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Integrating Circular Economy into Engineering Curricula: A Modular and Interdisciplinary Educational Concept

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Abstract

This paper presents the development and conceptual framework of a modular learning unit designed to promote comprehensive, practice-oriented education on the Circular Economy (CE) within the context of electronic system design. Responding to the growing need for sustainability-focused curricula, the learning unit integrates theoretical instruction with hands-on construction tasks, fostering interdisciplinary learning and facilitating the development of both, technical and social competencies. The instructional design is grounded in Bloom's taxonomy and aligned with the STEM (Science, Technology, Engineering and Mathematics) syllabus, while the methodological approach combines literature review, experimental design, and iterative variant development based on a morphological matrix incorporating CE-specific R-Strategies. In addition to promoting systems thinking, critical reflection, and collaborative problem-solving, the module aims to challenge prevalent misconceptions about CE and product quality. Early validation through implementation with school pupils within the academic ecosystem of Reutlingen University demonstrates the module's relevance and adaptability. The findings underscore the necessity of integrated and systemic educational approaches to sustainability and highlight the potential of cross-sectoral collaboration in addressing complex socio-technical challenges.

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Keywords: Circular Economy, Electrical Product Design, Learning Module, Practical Training, Interdisciplinarity

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1. Introduction

The accelerating depletion of natural resources, the increasing complexity of global value chains, and the urgent demand for climate resilience have placed the concept of the Circular Economy (CE) at the forefront of sustainability-oriented industrial transformation. In this context, engineering disciplines – and particularly electrical engineering – are confronted with the challenge of not only optimising technical systems with respect to their properties as efficiency, power density, functionality, but also rethinking product lifecycles, material flows, and system interdependencies from a circular perspective. Despite the growing strategic relevance of CE, its integration into formal education, especially within engineering curricula, remains fragmented and conceptually underdeveloped. Traditional educational models in engineering continue to emphasise linear production paradigms, while circularity demands a systemic, interdisciplinary, and application-oriented shift in how future professionals are trained. In response to this gap, the development of modular, scalable learning frameworks becomes essential – not only to convey CE principles, but also to enable learners to engage in complex problem-solving, critical reflection, and cross-disciplinary collaboration. Pedagogical frameworks such as Bloom's Taxonomy and STEM-based curricula (Science, Technology, Engineering and Mathematics) offer a foundation for competence-oriented learning but require contextual adaptation to address the specificities of circular production systems and engineering practice. In particular, practice-based instructional strategies, such as morphological modelling and constructive design tasks, hold potential for fostering both, technical knowledge and transversal competencies such as systems thinking, sustainability reasoning, and cooperative learning. Within this framework, the present study addresses the following research question:

How can a modular learning module on CE be designed within the context of electrical engineering, more precisely in electronic system design, in order to effectively promote both technical and social competencies in learners through interdisciplinary and practice-oriented teaching methods?

To answer this question, the study develops a modular didactic unit that combines theoretical instruction with applied construction-based learning. The conceptual design builds upon a combination of literature-based insights, morphological analysis using CE-specific R-Strategies based on Potting et al. [1], and iterative variant development aligned with educational taxonomies. By exploring the intersection of engineering education, sustainability didactics, and curricular innovation, this paper contributes to the advancement of integrated CE education and provides transferable insights for embedding circularity into the core of technical and vocational training.

2. Research Design

The study aims to design and implement a modular learning unit that fosters systemic understanding of the CE in electrical engineering education, while promoting technical and social competencies essential for addressing the multidimensional challenges of circular value creation in industrial practice.

To operationalise this objective, the research is guided by the following sub-goals:

1. *Conceptualisation of a modular learning framework* based on established didactic models and embedded within the structure of STEM education;
2. *Integration of CE principles*, particularly through the application of R-Strategies as core elements of both, theoretical and practical learning sequences;
3. *Development of practice-oriented learning tasks* using a morphological matrix for variant generation, enabling learners to engage in constructive, design-based problem-solving;
4. *Validation of the learning module* through iterative testing involving diverse target groups, with a focus on applicability, learner engagement and competence development;
5. *Analysis of the interrelation between technical learning outcomes and transversal skills,* such as systems thinking, sustainability reasoning, and collaborative capacity.

