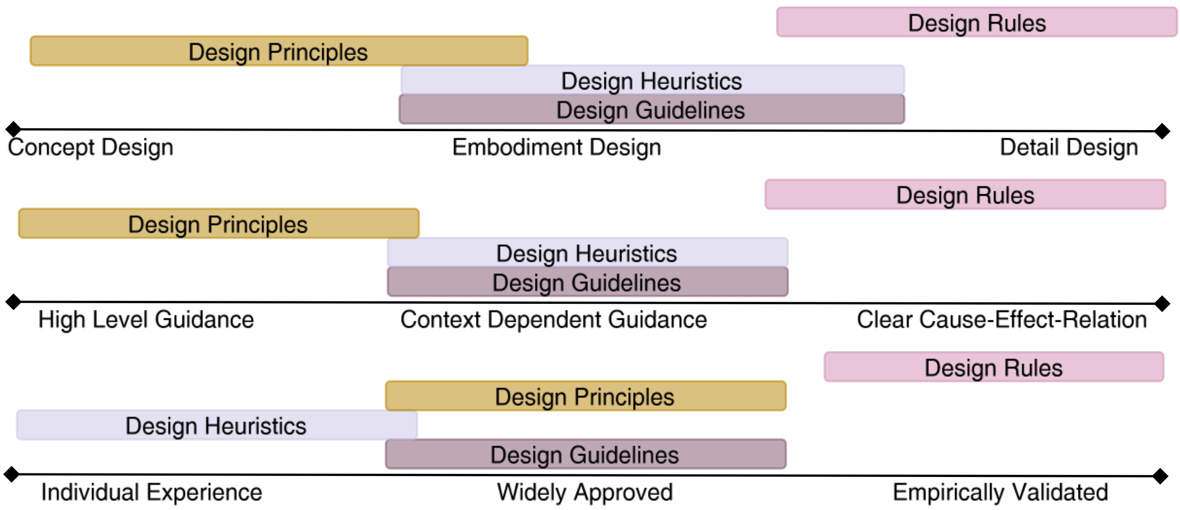

Figure 3: Classification of Linguistic Design Knowledge Based on Findings of (Fu et al., 2015; Ulrich & Eppinger, 2012)

These knowledge types can be understood as a spectrum, where rules are binding constraints, principles provide fundamental truths or directions, guidelines offer best practices, and heuristics suggest context dependent problem-solving techniques. Each level serves different functions in product development. Rules are structured approaches or strict constraints or criteria that must be followed to meet regulatory or safety standards. They are especially relevant in fields like the development of medical devices, in which the adherence to stringent standards and regulatory compliance is important (Christiansen & Varnes, 2009). Principles represent core design ideas, such as simplicity or durability, which guide overarching objectives in product development. For sustainable engineering, principles like "reduce, reuse, recycle" provide a foundation for eco-friendly design practices (Carey et al., 2021). Guidelines help designers to apply design principles and are less rigid than rules. They are often empirically evaluated or externalized in a written form. They suggest preferred practices or approaches, that are often differentiating from organisation to organisation due to their context dependence. Still, they are often shared on a general level as best practices for common objectives in product development. In this case they are often published as DfX (design for recyclability, assembly etc.). Especially in sustainable product design guidelines are often used to provide knowledge. An extraordinary broad set of examples for design guidelines for ecological sustainability can be found in (Vezzoli, 2018).

Heuristics, often described as "rules of thumb," are context dependent (like guidelines) and are used in the embodiment or detail design phase (like guidelines). But in contrast to guidelines, they are based on individual experiences and do not follow strict a formal empirical validation process. They provide practical guidance in uncertain or novel situations and are used on a near intuitive level. To reach this level of fast application, they are of formulated in an easy-to-understand way. Hence design heuristics were identified in this study to be important for providing knowledge to and share knowledge among students to achieve sustainability targets in product design.

Design Heuristics: Target-Oriented vs. Non-Targeted

Design heuristics can be classified into target-oriented and non-targeted heuristics. Non-targeted heuristics encourage creativity, making them an asset for designers dealing with complex, multifaceted challenges where predefined goals are not yet established. For instance, (Kramer et al., 2014) provided a set of 77 non-targeted heuristics on cards for students, aimed to come up with new ideas in design (see Figure 4).

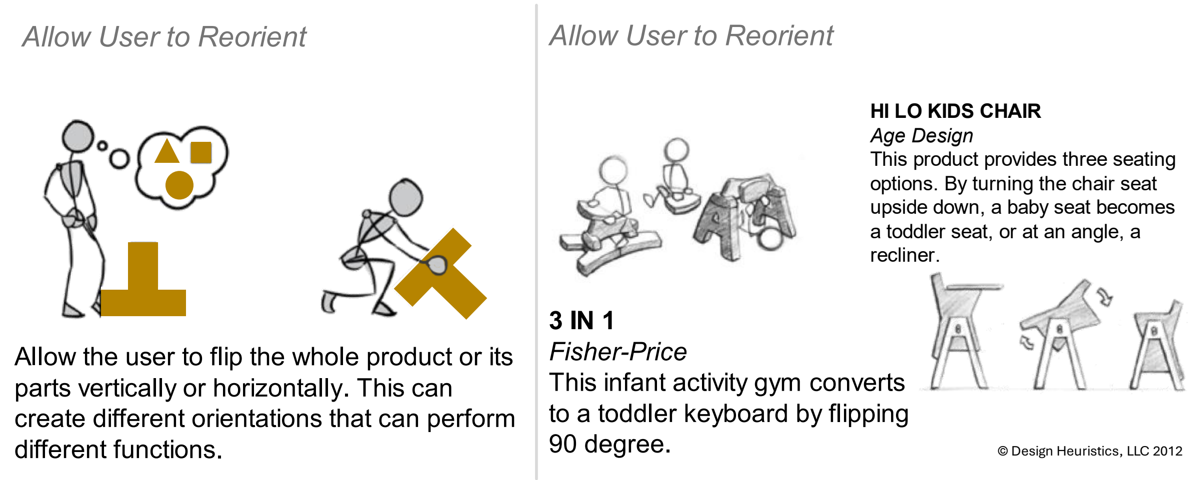

Figure 4: Example of non-targeted design heuristics by (Kramer et al., 2014)

The heuristics displayed in Figure 4 show an example of nontargeted or undirected heuristics. Instead of having a clear goal, e.g. reducing cost or improving the recyclability of a product, they rather give designers a new way of looking at the design. Therefore Yilmaz describes heuristics as “cognitive strategies for creativity in idea generation” (Yilmaz et al., 2016).

Target-oriented design heuristics are defined as “context-dependent directives, based on intuition, tacit knowledge, or experiential understanding, which provide design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution”(Fu et al., 2015). They focus on achieving specific objectives, such as minimizing waste, reducing energy consumption, or optimizing resource use. Both (Fu et al., 2015) and (Fillingim et al., 2020) emphasize in their research the importance of providing context in which the design directions when externalizing heuristic knowledge. An example from (Fillingim et al., 2020) in air and spacecraft here is “Use a nuclear power source”, which can only be seen with its context “if the mission is to an outer planet”.

Target-oriented design heuristics are particularly relevant for sustainable design, as they can target sustainability goals. Non-targeted heuristics, by contrast, are more general and aim to provide broader problem-solving strategies that are applicable across different contexts without specific outcomes in mind. Hence, only target-oriented design heuristics only are in scope.

Research on target-oriented heuristics has shown their effectiveness in achieving sustainability requirements in product design, where they provide users with actionable knowledge (Kremer, Peters, & Stark, 2023). In industry, target-oriented heuristics are perceived by engineers as helpful in developing new solutions, and are currently mostly based either own experience, derived from team studies or come from colleagues as (Fillingim et al., 2020) found out in a study in the domain of spaceship design, indicating the need for tools enabling to effectively capture and distribute heuristic design knowledge more widely than just the closest colleagues.

Knowledge Based Engineering Systems (KBES)

KBES are defined as “stand-alone applications, which are intended for engineering problem solving” by (Kügler et al., 2023) and can be seen as a specialized form of knowledge based systems (KBS) in the engineering domain. There are KBES, often those integrated in other engineering environments such as CAD systems, which are built to automate tasks, which is for instance explored in automated sustainable layout design (Ascheri et al., 2016). But our goal is not to automate product design tasks but to enable students to develop new solutions by providing them with the necessary knowledge to make informed decisions. Hence these types of KBES will be out of scope of this research paper. Instead we want to explore how KBES can be used for students and future product designers as assistant systems, hence systems that are “used to provide information to support employees [in our case: students] in their decision making process” (Stark et al., 2021).

KBS are software systems designed to mimic human expertise by utilizing structured knowledge to solve problems, make decisions, or perform tasks in specific domains. They are defined as systems that "use stored knowledge about a domain and inference mechanisms to solve problems that require expertise" and include “all those organizational information technology application that may prove helpful for managing the knowledge assets of an organization, such as expert systems, rule based systems, groupware, and database management systems” (Liao, 2003). KBS have their origin in the early phases of AI development with systems like DENDRAL (Lindsay et al., 1993) or MYCIN (Shortliffe, 1974), showing how knowledge of experts in domains can be encoded in software to provide others with knowledge. KBS started as highly specified systems. MYCIN for instance was strictly specified for selecting the correct antibiotics for certain infections. But through the new combination of reasoning approaches (rule-based, case-based, constraint-based etc.) and knowledge representation techniques (frames, semantic networks, etc.) KBS were able to handle more and more complex domains over time (Randall et al., 1993). In the engineering domain KBES, as a specialized form of KBS were first introduced in the 1980s and since then support various tasks ranging from direct activities such as design automation to supporting indirect activities such as financial assessments (Stark, 2022)

KBS have a generalized architecture as depicted in Figure 5 closely linked to knowledge management activities.

