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EDITED BY
Evi Viza,
University of the West of Scotland,
United Kingdom

REVIEWED BY
Ana Mat Said,
University of the West of Scotland,
United Kingdom
Enrica Vesce,
University of Turin, Italy

*CORRESPONDENCE
Yvonne van der Meer
✉ Yvonne.vanderMeer@maastrichtuniversity.nl

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The CIRCULAR pathway: a new educational methodology for exploratory circular value chain redesign

Cris Garcia-Saravia Ortiz-de-Montellano, Ali Ghannadzadeh and Yvonne van der Meer*

Faculty of Science and Engineering, Aachen-Maastricht Institute for Biobased Materials (AMIBM), Maastricht University, Geleen, Netherlands

The circular economy (CE) is gaining global relevance across countries and institutions as a tool to solve some of the most pressing global challenges derived from linear production and consumption systems. However, transitioning to a CE requires significant changes in how businesses and supply chains operate, including redesigning products, processes, and business models. These changes require that future professionals acquire knowledge and skills on the principles of CE, Life Cycle Thinking, and Systems Thinking. However, research on existing higher education programs signals a need for educational resources to develop these skills and knowledge in real-world settings. This paper outlines a new eight-step methodology to introduce students to the principles of CE through the exploratory redesign of a real-world product and value chain in a project-centered learning environment. This methodology was developed in four iterations and was used to teach 251 students from the BSc. Business Engineering at Maastricht University during the academic years 2020–2022. The findings indicate that this method supports students' understanding of complexity, linearity, and the importance of systemic change across the entire value chain, as well as their critical thinking, problem-solving, and decision-making skills. The methodology provided in this paper supports and encourages educational bodies to implement Education for CE in their curricula and further strengthens the complementary fields of Education for Environmental Sustainability and Education for Sustainable Development. Furthermore, educators, professionals and businesses can make use of this tested methodology for exploratory product redesign toward sustainable circularity transitions.

KEYWORDS

education for the circular economy (ECE), project based learning (PBL), circular design, teaching approaches and content, circular economy methodology

Introduction

The past three decades have seen the rapid development of the Circular Economy (CE) concept. Its early beginnings can be traced to the work of Pierce and Turner, who highlighted the closed relationship between economics and natural capital as a source and sink of resources and waste (Pierce and Turner, 1990). Its evolution has been tightly interwoven with the concepts of industrial ecology, industrial symbiosis, industrial metabolism, environmental sustainability, and sustainable development (Winans et al., 2017; Martín Gómez et al., 2018; Saavedra et al., 2018; Salomone et al., 2020).

The exponential increase in research and development in the field of CE in the last years (Calisto Friant et al., 2020) reflects the urgency to bring society and economics in balance with the environment under threatening climatic parameters. Nowadays, CE is defined as a systems-wide framework whose central goal is to use innovation to "eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature" (Ellen MacArthur Foundation, 2018).

However, despite the global pressure to transition toward a CE, in practice, several barriers and limitations still need to be overcome. These can be categorized into four dimensions: Social/Cultural, Institutional/Regulatory, Economic/Market and Technological (de Jesus and Mendonça, 2018; Paletta et al., 2019; Grafström and Aasma, 2021). In their study of CE barriers within the European Union, Kirchherr et al. (2018) signaled the social/cultural dimension as the strongest barrier to change. This dimension relates to mindsets, mental models, peoples' sensitivity, and awareness (Schultz and Reinhardt, 2022). Prominent social and cultural barriers include (1) Lack of stakeholder's awareness, interest and demand, (2) Reservation against CE or company culture, (3) Limited willingness for collaboration, (4) Lack or inadequacy of knowledge about CE principles and practices (Mangla et al., 2018), and (5) the absence of operational and implementation approaches, and adequate business models and product design strategies activities (Bonsu, 2020; Hina et al., 2022).

To progress these barriers and foster the creation of innovative solutions the participation of the knowledge triangle, which includes research, higher education, and business, is crucial (Smol and Kulczycka, 2019). This means that as CE strengthens across countries and regions such as China, South Korea, Japan, and the European Union (Geng et al., 2013; European Commission, 2015; Ministry of Education, 2020; Lee and Cha, 2021), adequate forms of education and training for the CE become a prominent requirement (Domingues Martinho and Reis Mourão, 2020; Keramitsoglou et al., 2023). The European Union, in particular, has identified "education and training systems as key instruments for accelerating the transition to a circular economy" (European Commission, 2015). However, despite solid evidence highlighting the essential role of education for "bringing change in knowledge, values, behaviors, and lifestyles" around sustainability and CE (Pandey and Vedak, 2010), the adoption of educational strategies on these themes is still limited (Wiek et al., 2014; Keramitsoglou et al., 2023).