While sub-goals 1 to 3 have been completed, sub-goals 4 and 5 are still in progress.

The research follows a design-based research (DBR) approach, which allows for iterative development, testing, and refinement of the educational intervention in authentic learning environments. This methodology is particularly suited for educational innovation, as it bridges the gap between theory and practice while allowing for the contextual adaptation of learning materials.

The study is structured in three core phases:

1. *Phase: Literature Review and Conceptual Design*: A systematic literature review on CE education, modular learning frameworks, and relevant didactic models provides the theoretical foundation for the design of the learning unit.
2. *Phase: Development of the CE modular learning module*: Based on the identified requirements and frameworks, the learning module is developed, including both, digital and physical components, and implemented in pilot settings at Reutlingen University.
3. *Phase: Evaluation and Validation*: Mixed-method evaluation is used to analyse the effectiveness of the learning module and derive implications for further refinement and broader application. This phase is ongoing.

By combining educational theory, sustainability science, and engineering pedagogy, this research contributes to the emerging field of CE education and offers a scalable, empirically grounded model for curricular integration in technical disciplines.

3. State of the Art and Science

The CE represents a systemic shift from linear production and consumption patterns toward resource-efficient, regenerative, and closed-loop systems. Its principles encompass design for durability, reuse, remanufacturing, recycling, and the minimisation of waste and environmental impact [2],[3].

A central conceptual framework in CE didactics is the application of R-Strategies [1], which categorise circular actions based on their proximity to the ideal of full circularity. These strategies provide a didactic entry point for teaching learners on how product design and production decisions influence resource flows and environmental outcomes [1]. Following Potting et al. [1] this research is referring to the R-Strategies as shown in Table 1.

Table 1. R-Strategies according to from Potting et al. [1].

R-Strategy	Definition of R-Strategy
Refuse	Refuse to use products or materials that are unnecessary or inherently unsustainable. Design products in a frugal way.
Rethink	Redesign materials, products, and business models to optimise resource efficiency.
Reduce	Lower resource and energy inputs by minimising material use and waste.
Reuse	Extend product lifespans by reusing products, components or materials in their original function.
Repair	Repair damaged or faulty products.
Refurbish	Restore and technically update used products in order to make their functionality comparable to the functionality of new products.
Remanufacture	Use working components of damaged products for the production new products with the same function.
Repurpose	Use working components of damaged products for the production of new products with another function than originally had.
Recycle	Reprocess materials into secondary raw materials for new production cycles.
Recover	If no other use is possible, use of materials for energy recovery.

The didactic integration of CE into formal education, particularly in technical disciplines such as engineering, is still at an emergent stage [4]. Several studies emphasise the need for transformative and interdisciplinary educational approaches to foster system-level understanding and agency among future professionals [5],[6]. This reflects a broader shift toward Education for Sustainable Development (ESD) and the call for curricular innovation anchored in real-world complexity [7]. Modular learning offers are promising instructional structure for integrating CE principles into technical education. Its key advantages include flexibility, scalability, and the possibility of differentiation across educational levels and learner backgrounds [8]. In STEM education, modular units can be aligned with competence-based frameworks and integrate problem-based learning, constructivist methods, and project-oriented design [9],[10].

Frameworks such as Bloom's Taxonomy [11] provide a cognitive scaffold for competence development, ranging from knowledge acquisition to creation. In CE education, such structures can be leveraged to progressively build skills – starting with conceptual understanding and advancing toward application, evaluation, and system design in real-

world contexts. Skills such as flexibility and adaptability are considered crucial for a transition to CE. The competency map by Vitti et al. [12] classifies CE-related competencies that should be taken into account when developing learning materials for groups. These include, for example, green transition skills, but also resilience and soft skills. Concluding, effective CE education must foster not only technical competencies, but also transversal skills such as:

- Systems thinking [6],[13]: The ability to recognise dynamic interrelations within production, consumption, and environmental systems.
- Sustainability literacy [12]: Understanding the socio-ecological implications of design and engineering decisions.
- Collaborative problem-solving: Working across disciplines and sectors to co-create sustainable solutions [6],[14].