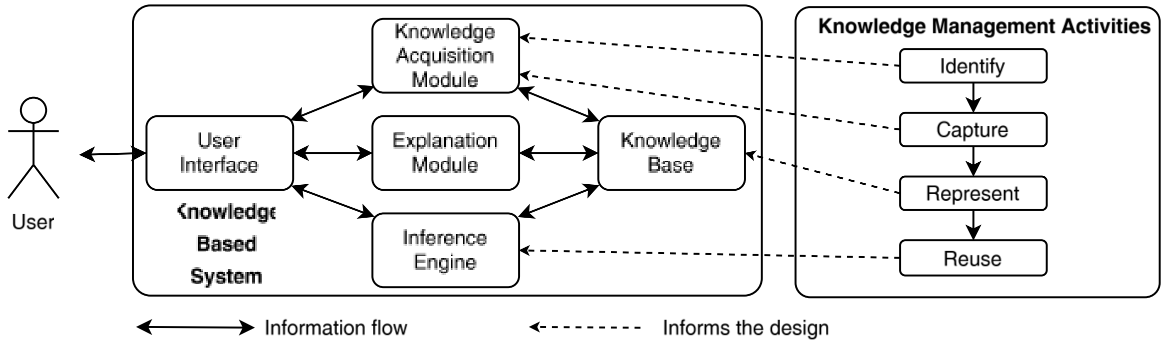

Figure 5: Depiction of the relationship of KBS components and knowledge management activities based on combined architectures of (Ayde Ergado, 2016; Li et al., 2011)

The knowledge base is the core repository of the KBS, storing domain specific knowledge in different representational forms. The inference engine is the component that applies reasoning techniques, such as case- or rule-based reasoning to derive conclusions or make decisions based on the context information it is given over the user interface by the user. The user interface in today's KBS often include graphical user interfaces (GUIs) e.g. explored by (Sipos, 2020) and natural language processing (NLP) as applied by (Besharati Moghaddam et al., 2024) for better usability. Some architectures for KBS also include learning modules or knowledge acquisition modules, which are used for integrating new knowledge or modifying existing knowledge. Furthermore, some KBS architectures also include explanation modules, often emphasized in KBS application context, in which the decisions of the KBS have a high impact, for instance for the usage of materials and its effect on the sustainability (Narjabadifam et al., 2022).

Knowledge Modelling for KBS

Knowledge modelling is the process of structuring and formalizing knowledge to be used in KBS and enable the user to capture, organize and apply domain-specific knowledge. To model the knowledge first the form of representation of knowledge needs to be determined.

(Scharei et al., 2020) developed a taxonomy for knowledge representation languages in which they differentiate between knowledge-based and logic-based representations in symbolic AI systems. The knowledge-based model language in the taxonomy consists of semantic graphs, such as petri-nets. Basic graph representations, solely focussing on representing real world systems, only mirror the systems in a processable format, and do not enable probabilistic analyses and reasoning processes. Logic-based representations, on the other hand, enable reasoning in KBES and consist of different types of deterministic models, like description logic, propositional logic and first order logic models. A propositional logic model is the most basic form of model and only verifies if a property is fulfilled or not. In the domain of sustainable product development, this would be the case if a KBS only states if a certain material is recyclable or not. First-logic models extend propositional logic models with functions and terms and by that allow simple reasoning by rules. An example for a simple first-logic model could be the rule that, if a component is made of recyclable material, then it is sustainable. When the material of a component is then defined as recycled, the KBS could state that the component is sustainable. Description Logic models extend capabilities of first-order logic models by representing semantic connections between its elements and therefore include conceptual representations of the real world in reasoning processes. An example for this would be, if an ontology was built based on the structure of a product to assess its sustainability.

To store knowledge that is represented in a knowledge language, it needs to be transferred in a knowledge representation scheme. Common knowledge representation schemes are frames, semantic networks, rules and constraints (Mabel & Selwyn, 2016). In Figure 6 the described knowledge representation languages and connected knowledge representation schemes are depicted.

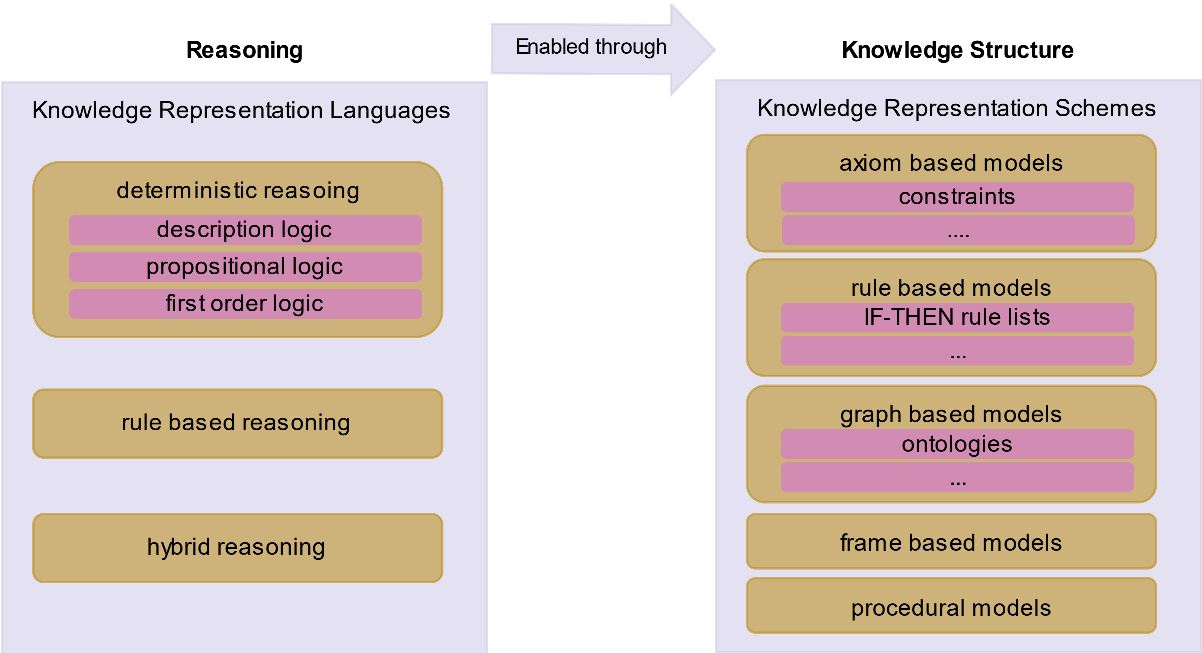

Figure 6: Depiction of the reasoning concepts and knowledge structures in knowledge modeling for symbolic AI systems

Frames structure the encapsulated knowledge by including properties and associated values (Ringland, 1988). An example for that could be the storage of information of LCA data of a certain product in a document-based database. A semantic network on the other hand stores the knowledge in a graph-based structure. This would be the case, when product-related information is stored together with the LCA data in a graph-database.

Integration of subsymbolic AI and other trends in KBS

AI can be divided into symbolic and subsymbolic AI. Classic KBS are based on symbolic AI, meaning that the knowledge is modelled in structured formats like rules, frames, or ontologies (L. Zhang et al., 2022). But also the usage of structured representations of knowledge derived from statistical analytics, such as decision trees, can be seen as KBS with symbolic AI (Patalas-Maliszewska et al., 2022). Subsymbolic AI, on the other hand, leverages data driven algorithmic paradigms like supervised, unsupervised or reinforcement learning often together with complex architectures such as convolutional neural networks (CNN). There are certain algorithmic paradigms and architectures that are transparent and explainable like creating decision trees from supervised learning, in which the importance of features for defining a certain label is analysed. An example for that can be found in the research of (Satinet & Fouss, 2022) in which they analysed the importance of clothes characteristics on their overall ecological impact. While the creation process is based on subsymbolic AI, the usage of the knowledge can be seen as symbolic AI. Other more complex architectures such as CNN on the other hand are used for more complex tasks such as computer vision tasks, which can be used for assisting tasks like the detection of wear, ultimately leading to longer usage times of products (Walk et al., 2023). Subsymbolic AI is mostly used when there is a lot of data and the patterns are complex, like in the case described in predictive maintenance. In sustainable engineering, subsymbolic systems have shown promise in predicting environmental impacts by analysing historical data on material use, energy consumption and even predicting multiple properties in life cycle assessments (LCAs) as shown by (Koyamparambath et al., 2022). However, subsymbolic AI’s reliance on data-driven pattern recognition limits its ability to explain its decision-making processes clearly, posing challenges for applications where transparency is essential.

Because of the strengths of subsymbolic AI in data-driven insights, and the strength of symbolic AI in structured, explainable decision support, latest research explores how both types can be used complementary, which is called hybrid AI. An example can be found in the assistance system developed by (Zhu et al., 2022) for the maintenance, repair and overhaul process of turbine blades, in which both a supervised learning model was used for the analysis of historical data on maintenance decisions as well as expert rules, constraining the decisions. In general, the area of explainable artificial intelligence (XAI) as a research area is growing. The area is not solely limited to providing the knowledge in a symbolic format but providing explanations in easy to understand visual support like heat maps (Roussel, 2024) or sunburst charts (Kremer et al., 2024).

3. Research Gaps, Preliminary Work and Objectives

As depicted in the previous sections, there is the need to provide designers and students with knowledge to help then design sustainable products. Linguistic knowledge provides enough freedom to develop new creative solutions while at the same time transport valuable insights from others. Heuristics are a form of linguistic knowledge that is often when experiential knowledge is transferred among people due to its easy understandability and its objective to reach desired targets. From an IT point of view, we can provide knowledge to people by KBS, when its addressing needs for engineers by KBES. These systems have reasoning capabilities by leveraging knowledge representation languages and fixed representation schemes of encapsulated knowledge. From a research perspective a KBES leveraging design heuristics could help designers reach targets in sustainable product design and could enable them to store own knowledge to provide it to others. Due to the internalization of this new knowledge students could improve their competences in sustainable product design when using the KBES additionally to classic engineering education concepts.

A literature review on the topic was conducted in the SCOPUS database with the strings:

TITLE-ABS-KEY (("Design Heuristic*" OR "Heuristic* in design" OR "cognitive heuristic*" OR "heuristic*") AND ("Product Development" OR "product design" OR "engineering design" OR "product creation" OR "product manufacturing") AND ("KBE" OR "KBES" OR "KBS" OR "knowledge based engineering" OR "knowledge-based engineering" OR "knowledge based engineering system*" OR "knowledge-based engineering system*" OR "knowledge based system*" OR "knowledge-based system*" OR "expert system*" OR "knowledge modelling" OR "knowledge modeling"))

Only 33 papers were published after 2016. The abstracts of these 33 papers were analysed. From the 33 papers only four papers were considered relevant for the conducted research. The rest of the papers issued heuristic approaches in machine learning or were papers by one of the authors. In none of the 4 papers analysed in detail, a KBS that utilized design heuristics was developed. Only 1 of the papers (X. Zhang et al., 2020) mentioned the potential usage of design heuristics in a generalized framework for KBS that includes rules and model-based methods for sustainability assessment of products. Only one of the papers conducted an evaluation of the usage of design heuristics. In it (Restrepo et al., 2018) found out, that methods including design heuristics improve the innovativeness of products and lead to a larger variety of results in the concept design phase. Only one of the papers was issuing engineering education. In it (Narayanan & Murthy, 2022) proposed a framework for engineering education, that also utilizes heuristics to provide knowledge to students. In their publication they argument that especially young designers and students can not envision a big solution space of possible design solutions and hence need this heuristic knowledge of others for expanding their view on possible solutions.