While the research field on Education for Circular Economy (ECE) is just emerging (Kirchherr and Piscicelli, 2019), its roots are strongly connected to those of Education for Environmental Sustainability (EES) and Education for Sustainable Development (ESD). EES strongly focuses on the relationship of humans with nature; its consequences, challenges, and opportunities; and ways to best manage the human-nature space (Frantz and Mayer, 2014; Kibbe et al., 2014). On the other hand, ESD takes a broader approach, incorporating social elements such as poverty, inequality, and economic development (Pandey and Vedak, 2010; UNESCO, 2014). EES and ESD have been regarded worldwide as essential for providing lifelong tools, skills, knowledge, attitudes, and values for conscious decision-making (UNESCO, 2014; Garcia et al., 2017), with universities and higher education programs considered significant contributors to this goal (Karatzoglou, 2013). As an evolving framework from EES and ESD, ECE also considers the role of nature and society but incorporates them into a systems perspective centered on the role of businesses, and their products, value chains, and ecosystems as change makers for sustainable development.

This perspective makes teaching CE vital in preparing future leaders and innovators to foster the transition to a sustainable economy (Saini and Agarwal, 2020). By incorporating ECE into higher education, students can gain the necessary knowledge and expertise to design and implement sustainable systems and business models that promote sustainable development. Moreover, the systems approach of ECE fosters interdisciplinary collaboration across the knowledge triangle. It requires a systems thinking approach, encompassing an integrated understanding of the interdependent economic, social, and environmental systems (Kordova et al., 2018), which can help students develop critical thinking skills, broaden their perspectives, and design innovative solutions to complex sustainability challenges.

It is noteworthy to mention that teaching CE still faces several challenges, including the fact that CE is a broad concept (Rödl et al., 2022). The need for multi-disciplinary and systems thinking approaches can be challenging to convey to students with diverse academic backgrounds, making the learning curve steep and risking leaving students out of the learning process (Wiek et al., 2014). Furthermore, the implementation of ECE aims to change established business practices and models, which may require students to rethink traditional economic models and paradigms. This difficulty means that one must teach the students to "think outside the box," a primarily internal process that cannot be forced, just fostered. While there is not yet a defined or best teaching style for ECE, Lim et al. (2015) conclude that teaching ESD in higher education requires pedagogical strategies to move from transmissive to discovery learning, teacher-centered to student-centered, and from theoretical to practice-oriented. It can be concluded that this is also the case for ECE. A suitable pedagogical strategy for teaching ECE is Problem-Based Learning (PBL), which is a collaborative, student-centered strategy that has been widely applied to stimulate learning motivation, problem-solving, and research skills, and is student-centered (Wiek et al., 2014; Chang et al., 2018; Randles et al., 2022). The Maastricht University (UM) uses PBL, and variations of it, such as Research-Based Learning, and Project-Centered Learning (PCL), as a key teaching strategy in all its educational programs (Department of Educational Development Research FHML, 2018).

The PBL philosophy of UM has four pillars: constructive, collaborative, contextual, and self-directed learning (CCCS) (Dolmans et al., 2005). PCL and the CCCS values were used to guide the development of this methodology. The methodology centers around a challenge that students need to solve for a company. To do so, students must engage actively and use their own knowledge

Abbreviations: CCCS, Constructive, Collaborative, Contextual and Self-directed learning; CE, Circular Economy; ECE, Education for Circular Economy; EES, Education for Environmental Sustainability; ESD, Education for Sustainable Development; FU, Functional Unit; LCT, Life Cycle Thinking; PBL, Problem Based Learning; PCL, Project centered Learning; ST, Systems Thinking; TCP, The Circular Pathway; UM, Maastricht University.

and skills across academic fields to solve it (constructive learning). Students must work in teams, and the methodology requires them to use collective brainstorming and create value chain scenarios to encourage them to work collaboratively instead of just separating tasks (collaborative learning). By using specific cases but creating different solutions across the value chain, students must look at the challenge from different perspectives (contextual learning). Finally, by letting the team plan and monitor their learning progress and evaluating both the process and product, the methodology encourages self-directed learning.

The objective of this paper is to present an ECE methodology developed for teaching CE in higher education at UM. The method applies specific CE principles in a real-world case study and an eight-step approach called The Circular Pathway (TCP). TCP provides a practical and effective way to support ECE, including Systems Thinking (ST), and Life Cycle Thinking (LCT). This method offers students a well-defined set of skills to apply in their future careers. The approach guides students through the iterative process of product and process redesign while remaining accessible to those without prior expertise in sustainability. This paper provides the principles and details of the developed ECE methodology so that other educational institutions can use it for the development of their own CE education.