Studies show that learners engaged in interdisciplinary, practice-oriented learning environments (e.g., learning factories, living labs) develop a more integrated understanding of CE and are better prepared for real-world challenges [15],[16]. Initial educational concepts have been developed to integrate CE principles into learning factory environments. Notable examples include the learning factory-based corporate training concept by Dvorak et al. [17] and the "overarching learning module for circular economy" developed by Barth et al. [18]. These concepts, still in development, are primarily designed for employees and industrial leaders, and in some cases also target university students who participate in learning factory-based education [17],[18]. There is a gap in the field of CE learning modules that are designed for pupils in schools and address the curricula of STEM subjects.

4. Development of the Circular Economy Learning Module for Applied Engineering Education

The development of the Circular Economy Learning Module for STEM followed an iterative, design-based research process structured along the pedagogical and technical requirements identified in the preceding phases. The aim was, to create a modular learning format that not only conveys CE principles but also enables learners to engage with complex interdependencies in product design, material cycles, and value creation systems within electrical engineering. The learning module presented here differs from the approaches of Barth et al. [14] and Dvorak et al. [13] in terms of its target audience, field of application, and pedagogical objectives. In contrast to existing concepts for CE learning modules, it is specifically designed for use beyond the learning factory environment, allowing teachers to independently implement it in school settings with pupils aged 13 to 17. Introducing important topics to pupils can increase motivation, foster interdisciplinary connections, and support long-term competence development.

4.1. Didactic Structuring and Competency Orientation

The design of the learning model was anchored in Bloom's revised taxonomy [11], ensuring a competency-oriented progression from foundational knowledge toward higher-order cognitive and practical skills. The learning outcomes were mapped to the three dimensions of the CE competence framework:

- Cognitive (knowledge-based): Understanding CE principles, R-Strategies and life cycle models.
- Technical (application-based): Implementing circular design choices in engineering tasks.
- Social (reflective-collaborative): Engaging in team-based problem solving and systems thinking.

This structure was aligned with both, STEM curriculum goals and explicitly embedded interdisciplinary content, combining elements of electrical engineering, environmental science, and sustainability assessment.

4.2. Methodological Design for Engagement and Multimodal Learning

To ensure both accessibility and learner engagement, the learning module employs a multifaceted instructional approach grounded in contemporary pedagogical principles. The content delivery is structured through a presentation-based format and follows the hierarchical structure of Bloom's revised taxonomy [11], thereby scaffolding cognitive development from foundational knowledge acquisition to higher-order analytical and evaluative thinking. In line with best practices for multimodal learning, the module integrates a variety of digital media formats, including educational video content, interactive quiz applications, and visual learning aids. These elements support a differentiated access

and enhance learner engagement by appealing to diverse learning preferences. To further increase motivation and active participation, the module incorporates gamification elements. Among these are a circularity assessment game and dynamic knowledge quizzes facilitated through platforms and tools such as Mentimeter [19]. These tools are designed to promote real-time feedback, healthy competition, and deepened knowledge retention.

At the core of the module lies a practice-oriented case study cantered on the design and evaluation of a bicycle-powered dynamo charging system. This real-world engineering challenge serves as a tangible anchor for theoretical concepts and facilitates interdisciplinary learning by bridging domains such as sustainable energy, mechanical and electrical engineering and digital literacy.

The learning experience is further enhanced through a narrative-based instructional framework. A fictional scenario – involving, for example, a depleted mobile phone in a forest setting and the need to generate emergency power – serves as a contextual storyline. These narrative fosters both, emotional engagement and cognitive contextualisation, thereby increasing the relevance, authenticity, and memorability of the learning content.

4.3. Pedagogical Structure and Interdisciplinary Integration of the Circular Economy Learning Module

The CE learning module systematically integrates the thematic domains of CE and electrical engineering. Transitions between the two subject areas occur repeatedly throughout the module and become increasingly seamless, reflecting a progressive interweaving of disciplines. This convergence culminates in a holistic educational experience that fosters both technical understanding and sustainability literacy. Additionally, interdisciplinary links – including references to civics, economics, geography, physics, and informatics – are deliberately embedded to enrich learners' systems thinking and contextual awareness. The module is divided into three progressive sections (see Fig. 1), each combining instructional and constructive elements. While the first section emphasises knowledge acquisition, subsequent sections gradually shift toward applied learning and critical evaluation.