Preliminary Work

The research team conducted a descriptive study with 26 semi-structured interviews with both experienced product developers and academic educators. Through the interviews key requirements for a standardized notation for design heuristics and for KBES functionalities were derived and published. In (Kremer et al., 2022) the authors developed a standardized notation of design heuristic incl. tags for heuristics (e.g. applied in which industry, standardized sustainability effects such as recyclability or durability). In (Kremer, Peters, Bingoel, et al., 2023) a catalogue of required functions of the KBES such as search-, filter-, comment- or rate functions was presented. In (Kremer et al., 2024) a visualization was conceptualized, consisting of a dynamic sunburst chart combined with a heat map to visualize potential positive and negative effects of design heuristics on sustainability aspects of products.

Still, there existed a significant research gap in how to model the heuristic knowledge to integrate heuristics in the KBES and enable the conceptualized visualization. Also, it was still open how to design the knowledge acquisition module in a KBES which enables students to capture their own experiential knowledge for next generations of students. Furthermore, it has not yet been analysed how to integrate a KBES in engineering education and whether it will contribute to the perceived competence gain of students.

Research Objectives

The first research objective was to conceptualize a knowledge modelling approach that enables a good comprehension of design heuristics for users. Based on the concept, the objective included the development of the KBES including the design of a knowledge acquisition module. The second objective was to develop a concept for engineering education that includes the usage of the KBES. The third objective was to evaluate the usage of the KBES. The evaluation was aimed at validating whether the knowledge modelling approach enables designers to understand the heuristics properly and if the knowledge acquisition module enables the designers to capture their own heuristic design knowledge. Moreover, it should be evaluated whether the usage of KBES improves the gain of perceived competencies of students.

4. Design and Results

The following section conceptualizes how heuristic design knowledge can be represented within the KBES. The goal is to ensure that heuristic knowledge is structured efficiently while also being comprehensible within the KBES. Subsequently, key elements of the tool will be introduced based on selected components of the user interface. Also, the concept for integrating the KBES into university teaching will be presented.

Knowledge Representation of Design Heuristics and Development of the KBES

Based on the scientific foundation and the results of the standardized description for design heuristics derived from the interview study in (Kremer et al., 2022), a knowledge modelling approach was developed to ensure the clear representation of heuristics. Beyond only providing design heuristics as a collection, an inference mechanism was required to support the functions, such as searching, filtering and visualizing, as specified in (Kremer, Peters, Bingoel, et al., 2023). To support all required functions, a descriptive logic approach combined with an appropriate representation scheme was implemented, which is shown in Figure 7.

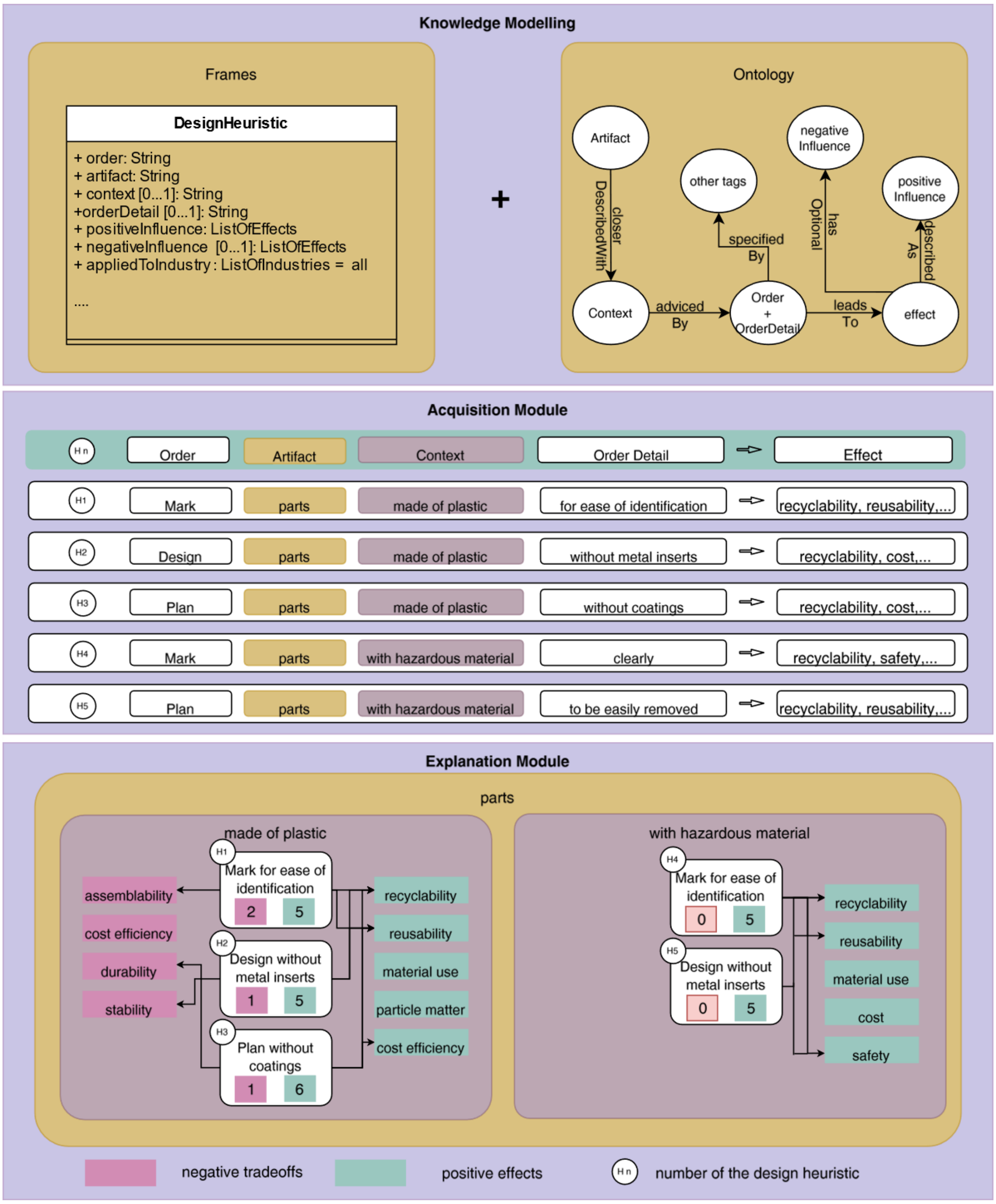

Figure 7: Depiction of the developed knowledge modelling approach and corresponding implication for acquisition and explanation module

A frame-based approach was selected to provide the necessary additional information on heuristics. This approach includes all supplementary details identified in the interview study that enhances the usability of presented heuristic knowledge. To improve the presentation of relationships between heuristics, a lightweight ontology was also developed. This ontology contains both the syntactic elements of the heuristics and their associated effects. Many KBES are solely depending on ontologies and do not include the frame-based approach described here. However, in the KBES in our case, users should be able to capture their own experiential knowledge. Hence, the elements, the individual heuristics are composed of, cannot be predefined before the KBES is in usage. This variability arises from the highly individualized nature of heuristic formulation by users.

By combining these representation forms, all required functionalities could be implemented, allowing users to compare heuristics in a detailed view. Additionally, this modelling approach enables seamless input of new heuristics without requiring modifications to the ontology, as it serves only as a foundational framework. Instead, new heuristics can be quickly recorded using the frame schema.

Following the knowledge representation development, the KBES, including all desired functionalities, was implemented. Moreover, over 400 heuristics were collected from literature and converted into the standardized description format. Figure 8 shows the architecture of the KBES including the used frameworks.

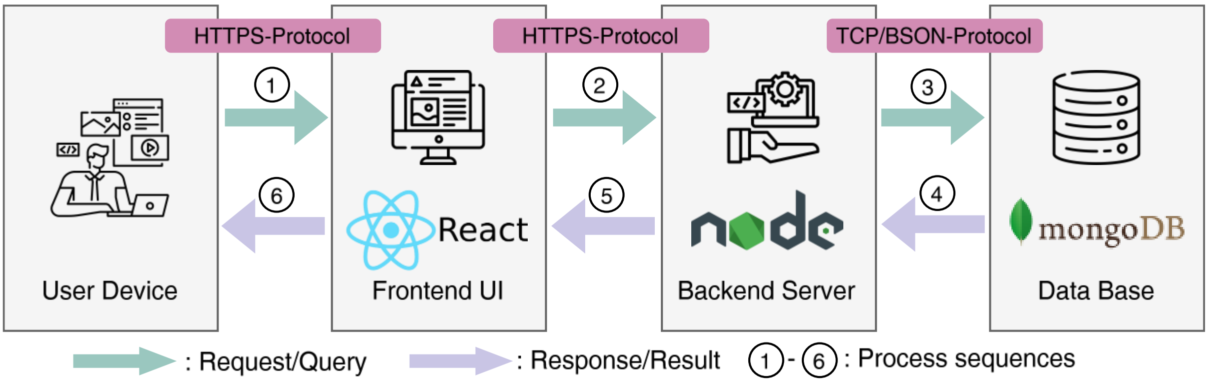

Figure 8: Architecture of the KBES including frameworks and protocols

The choice of frameworks followed a structured evaluation. On the front end, React was preferred over Angular, Vue and Svelte because its large community, frequent updates and the availability of React Native offer a reliable evolution path and strong support, whereas competing frameworks either impose a steeper learning curve or still suffer from limited ecosystems. On the server side ExpressJS emerged as the most suitable partner for React: it shares the JavaScript runtime with the front end, and unlike Django, Laravel or Ruby on Rails, it fits naturally into the standard MERN constellation that includes MongoDB as the database. MongoDB itself was selected because its document orientation fits the highly variable, tag-rich heuristic frames, while its built-in full-text search and horizontal-scaling options satisfy the functional requirements identified in the preliminary interviews. All traffic that crosses trust boundaries is TLS-encrypted (HTTPS between browser and React assets, HTTPS between React and the REST API). The internal link between Node and MongoDB can remain on plain TCP inside a protected network segment.

The code of the developed KBES is publicly available (Kremer & Bingoel, 2023).

Workflow and Key Components of the User Interface

A typical workflow of a student searching for new knowledge or capturing own knowledge is depicted in Figure 9 .