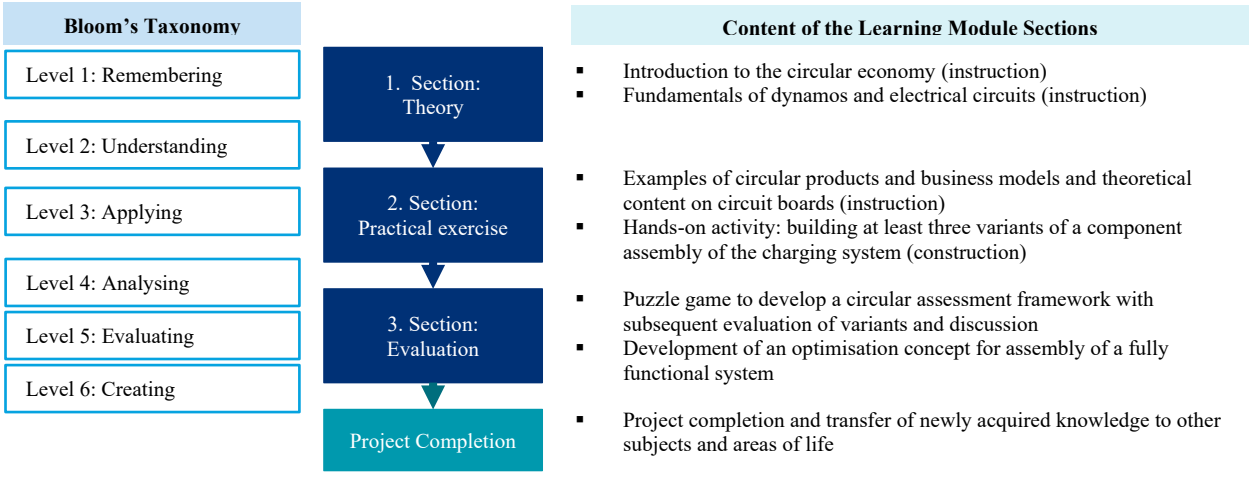

Fig. 1. Circular Economy Learning Module Structure and its relation to Bloom's Taxonomy.

Section I: Theoretical Foundation and Initial Engagement

The first section introduces the overall project framework and provides the theoretical foundations for understanding the CE. Through a fact-based sensitisation, learners are made aware of the relevance of CE, not only from an ecological perspective but also in relation to resource scarcity, economic viability and social justice. This is followed by a structured introduction to key CE concepts and an overview of technical knowledge, such as the functioning of electrical circuits and dynamos, as contextualised through the case study. Transitions between CE and engineering content are repeated and intentional, particularly in this early phase, to maintain cognitive engagement and reflect real-world complexity. To address diminished attention spans observed in younger learners due to constant digital stimulation, the module employs emotional activation techniques, novel content, and rhythmic alternation

between challenge and familiarity. Short relaxation or reflection exercises facilitate emotional resonance and cognitive recovery, while also enhancing learner motivation. These didactic elements aim to stimulate curiosity and establish early personal relevance – critical factors in sustaining attention and promoting long-term learning.

Section II: Application and Design through Practice

The second module section focuses on hands-on learning. Learners are introduced to existing circular products and business models before turning to the focal application: The design and assembly of a simple electronic device, that is a bicycle-powered charging system. At least three device variants are constructed, enabling learners to experience how design decisions influence circularity. An additional learning outcome demonstrates the trade-off between circularity, size and costs. This section deepens technical and conceptual understanding by moving from "understanding" to "applying" within Bloom's framework. Learners begin to link theoretical principles with real-world technical choices and are encouraged to assess the trade-offs embedded in design configurations.

A morphological matrix was used for the definition of the device variants. It was developed in three steps, resulting in three different matrices, that are used as additional material. The morphological matrix (see Fig. 2) allows teachers and learners to systematically vary product attributes and assess the implications of their design decisions.

The morphological matrix was developed in three steps and contains those as additional material:

1. **Preparatory sheet**: In a two-dimensional matrix, the influence factors for CE identified by Ruzicic et al. [20] were related to the R-Strategies. Check marks were used to indicate which influencing factors could be addressed by which R-Strategy.
2. **Compilation of potential components and connection types for the device variants**, including an assessment of their respective advantages and disadvantages considering the R-Strategies.
3. **Morphological matrix for the definition of variants (Fig. 2):** Circularity, performance, product size, and production costs are evaluated for each item. The evaluations are based on the practical experience of the experts involved in the project. A separate sheet was used to document the explanations and arguments underpinning the evaluations of the morphological matrix.

Categories	Less circular				Tendency												More circular
Mount type	Only Surface Mount Technology (SMT)				SMT & THT for the capacitor mounting					Only Through Hole Technology (THT)							
	PE: 0	PC: 2	Size: 2	CE: 0	PE: 2	PC: 0	Size: 0	CE: 1		PE: 1	PC: 1	Size: 0	CE: 2				
Capacitor configuration	Single large capacitor									2 filter capacitors (small) in parallel							
	PE: 0	PC: 2	Size: 1	CE: 1						PE: 2	PC: 1	Size: 1	CE: 2				
Rectifier structure	Monolithic bridge rectifier (integrated package)									Discrete diode bridge rectifier							
	PE: 1	PC: 2	Size: 2	CE: 0						PE: 2	PC: 1	Size: 0	CE: 2				
Capacitor type	Electrolytic capacitor					Ceramic capacitor					Film capacitor						
	PE: 2	PC: 2	Size: 1	CE: 0		PE: 1	PC: 1	Size: 2		CE: 1		PE: 1	PC: 0	Size: 0	CE: 2		
Connection type	Glued connection				Wires directly soldered onto the board					Screw terminal connector					Bolted crimped connections		
	PE: n.a.	PC: 1	Size: 2	CE: 0	PE: n.a.	PC: 2	Size: 2	CE: 0		PE: n.a.	PC: 1	Size: 1	CE: 1		PE: n.a.	PC: 0	Size: 0	CE: 2

PC = production costs; production process / effort (like material and manpower)
Size = product size
CE = circularity
PE = performance (efficiency / flexibility)

0 = unfavourable characteristics
1 = medium favourable characteristics
2 = favourable characteristics
n.a. = no impact / not applicable

blank field used as a placeholder to enhance readability

Fig. 2. Morphological matrix for the definition of variants.

The categories of possible parts and connection types are named in the left column. Their options including the rating of the alternatives of each category for four criteria are shown in the matrix. The order of the alternatives follows tendentially from less to more circular options. Pupils will receive the morphological matrix (Fig. 2) as puzzle and without the given estimations. With content of the CE learning module and additional research the pupils will complete the morphological matrix puzzle and give their own estimations and analyse the given device variants by this worksheet.

Section III: Evaluation and Creative Problem Solving

The third section emphasises critical analysis and solution development. Learners are tasked with constructing their own circularity assessment framework for evaluating the previously assembled device variants. Therefore, pupils will receive the morphological matrix (Fig. 2) as puzzle and without the given estimations. With content of the CE learning module and additional research the pupils will complete the morphological matrix puzzle and give their own

estimations and analyse the given device variants by this worksheet. This is followed by a structured group evaluation and reflection process, which includes the identification of the most circular design, the discussion of design trade-offs, and the observation of potential classification conflicts in circular assessments.

Learners engage in deeper analytical reasoning, to address the fourth and fifth levels of Bloom's taxonomy (analysing and evaluating), see Fig. 1. Finally, they are challenged to develop optimisation proposals – including suggestions for redesigning the device or improving the system as a whole – and to conceptualise suitable circular business models. This activity completes the sixth cognitive level (creating), thereby fostering comprehensive design competencies.

4.4. Didactic Features and Interdisciplinary Linkages

Table 2 presents the didactic structure of the CE learning module, illustrating the alignment between content areas, learning objectives (based on Bloom's revised taxonomy), teaching methods, key competencies, and interdisciplinary connections. The modular design follows a progressive learning pathway that begins with foundational knowledge and culminates in higher-order skills such as evaluation and creative problem-solving.

Table 2. Didactic Overview Table | Circular Economy Learning Module for Applied Engineering.