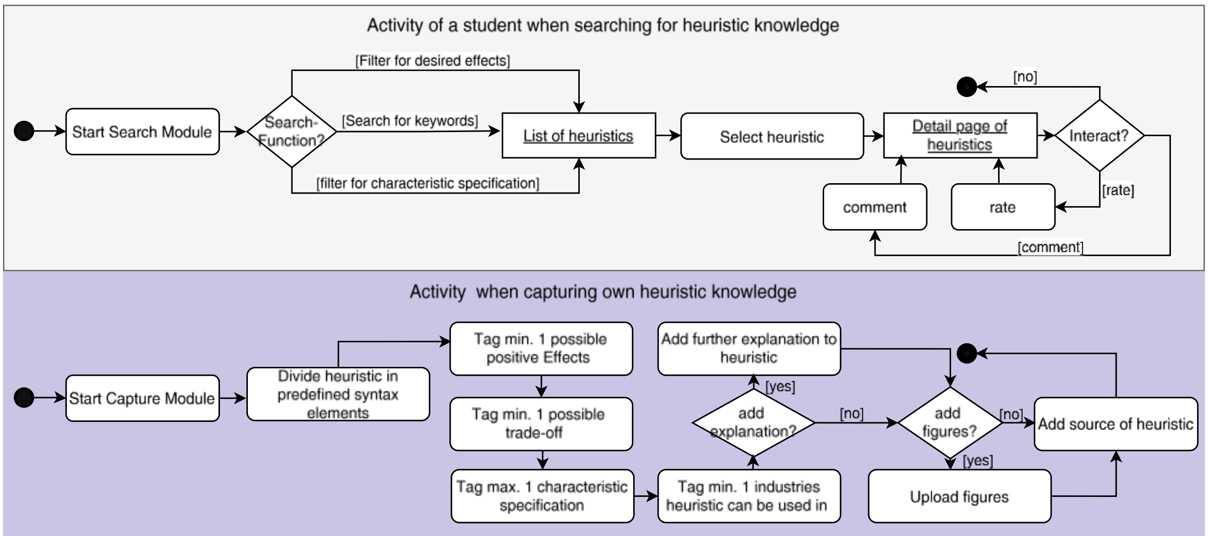

Figure 9: Activity diagram of users when searching for/capturing heuristic knowledge

In the main view of the KBES, users can filter heuristics. These filtering options are enabled by the tags defined in the description standard. This allows users to filter heuristics based on desired effects or the classification of the respective product characteristics (e.g., geometry, material). The heuristics are displayed in a list view as concise design advice statements. Moreover, users have the option to search for strings in a heuristic. When users click on the statements, they are directed to a detailed view, illustrated in Figure 10 (left) . Additionally, users can contribute their own heuristics via the knowledge capture module, which is depicted in Figure 10 (right).

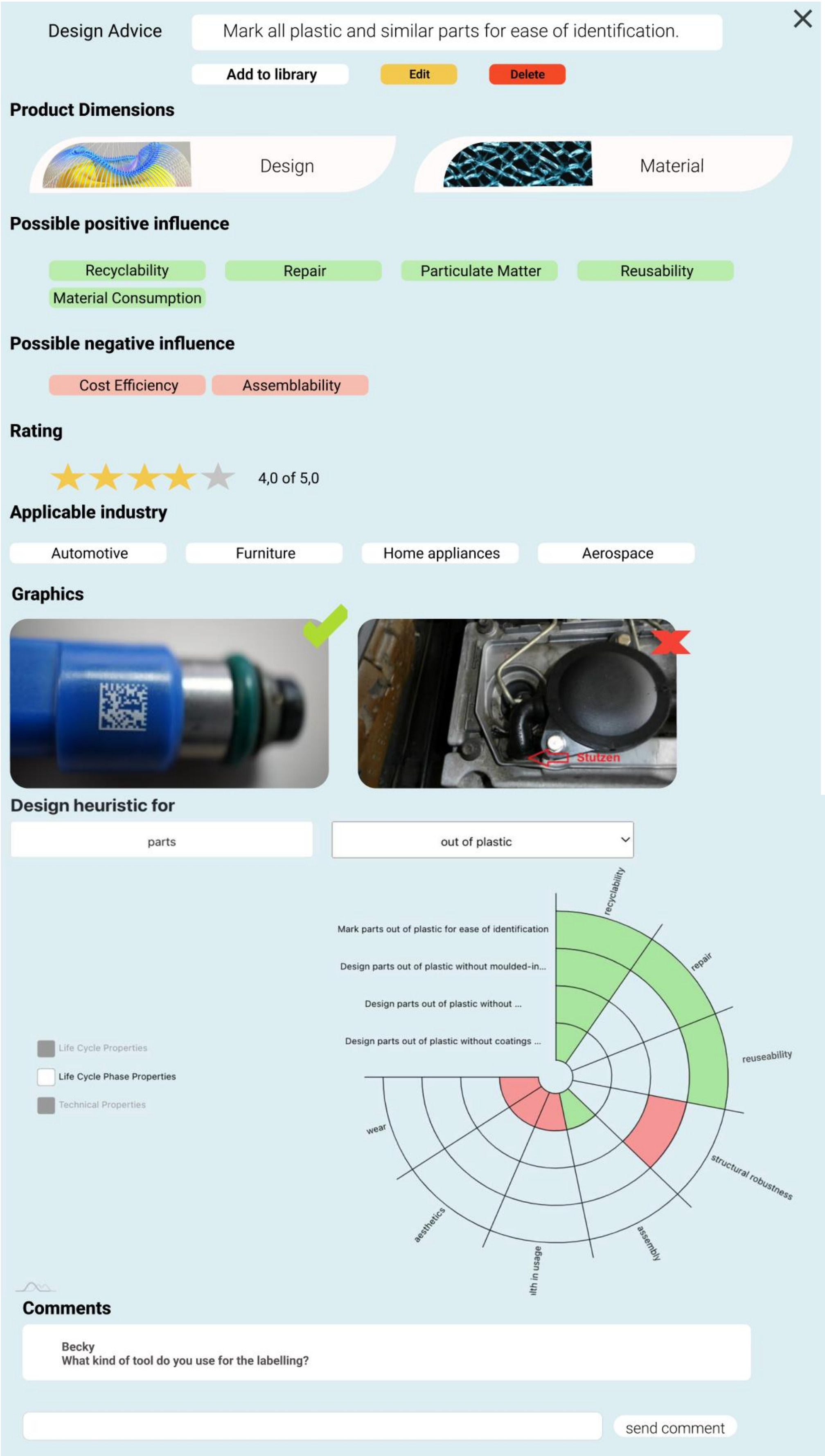

Figure 10: Screenshots of the User Interface Design to Display Specific Design Heuristics

In the detailed view, the heuristic is first presented as a short sentence. In Figure 10 an example view of the heuristic “Mark all plastic parts for ease of identification”, which shows positive effects on the recyclability, repairability and reusability but could potentially have trade-offs regarding cost efficiency. Users then see the potential positive and negative effects associated with the heuristic, along with the selected tags. Furthermore, an optional, more detailed description and images illustrating positive and negative examples of heuristic application are available. Additionally, a dynamic visualization is provided, allowing users to explore other heuristics related to the same product feature and context, which is based on the logic described in the ontology. The sunburst chart with an integrated heat map displays the effects of these heuristics, enabling users to compare them effectively. Moreover, users have the option to rate and comment on heuristics.

To enable students to integrate own heuristic knowledge into the KBES, a knowledge capturing module was developed within the KBES. Over an template based UI, students were able to capture own knowledge based on the developed standardized description of design heuristics. A screenshot of the module can be found in Figure 11.

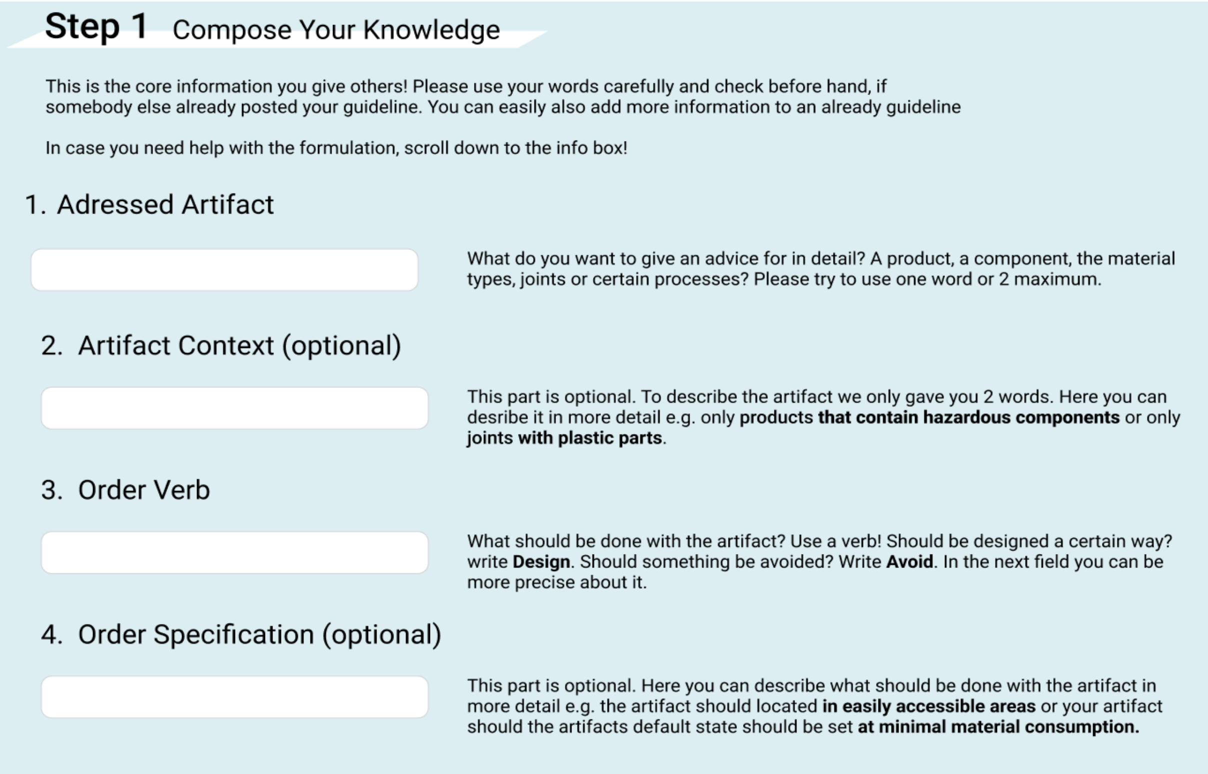

Figure 11: Screenshots of the User Interface Design to Capture Own Design Heuristics

The knowledge capturing module guides users through the process of adding new heuristics. Due to the structured knowledge modelling approach, users must decompose their design heuristic into different components. The specify the product component, the context of the component, and then their design recommendation. Next, they define the effects of their heuristic, select the relevant tags, and optionally upload images or an explanatory text to support the understanding of their design heuristic.

Teaching Concept & Use Case

The project seminar in this form has been offered at the department since October 2017 and has been continuously developed over the last five years. It has been constantly adapted to current events, the learning needs of students and the didactic insights of lecturers. The aim of the seminar is not only to impart specialist engineering knowledge, but also to promote students' ability to integrate knowledge and strengthen their cooperation in interdisciplinary teams.

The teaching concept was designed to support active engagement with design heuristics and promote sustainability competencies among engineering students. The intended learning outcomes included: (1) understanding the role of design heuristics in sustainable product development, (2) applying heuristics to real-world design problems, and (3) reflecting on design decisions in light of environmental and societal impacts.

The assessment criteria were derived from these results and included the clarity and creativity of the proposed solutions, team collaboration, the consistent application of sustainability methods in concept development and implementation, the ability of students to justify their decisions in reflective reports. Evaluation by the participants and feedback from the lecturers were also part of the assessment process. The students also had to evaluate each other as part of the second design review and compile a lessons learnt about their work at the end.

The learning outcomes are explicitly aligned with sustainability competencies as defined by UNESCO and the EUR-ACE framework (Tsaldari et al., 2024). Specifically, the course aimed to foster systems thinking, anticipatory thinking, collaboration, and normative competence. Challenge-based learning tasks, combined with digital heuristic tools, offered authentic learning environments for developing these competencies.

The iterative use of the KBES within a real design project allowed students to connect heuristic knowledge with concrete sustainability goals, thereby reinforcing the integration of digital, creative, and sustainable thinking in engineering education.

Each project team is made up of 8-9 students and goes through the entire product development process - from the initial idea to the implementation of a functional prototype. The approach largely follows the methods commonly used in industry. The students have different technical backgrounds and are enrolled in one of two modules, both of which are part of the engineering master's programs at TU Berlin. While the *Development and Management of Digital Product Creation Processes* (EMP) module focuses on management, the *Applications of Industrial Information Technology* (AIIT) module concentrates on technical development.

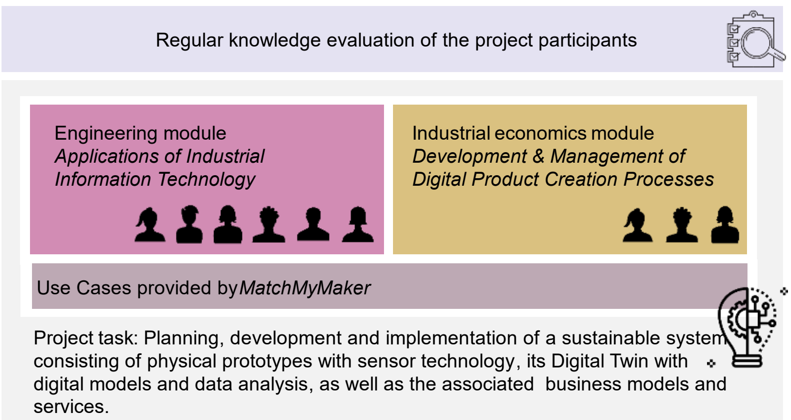

Figure 12: structure of the project

By combining both modules in a joint Problem-Based Learning (PBL) approach (see Figure 12), students are given the opportunity to learn about the challenges and interactions of different tasks, interests and priorities in real product development projects in industry. The closeness to reality is achieved above all through the cooperation with the NGO *MatchMyMaker*. This non-profit organisation works with disabled and sick people who have a specific problem that cannot be solved by the standard healthcare system. Particularly difficult problems were passed on to the department and a solution was developed together with the students as part of the semester project. This also involved working with real clients.

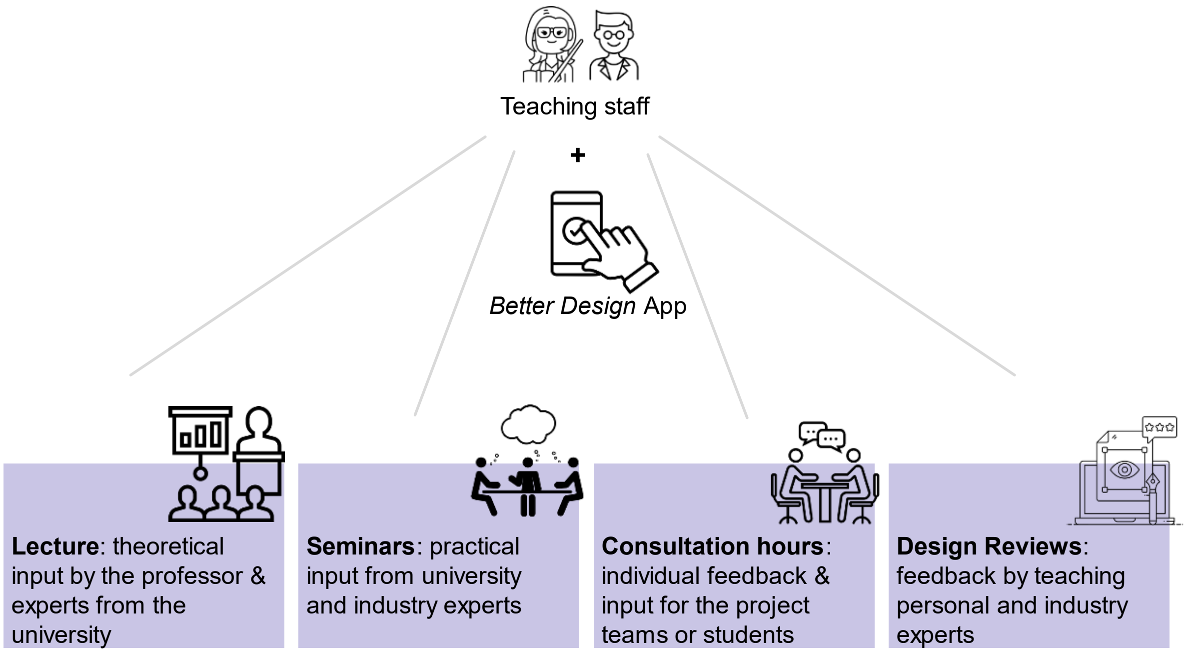

Figure 13: Depiction of the Teaching Concept

The technical input for the project was provided to the students both by the teaching staff and by specialists from industry. **Error! Reference source not found.** illustrates the structure of the seminar and the integration of the *Better Design app*, which was the name the developed KBES was called. During a seminar session, the app was introduced to the students and its functionality explained. They were then given a practical introduction to using the app in a short application scenario. The decision to use the app during the project was left up to the students.

During the semester, the knowledge and methodical application of the project participants was regularly evaluated.

5. Evaluation

In the following chapter the evaluation is described. It starts with a description of the evaluation design. Then the demographic of the survey is described. Afterwards the results will be presented and discussed.

Evaluation Design

The evaluation was conducted across two consecutive winter semesters (21/22 and 22/23) at the Technische Universität Berlin. The study focused on students enrolled in the courses "Application of Industrial Information Technology" (AIIT) and "Development and Management of Digital Product

Development Processes" (EMP). Both courses required students to collaboratively design products with a strong emphasis on sustainability and inclusivity for individuals with disabilities.

Surveys were conducted at the beginning and end of each semester. These surveys aimed to assess students' perceived own competence and evaluate the usability of the acquisition module, the usage objective of the KBES and the understandability of the provided design heuristics. In the winter semester 21/22 students did not use the KBES, serving as the control group. The surveys focused on self-assessed competence in areas such as sustainable product development and user-centred design. In the winter semester 22/23 students were introduced to the KBES through a detailed presentation and tutorial. The surveys assessed the same competence areas as the control group but included additional questions on the usability of the KBES acquisition module and the sufficiency of the knowledge representation. Furthermore 16 semi structured interviews were planned with four students from each project working group.

Demographics

In the winter semester 21/22 51 students participated in the course and took part in the first journey. 49 students finished the course and took part in the final journey. 43 of the participating students that finished the course provided consistent identifiers to track individual competence gains. From these 43 students 77,55% were male and 22,45% were female. In the winter semester 22/23 28 students participated and finished the course and took part in the surveys but only 21 provided consistent identifiers resulting in only 21 students for the assessment of competence gain. Still, all 28 that conducted the final survey were integrated in the assessment of the effectiveness of the knowledge representation and the usability of the knowledge acquisition module. From the 28 students 78,57% were male and 21,43% were female. The inserted matriculation number served as the identifier.

In the qualitative interviews only 14 out of the 16 requested students arrived at the interview appointments. The background of the students interviewed will be shown together with their answers in the result section.

Results

The survey results offer insight into the sufficiency of the KBES regarding the understandability of provided design heuristics enabled through the KBES, the ability to capture and share own experiential knowledge, and the overall impact on perceived competence. The results for knowledge representation can be found in Figure 14.