Module Section	**Learning Objectives** (Bloom`s Taxonomy)	**Topics / Content**	**Methods & Media**	**Key Competencies**	**Cross-Disciplinary Links**
1. Introduction & Foundations	*Remembering, Understanding*	Fundamentals of CE, environmental impacts, resource scarcity, basics of electrical engineering (circuits, dynamos)	Presentation, explainer videos, interactive quizzes, narrative elements (storyline)	Environmental awareness, domain-specific knowledge, attention & motivation	CE, Geography, Civics, Physics
2. Application & Construction	*Understanding, Applying*	Assembly of device variants, CE design principles, link between engineering and sustainability	Hands-on group work, prototyping, design variants, worksheets	Design literacy, problem-solving, collaboration	Technology, Economics, Computer Science
3. Evaluation & Optimisation	*Analysing, Evaluating, Creating*	Design assessment, trade-offs in circularity, development of optimisation concepts and business models	Gamified assessment (custom rubrics), group discussion, feedback, sessions, concept development	Critical thinking, creativity, innovation capacity	Mathematics, Business, Ethics
Across All Sections	*Meta-competencies*	Reflection, perspective-taking, sense of agency, systems thinking	Reflective exercises, learning checks, peer feedback, quizzes	Systems thinking, sustainability literacy, autonomy	ESD, Sustainable Development Goals (SDGs)

The three core sections of the module – Theory (*Introduction & Foundations)*, practical exercise (*Application & Construction)* and Evaluation (*Evaluation & Optimisation)* – are designed to scaffold cognitive development and support experiential learning. Each section integrates multimodal instructional strategies, including narrative elements, hands-on activities, and gamified assessments, to enhance learner engagement and retention. Within the modular sections, the order of the chapters, as well as the chapters themselves, can be rearranged and adjusted without compromising the central instructional design. This approach allows for flexibility in adapting to curriculum changes, different training levels, or fields of study, and facilitates the implementation of the CE learning module at universities beyond Germany. The enclosed instructions for teachers and additional materials provide support in this regard.

Cross-curricular links to subjects such as geography, economics, and computer science are intentionally embedded to promote systems thinking and foster an understanding of circularity as a transdisciplinary challenge. Table 2 further highlights the development of both, technical and transformative competencies, in alignment with the goals of ESD and the United Nations Sustainable Development Goals (SDGs). Each chapter of the learning module concludes with formative assessment questions and quizzes. These are intended to support both, pupils and educators: Teachers gain feedback on learning progress, while learners may use the questions for self-assessment and exam preparation.

Throughout the module, intentional interdisciplinary connections are incorporated via knowledge refreshers, inquiry-based tasks, and educational games. For example, the concept of decoupling resource use from economic growth serves as a gateway to macroeconomic and accounting topics, while aspects of geographic distribution and material availability are addressed in the introduction. Additional cross-curricular links include:

- Platform economies and digital ecosystems (informatics)
- Circular supply chain optimisation (mathematics)
- SDGs (civics and global learning)

Participants are encouraged to actively contribute prior knowledge, personal experience, and individual perspectives throughout the learning process. This participatory approach enhances autonomy, fosters deeper engagement, and reflects the broader goals of ESD. A central focus lies on enhancing learners' ability to identify, analyse and respond constructively to goal conflicts. Rather than viewing such tensions as barriers or veto points, pupils are encouraged to perceive them as opportunities for compromise, innovation and the development of creative, multi-perspective solutions. In addition to fostering this reflective and solution-oriented mindset, the module strengthens key skills in collaborative group work, including communication, negotiation, and empathy. These skills are complemented by the cultivation of analytical thinking, methodical problem-solving, and structured planning – particularly in the context of interdisciplinary tasks, that require both, technical understanding and social awareness.

Learning outcomes and competence development are assessed through periodic quizzes, with both mid-lesson and end-of-lesson checks. Key metrics include pupils' scores, completion time for exercises, and the reduction of recurring error types over the course. Moreover, the ability to transfer acquired knowledge to practical and interdisciplinary tasks is considered a central indicator of learning success. This is evaluated through exercise results, contributions to discussions, and reflections during the final review.

Overall, the module promotes a holistic competence profile, that prepares learners to engage responsibly and innovatively with the challenges of a CE in both academic and real-world contexts.