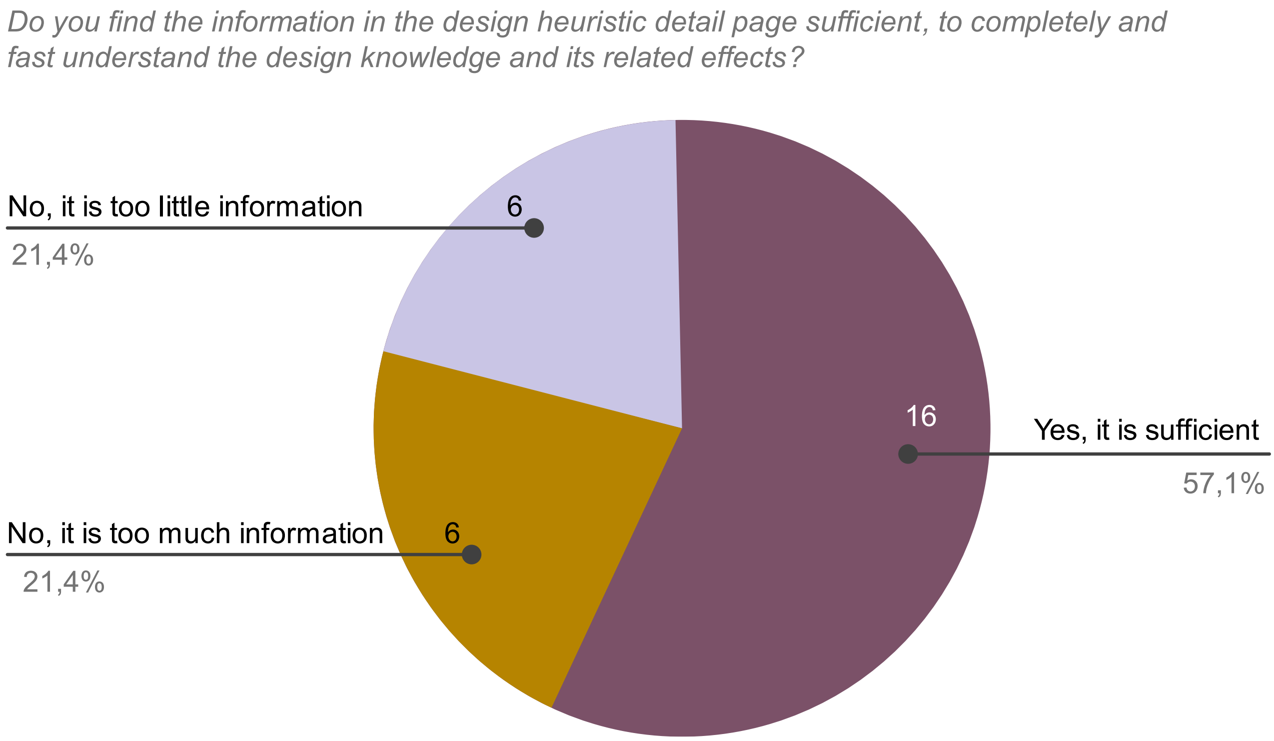

Figure 14: Evaluation of the Sufficiency of Knowledge Representation for Understandability

Most students (57,1%) stated that the information provided on the detail page is sufficient for understanding the knowledge fast and complete. The minority found it was either too little information or too much information, indicating that they either do not completely or fast understand the provided knowledge.

In Figure 15 the evaluation results of the knowledge acquisition module can be seen.

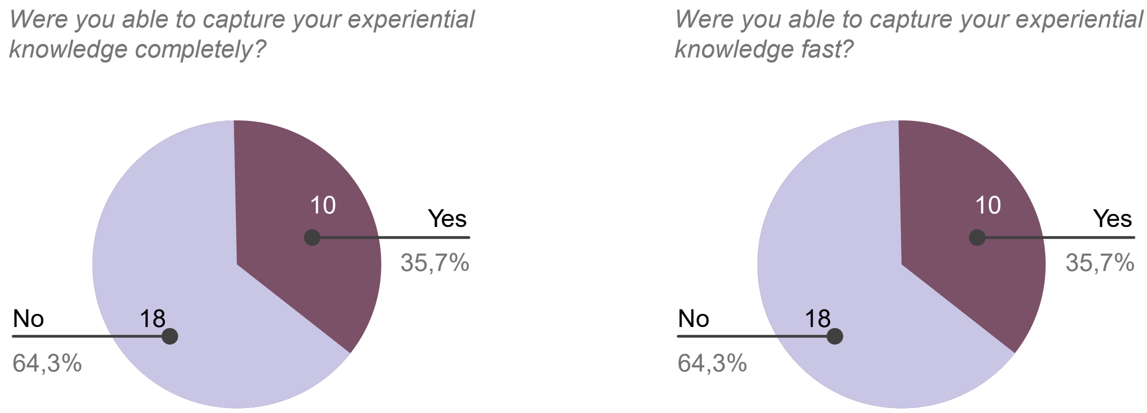

Figure 15: Evaluation of the Knowledge Acquisition Module

The functionality, which allows students to capture and share their own heuristics, revealed mixed results regarding its effectiveness. Most students (64,3%) stated that they could neither completely capture their own knowledge nor was it fast to capture the knowledge. Only a minority of 35,7% stated the opposite.

Students also answered their preferred input methods for their own experiential data. The 28 questioned students here had the options to vote for multiple modalities. The results can be seen in Figure 16.

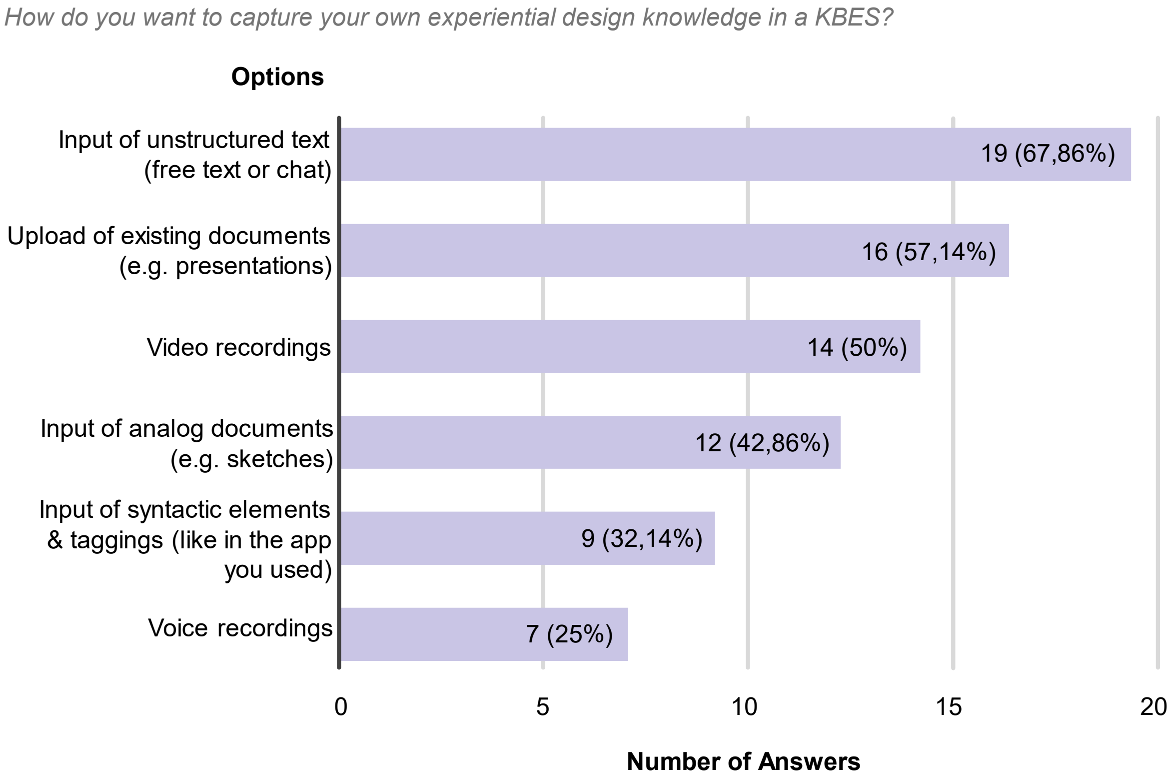

Figure 16: Preferences in Modalities of Knowledge Capturing in a KBES

When asked about their preferred methods for documenting experiential knowledge, most students expressed a clear preference for either input of free text formats (unstructured text input) or the upload of already existing documents like meeting notes or presentations. The way the knowledge capturing module was designed was seen as nearly the least favoured option with only 32,14% voting for the option.

Competence gain was measured in three areas: Product development, development of sustainable products, and user-centred product development. The students could rate their own competence on a scale from 1 (Topic unknown and never applied) to (Topic well known and applied). The results are shown in Figure 17.

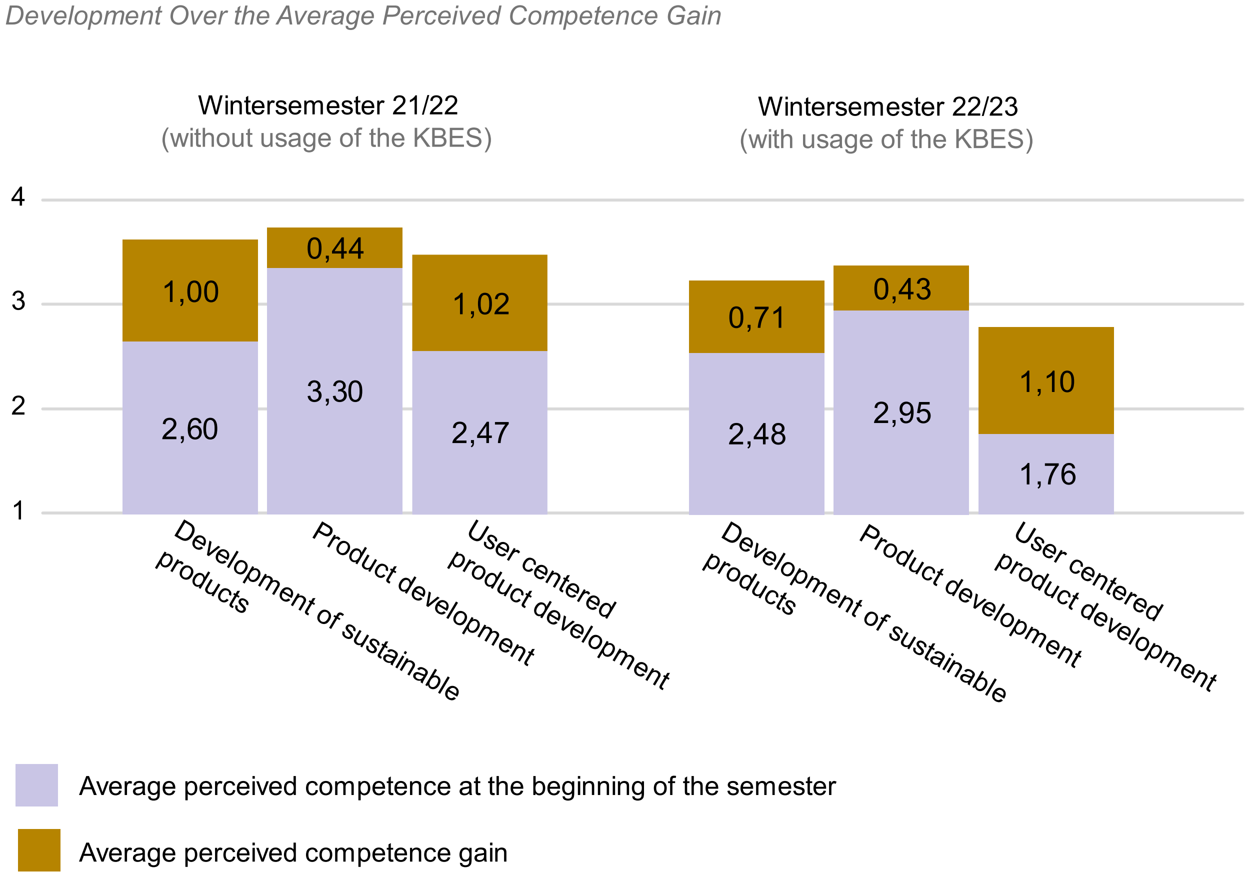

Figure 17: Average Perceived Own Competence in Different Areas of Expertise in Product Development

Competence gain was measured in three areas: Product development, development of sustainable products, and user-centred product development. The students could rate their own competence on a scale from 1 (Topic unknown and never applied) to 4 (Topic well known and applied). The mean competence gains in product development in WS 21/22 was 0,44 and in WS 22/23 0,43, so there was only a minimal difference of 0,01. Also, the competence gain in user-centred product development had only a small difference between the semesters of only 0,08 (WS 21/22: 1,02 and WS 22/23: 1,10). The highest difference in the competence gain was indeed in the field of development of sustainable products (0,29). The perceived competence level of students in WS22/23 was lower at the start of the semester the KBES was not used. But unlike assumed, the competence gain was significantly higher (1,00) in the semester the KBES was not used than in the semester it was used (0,71). Since the KBES focused primarily on this aspect, this result is unexpected and will be discussed in detail in the following chapter.