4.5. Pilot Testing and Evaluation Strategy

To ensure the didactic quality, practical relevance and transferability of the CE learning module, a multi-stage pilot phase is planned in diverse educational and professional contexts:

1. Stage: The first pilot phase will involve secondary school groups from the surrounding region and undergraduate students from Reutlingen University. Module effectiveness will be evaluated through formative assessments and structured feedback (e.g., surveys and guided reflections), providing insights into learners' cognitive development, engagement, and content retention. Building on Valls-Val et al. [21], the surveys will be expanded with education-specific questions. The pilot is scheduled for the fall 2025, enabling iterative refinement and digital implementation by year's end.
2. Stage: Beyond academia, the CE learning module will be tested with industry stakeholders from the Werk150 ecosystem. As key actors in the diffusion of CE principles, their understanding of circularity is crucial for developing resilient, regenerative business strategies, while insufficient knowledge risks misalignment or resistance to innovation.
3. Stage: By integrating feedback from educational and corporate pilots, the evaluation will generate insights for adapting the module to diverse learner needs and inform its final optimisation and dissemination. Detailed results, including evaluation data, metrics, and feedback, will be reported in a subsequent publication.

The learning success of the CE learning module considering aspects as students' understanding, level of difficulty, and the learning scope will be measured as shown in Table 3. Measurement will take place before, during, and after implementation of the learning module with every school class participating. One possible evaluation method for the suggested framework is the use of the model introduced by Rana et al. [22]. Here, qualitative and quantitative ratings are used and combined. For qualitative assessment questions like "How would you assess your prior knowledge?" and "How much have you learned?" are used. This model of evaluation will be considered in future work.

Table 3. Methods and indicators for measuring competence development in correlation with Bloom's Taxonomy.

Learning Objectives (Bloom`s Taxonomy)	Measurement method	Indicators
Remembering	Quizzes as written tests (digital or on paper), learning success control questions in the middle of and at the end of chapters via tools like Mentimeter	Points achieved, average and median grade across all participants, grade distribution, number of correctly answered questions, and points achieved
Understanding	Learning success control questions in the middle of and at the end of chapters via tools like Mentimeter with understanding-based questions, discussions, reflection and proceeding with tasks	Number of correctly answered questions, points achieved, discussion flow with ideas and arguments used, completion time for exercises, reduction of recurring error types and success rate in exercises
Applying, Analysing, Evaluating, Creating	Peer reviews, evaluation of the device variants, and presentations of pupils' ideas for the optimisation and solutions of the optimised devices.	Task completion time and success rate in exercises, correct assessments of the variants: most circular, most cost-efficient, and compromise variant, improvement suggestions for the variants, and functionality of the optimised device

5. Conclusion and Educational Implications

The CE learning module demonstrates how the integration of CE principles into engineering education can effectively foster both, technical expertise and sustainability-related competencies. By combining theoretical instruction, practical application, and interdisciplinary linkages within a structured, modular format, the module offers a pedagogically sound and scalable framework for addressing complex socio-technical challenges in a curricular context. From a didactic perspective, the module is aligned with Bloom's taxonomy, ensuring a systematic development of cognitive skills ranging from knowledge acquisition to creative problem-solving. The combination of constructive learning tasks, narrative-based engagement, and formative assessments supports differentiated learning and maintains high levels of motivation – particularly among younger learners with diverse attention patterns and media habits.

For educators, the CE learning module provides a structured and ready-to-implement instructional design, complete with learning objectives, interdisciplinary teaching cues, and quiz-based assessment tools. These features enhance the module's usability across various educational levels, including secondary education, vocational training, and introductory university courses. Its flexible architecture aligns with ESD and international frameworks such as the UN SDGs, and supports both STEM-focused and cross-curricular teaching. The module's design fosters not only technical knowledge and environmental literacy, but also key 21st-century skills such as systems thinking, collaboration and innovation capacity. As such, the CE learning module represents a transferable and impactful tool for advancing transformative education in line with the principles of the CE and the broader goals of a regenerative, future-oriented society.

Future work envisions extending its application to an open-access digital learning environment for pupils, conceived as an integral part of the learning module presented in this paper. This environment will feature interactive tasks, chat functionalities for pupil inquiries, and analytics for evaluating learning outcomes. The assessment of the learning process will be based on chapter-based quizzes, the time required to complete tasks, and the learners' ability to transfer newly acquired knowledge to practical applications and interdisciplinary contexts. A subsequent paper will focus on the evaluation of the learning module including methods and metric for measuring learning improvements.

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