Due to the usage of identifiers, it was possible to measure the transition of individual perceived competence levels. All transitions can be seen in Figure 18.

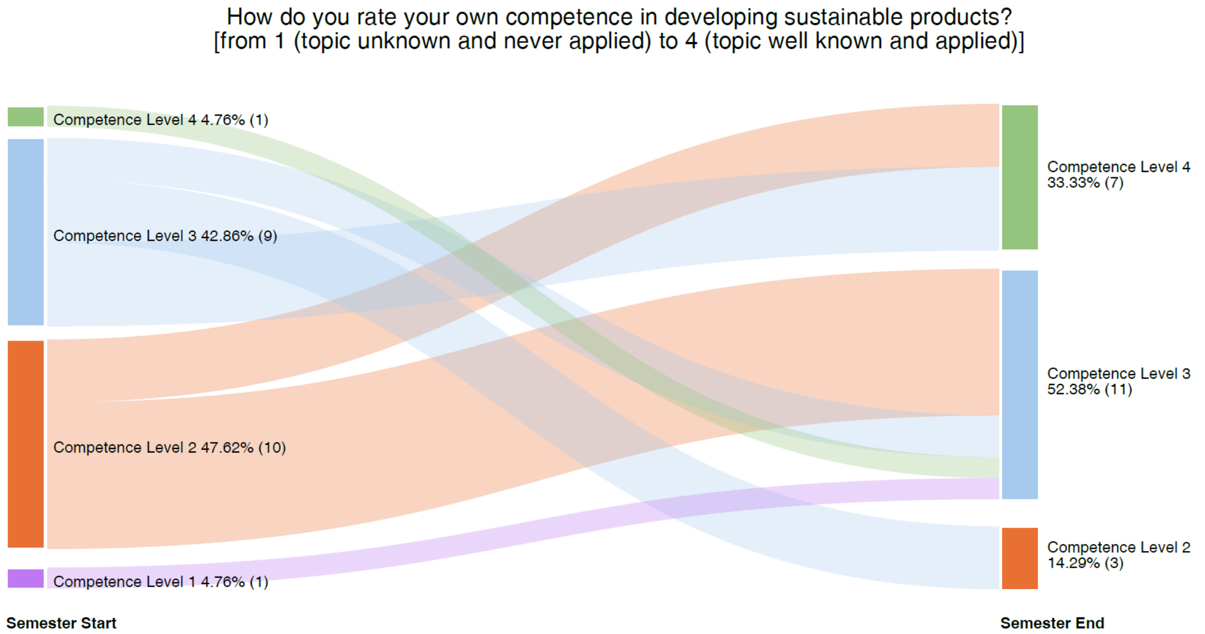

Figure 18: Transition of perceived competence levels in developing sustainable products

The chart shows a general upwards trend in perceived competence with ⅓ of students perceiving their own competence on the highest level and over 85% reaching perceiving their own competence in developing sustainable products above average. However, four students perceived a lower level of competence in the end of the semester compared to the beginning.

In the qualitative interviews the students were asked about their general view on the efficacy and perceived usefulness of knowledge formulated as design heuristics and presented in a KBES. Moreover, they were asked about their opinion on when to share own experiential knowledge in projects and if they need external impulses for sharing. The full list of questions and answers of students was published on a repository (Kremer, 2023). In table 1 the demographics and answers of students can be found.

Table 1: Answers of the the students regarding the efficacy of heuristics and desired timeline for knowledge capturing

Role	*Work experience*	*Do you consider the design heuristics presented in the app an appropriate way to provide and capture design knowledge?*	*At what point in the development process should knowledge be captured or shared? Does it need external impulses?*
Technical Manager	Metal- and façade-construction supervisor	A good concept for presenting design knowledge, because you still have to think further yourself.	Ideally distributed across the project after each milestone; a milestone can be used to identify new knowledge.
Project Manager	Project manager in exhaust-gas systems	Yes, but I would also have liked explanatory videos.	At milestones.

Role	*Work experience*	*Do you consider the design heuristics presented in the app an appropriate way to provide and capture design knowledge?*	*At what point in the development process should knowledge be captured or shared? Does it need external impulses?*
Sustainability Manager	Trend scouting & innovation management	Basically good and helpful. At first you think they are only lists, but the structure gives orientation when you have no idea what to do.	Knowledge management works very poorly in my job. A company-wide digital solution would help something social-media-like (sharing, followers, gamification).
Design Engineer	Quality-management, manufacturing	Not really. OK as a rule of thumb, but not for deeper topics.	At milestones; there used to be a kind of report. People mainly need impulses to share their own knowledge.
Technical Lead	Engineering at an elevator manufacturer	Depends on the requirement. Rules of thumb are good because they are easy to understand while implementing.	As soon as I know the content is valid; an impulse is generally useful.
Technical Staff	Technical drafter	Much of the knowledge in the app was already covered during university.	Should work by itself and need no special impulse.
Sustainability Officer	Office manager	Definitely useful. Especially in work situations. For onboarding new employees, because it is quick and easy to understand.	Not only at project end; I would share continuously.
Sustainability Officer	Digital-twin department (building sector)	Many heuristics were obvious, but the structured preparation is a good idea; otherwise everything would be unorganised.	External impulses are absolutely necessary.
Programming & Prototyping	Design engineer & product developer	Yes, because it simplifies requirement definition and implementation.	People often ignore tips from others and *want* to make their own mistakes.
Technology Team	Procurement engineer	Very good idea for inspiration; afterwards you can research further.	During the process, when I am convinced the knowledge is correct.

Role	*Work experience*	*Do you consider the design heuristics presented in the app an appropriate way to provide and capture design knowledge?*	*At what point in the development process should knowledge be captured or shared? Does it need external impulses?*
Project Manager	Consulting (Digital Products & Services)	Basically, very good. if content is too extensive no one reads it. Examples help.	When you have done something right yourself e.g., in a knowledge-exchange workshop.
Finance Manager	none	Yes, very logical and provides a good overview because the knowledge is so concise.	Should be recorded immediatel. The Aha' moment must be fresh otherwise it will be forgotten; an external impulse is necessary.
Technical Manager	Software developer	Hard to judge; I have not dealt with sustainability in the project group, therefore not understandable for me.	Certainty is only achieved at the end of the project, so rather then.
Project Lead	Operations engineer in laboratory	Possible pitfalls: some things are self-evident; it depends strongly on one's own knowledge level.	At the end. Otherwise, the knowledge might not be valid at all.

Discussion of Results Regarding Knowledge Modelling

More than half of the students found the detail page of the KBES sufficiently informative. This indicates that the structured representation of design heuristics successfully supports comprehension. However, a notable number of students found the information either insufficient or overwhelming. According to cognitive load theory, presenting content in layers can address this issue: beginners benefit from concise explanations, while advanced learners prefer more detailed options (Dönmez, 2021; Sweller et al., 2019). These findings support the implementation of adaptive interface designs that offer basic overviews with expandable sections. Such approaches have been shown to improve user understanding and satisfaction (Haleem et al., 2022).

Another possible explanation for the lower competence gains in the KBES group might be cognitive overload. Students had to familiarize themselves with an additional tool, which may have distracted them from traditional learning activities. Furthermore, the depth of engagement with KBES was not explicitly measured, meaning some students might not have used it effectively. Future research should examine the extent to which students engage with KBES and whether additional training could mitigate these effects.

Discussion of Results Regarding Guided Knowledge Acquisition Module

In contrast, the guided knowledge acquisition module—intended to support students in capturing and sharing their experiential insights—received mixed evaluations. Many students questioned its efficiency and completeness, suggesting usability limitations. This feedback is consistent with findings in the literature, which indicate that overly structured interfaces can restrict the flexibility needed to capture tacit, context-dependent knowledge effectively. For instance, Nabavi et al., 2023 showed that integrating natural language processing (NLP) to support free-text input enables users to articulate complex experiences more naturally than rigid, form-based systems. Similarly, Shneiderman & Plaisant, 2010 argue that constrained input formats may hinder users from expressing nuanced insights—particularly problematic when documenting experiential knowledge. Wang et al., 2022 further highlight that NLP-based approaches not only enhance the precision but also the adaptability of knowledge capture. Collectively, these findings suggest that redesigning the acquisition module to allow more flexible, NLP-supported input could better accommodate the varied ways in which students articulate and reflect upon their personal experiences and ultimately improve the integration of student-derived knowledge into the system's evolving database.

Discussion of Results Regarding Competence Gain

The overall evaluation indicates a positive trend in perceived competence across all domains. However, gains in the area of sustainable product development were lower. Although the KBES-supported group performed slightly below the control group in this domain, the difference was not statistically significant ($p = 0.41$). Based on the current sample size, the minimum detectable effect size for significance would be 0.791 —substantially higher than the observed effect of 0.24. Interestingly, the control group showed a higher mean competence gain (0.95) than the KBES group (0.71).

This seemingly counterintuitive result can be interpreted in several ways. One plausible explanation draws on the Dunning–Kruger effect: as students deepen their understanding of sustainable design, they may become more aware of its complexity and, in turn, more critical of their own abilities. Similar effects have been observed in sustainability education, for instance in the domain of sustainable tourism (Fuchs, 2023). In such cases, increased knowledge can lead to more conservative self-assessment.

Beyond the Dunning-Kruger interpretation, additional factors may explain the lower self-reported sustainability competence in the KBES cohort. First, actual tool engagement was not monitored due to privacy concerns. Learning-analytics research shows that variables such as login frequency, time spend on the platform and contribution events are robust predictors of achievement; when students could access a knowledge base but make little use of it, learning gains are limited (Bergdahl et al., 2024). Second, the KBES may have imposed extra workload and cognitive load. Students had to understand a new user interface while simultaneously working in a complex project, which could potentially be a combination that can depress self-efficacy and perceived competence, which are effects that are documented in cognitive-load theory (Skulmowski & Xu, 2022).

Furthermore, research on digital tool integration in education suggests that the effectiveness of tools is highly contingent on how well they are embedded within an instructional framework (Bower, 2017). Providing users with a deeper understanding of the theoretical foundations behind a digital tool can facilitate the development of accurate mental models, thereby enhancing effective use. When users are familiar with the underlying principles of knowledge modelling and system design, they can form clearer expectations of the tool's behaviour and functionality. This is also formulated in the theory of situation awareness by (Endsley, 1995), which states that a solid theoretical framework can enhance problem solving in complex environments by enabling users to better anticipate system responses and adapt their strategies accordingly. In our study, the KBES was provided as a standalone resource without extensive training on its underlying knowledge modelling or strategies for its effective use. This lack of integration may have contributed to the modest or even lower perceived competence gains in sustainable product development.

Discussion of Results Regarding Interview Results

The interview findings reveal that students generally viewed the use of design heuristics via a KBES as a convenient way to provide and capture design knowledge, while also expressing concerns about depth and context. Many participants described the heuristics as a "good concept" for presenting design knowledge in a concise, thought-provoking form that forces the user to think further rather than handing out solutions directly. This aligns with research on design heuristics indicating they function as cognitive "shortcuts" or rules-of-thumb derived from intuition and prior experience, which can guide designers towards useful patterns without exhaustive detail. Students appreciated that the KBES's heuristics were easy to understand and provided a broad overview, which is consistent with the literature that finds heuristics boost creativity in early conceptual design by reducing search time and prompting idea generation (Jin et al., 2021).

However, the students also identified important limitations and context for the appropriate use of heuristics. One student suggested a need for additional guidance ("a guideline…when you have no idea what to do"), highlighting that less experienced designers might require more process-oriented support in conjunction with heuristic knowledge. Additionally, some students felt that many of the provided heuristics were "obvious" or already taught in prior coursework, suggesting that more experienced team members did not gain much new knowledge from them. This sentiment resonates with the understanding that expert designers often internalize such heuristics through experience (Fu et al., 2015); what is revelatory for a novice design student may appear as common sense to an expert. Moreover, some students answered that heuristics alone are "not for deep things" – they serve as general rules of thumb or starting points, but not detailed instructions for complex engineering problems. Hence, the KBES with heuristics can never be seen as one-fits-all solution for knowledge for designers. Heuristics provide direction but are not a substitute for thorough domain knowledge or systematic methods. Instead, heuristics are often categorized as tools to stimulate creativity (Yilmaz et al., 2016), to be used alongside analytical tools and other types of knowledge such as guidelines, rules or factual knowledge.

The second focus of the interviews on when and how experiential knowledge should be captured or shared in the product development process offered different perspectives. Several students favored capturing knowledge at natural breakpoints, such as after project milestones or at the project's end, once results were validated. However, the downside – noted by other students – is that waiting until the end can lead to lost opportunities for learning and improvement during the project. One respondent observed that if knowledge is not shared during the process, it "might be forgotten," and another stressed that the "'Aha' moment must still be fresh" to be properly recorded. This corresponds with research on tacit knowledge which warns that experiential insights are context-dependent and can be forgotten fast, if not captured (Zammit et al., 2018)

6. Conclusion

This study demonstrated that integrating a Knowledge-Based Engineering System (KBES) into engineering education effectively supports structured knowledge dissemination. However, contrary to expectations, students using KBES reported a lower perceived competence gain in sustainable product development than those in the control group. This indicates that while KBES is useful for knowledge organization, its current implementation may not fully translate into improved competencies.

This paper explored the role of a KBES in supporting sustainable product development within engineering education. The system was designed to provide structured access to design heuristics while allowing students to contribute their own experiential insights. The study examined both the knowledge modelling approach and the guided knowledge acquisition module, as well as the impact of the KBES on students' self-perceived competence in sustainable product development.

The evaluation revealed that the knowledge modelling approach was well-received, with most students finding the KBES's interface and structured heuristic descriptions sufficient. This confirms that a structured, frame-based and additionally ontology-supported representation of knowledge can enhance comprehension, particularly when cognitive load is carefully managed (Sweller et al., 2019). However, the guided knowledge acquisition module received mixed feedback, as students preferred more flexible input methods over rigid, structured templates. This aligns with prior research on digital learning environments, which highlights the importance of NLP and adaptive interfaces in facilitating more effective user engagement and knowledge capture (Wang et al., 2022).

The study also assessed the KBES's impact on students' perceived competence. While an overall increase in self-assessed competence was observed, students in the KBES group reported lower perceived competence gains in sustainable product development compared to the control group. This could be explained by the self-assessment bias described by (Kruger & Dunning, 1999), in which increased knowledge exposure makes learners more aware of their own limitations.

Implications for Research

This study raises several important questions for future research. First, the small sample size limits the generalizability of our findings. Larger studies involving diverse student demographics could provide deeper insights into which learner groups benefit the most from KBES integration. For example, it would be valuable to explore whether prior engineering experience, digital literacy, or cultural background influences students' engagement with structured digital knowledge systems. Furthermore, in this study only the perceived competence gain of students was assessed due to ethical considerations of the researchers. According to the ethical guidelines of the university, participation in the evaluation can only be voluntarily and the non-participation cannot carry any academic consequences. Linking the objective competence gains could have been assessed through grades in the courses or an extensive voluntary additional assessment, which is why in this research a perceived competence gain was chosen. Future research could also consider objective competence assessments of students.

Second, this study focused solely on sustainable product development. While sustainability is a critical design challenge, future work should examine how KBES affects competence development in other areas of engineering, such as manufacturability, cost efficiency, or human factors engineering. This would provide a more comprehensive understanding of the tool's impact across multiple domains. Furthermore, this study only measured perceived competence - an important but subjective indicator. Future research should incorporate objective testing of students' actual competence to determine whether digital knowledge systems like KBES lead to measurable improvements in knowledge application and problem-solving ability. Additionally, this study assessed short-term learning outcomes. While the KBES demonstrated immediate benefits in structuring knowledge and supporting learning, it remains unclear whether these effects persist over time. Longitudinal studies could explore whether students retain and apply KBES-supported knowledge in future projects or professional settings.

Also, it needs to be further explored how to design appropriate knowledge acquisition modules for students (e.g. through the usage of LLMs), since it has proven beneficial for competence gains of students, because it not only enables knowledge sharing. It also has a positive effect on the knowledge internalization by reflecting on own experiential knowledge acquired during studies (Stepanova, 2020). Future research could also explore the integration of intelligent guidance features in KBES. Adaptive learning mechanisms, such as AI-driven prompts that guide students in using the system more effectively, could enhance user engagement and comprehension. Such features could include interactive tutorials, real-time feedback, or context-aware suggestions that help users navigate complex design decisions more intuitively (Wang et al., 2022)

While this study focused on short-term learning outcomes, future work should investigate the long-term effects of KBES on students' ability to apply design heuristics in real-world product development. Longitudinal studies tracking students' application of knowledge in industry settings would provide deeper insights into the lasting impact of KBES-based learning.

Implications for Engineering Education

For practitioners, the findings underscore that the mere deployment of digital tools like the KBES is insufficient to guarantee improved learning outcomes. The clear success of the knowledge modelling strategy suggests that structured and layered representations of design heuristics can significantly aid in the understanding of complex concepts. However, to fully harness these benefits, engineering education must integrate these tools within a well-defined instructional framework. This includes providing targeted training that explains the underlying modelling principles and effective usage strategies. Additionally, other research suggests that modest incorporation of gamification elements, such as achievement badges or leaderboards, could enhance engagement and motivation, although these should serve to complement rather than overshadow the core educational objectives (Hamari et al., 2014).

In summary, this paper contributes to the growing body of research on digital tool integration in engineering education by demonstrating that while a robust knowledge modelling approach can effectively convey design heuristics, flexible methods for knowledge capture and deeper curricular integration are essential for maximizing the impact on student competence. The implications for both research and practice emphasize the need for a holistic approach that combines technological innovation with targeted pedagogical strategies.

Beyond academia, these findings are also relevant for industry practitioners seeking to implement KBS in design teams. According to (Stark, 2022) engineering systems of the future consist of new types of *engineering intelligence*, combining both human heuristic knowledge together with data analytics and model intelligence. Ensuring that such systems effectively integrate experiential knowledge and provide context-sensitive guidance will be crucial for their adoption in real-world engineering environments. Still, it needs to be further analysed how the integrated heuristic knowledge can be validated through data along the product life cycle. Furthermore, it is yet to be investigated how KBES integrating heuristic knowledge can be used for knowledge provision to designers in industrial settings and how the systems can be leveraged for continuing professional development of designers.

Ethical approval

The use of questionnaires and the handling of gathered data was approved through a self-assessment provided by the ethics committee of Technische Universität Berlin by completing a 13-item checklist. All items were answered in the negative: data were collected anonymously and stored in accordance with the data-protection guidelines; participation was voluntary and carried no academic or financial consequences; no vulnerable groups, deception, invasive procedures, or sensitive personal questions were involved; and no external funding agency required a formal ethics submission. Because none of the checklist criteria that trigger a full ethics-board review applied, the study was classified as ethically unobjectionable, and no additional approval was necessary.

Acknowledgements

The work was supported by Deutsche Forschungsgemeinschaft (grant 426205459).

Declaration of Interest

There was no potential or perceived conflict of interest associated with the work.

Notes on Contributors

Gerald Kremer, M.Sc. holds a master's degree in Industrial Engineering from Technische Universität Berlin and is currently pursuing a PhD in the field of Industrial Information Technology. His doctoral research explores how knowledge based engineering systems can capture, structure, and deliver experiential design knowledge to accelerate the development of sustainable products. He supervised the research project reported in this paper. Beyond his PhD work, his studies focus on assistance systems for product development, including the qualification of sub-symbolic AI solutions in industrial environments and the design and deployment of digital twins.

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