This methodology is the outcome of 3 years of iterative development with students from the BSc Business Engineering at UM from 2020 to 2022. The paper is structured as follows: the methods section discusses the process of development, testing, iteration, and improvement of the methodology with a focus on the course design of the method, including the use of PCL. The results section describes each step of the methodology, key processes, outcomes, and guiding questions for tutors. The discussion section elaborates on the outcomes of using the TCP and points toward its strengths and challenges identified by the students. Finally, the conclusion section draws upon the experiences of testing this methodology to elaborate on its relevance, limitations, and future outlook.

Methods

The development of this methodology, from the educational standpoint, was designed around the PCL teaching method. The PCL method is small-scale and student-oriented, and, differently from PBL, it is focused on a specific student output: a project (Cattaneo, 2017). Students work in small groups on complex, relevant, and challenging real-world projects that require them to work collaboratively and develop creative, analytical, and problem-solving skills (Barron and Darling-Hammond, 2008). Specifically, this course was given within the "Project period" block of the BSc Business Engineering: a 4-week period where students follow only one course, the Circular Economy Course.

From a content perspective, this methodology has three transformational frameworks at the center: Circular Economy (CE), Life Cycle Thinking (LCT), and Systems Thinking (ST). The CE principles are based on the paper by Garcia-Saravia Ortiz-de-Montellano and van der Meer (2022), the frameworks for CE developed by the Ellen MacArthur Foundation (2015), and the business and design principles of Bocken et al. (2016) and Moreno et al. (2016). The overarching focus of this framework is the importance of value retention strategies to increase circularity. LCT is a framework that emphasizes the importance of understanding a product's entire life cycle, from extraction to end of life, not only its composition or processing stage (Heiskanen, 2002). Finally, ST is understood as the process of placing the product and its value chain into a broader context of social, economic, cultural, and behavioral events, both in the short and long terms (Anderson and Johnson, 1997). The three concepts of CE, LCT, and ST run across the foundation of the methodology.

Course testing and development

The main learning objective of this course, given during the years 2020–2022, was to apply the analysis and design principles of the CE to the current value chain of a specific product. Transversal to the learning objective, the course had four intended learning outcomes for the students: (1) demonstrate the ability to plan and perform a group-led scientific research project in the Circular Economy field; (2) develop teamwork and communication skills; (3) critically reflect on research work quality, group work, and scientific ethics; and (4) effectively communicate science both in writing and orally.

In total, more than 250 students have used this method at UM. Additionally, two external workshops were given at the Erasmus University Rotterdam in 2022 and the Dutch TI-COAST Analytical Sciences Talent Program in 2023, both of which provided valuable feedback on the applicability of the method for longer (6 months) and shorter (6 h) study periods, respectively. However, this paper does not discuss the workshops due to insufficient trials. Table 1 summarizes the development of the different iterations and their application to various case studies at UM.

The initial methodology, "Version 1" (V1) was delivered to master's students in the program of Biobased Materials during the 2019–2020 academic year as a pilot. The results from this pilot revealed important gaps that limited the student's ability to measure the linearity or circularity of their project. The first iteration (V2) strengthened these gaps and the overall structure of the method. V2 was delivered to bachelor students from BSc Business Engineering during the academic year 2020–2021. The increase in overall group size required better standardization of the methodology and clearer expectations from the students. The outcome of V2 was iterated once more (V3) for the academic year 2021–2022, incorporating improvements on the scoring matrixes and step definitions. With the feedback collected from V3, V4 was developed, which is described throughout this paper. The main changes for this version are the use of visual matrixes, improved circularity assessment tools, and the integration of the methodology within the "CIRCULAR" acronym. It is important to note that the number size and education level of the groups were not controlled by the research group, but organized by the university's office of student affairs.

We used two forms of feedback to improve each version: informal conversations with each team during the mentoring sessions throughout the project period (twice per week), written feedback on the "Discussion" and "Conclusions" sections of each

TABLE 1 Summary of groups and projects that have used the methodology.

Year	Total students	No. teams	av. group size	teams/case study	Industrial sector of case study	Report codes	Version
2020	6	1	6	1	Synthetic materials/kitchen sponges	[Y0T1]	V1
2021	141	28	5–6	5	Apparel/footwear	[Y1T01]–[Y1T05]	V2
				5	Packaging/release liners	[Y1T06]–[Y1T10]	
				6	Textiles/carpets	[Y1T11]–[Y1T16]	
				6	Biobased materials/seaweed	[Y1T17]–[Y1T22]	
				6	Primary chemicals/polyolefins	[Y1T23]–[Y1T28]	
2022	110	19	5–6	4	Furniture/commercial	[Y2T01]–[Y2T04]	V3
				4	Apparel/bags	[Y2T05]–[Y2T08]	
				4	Waste/citrus waste	[Y2T09]–[Y2T12]	
				4	Primary materials/rubber production	[Y2T13]–[Y2T16]	
				3	Primary chemicals/methanol	[Y2T17]–[Y2T19]	

team's report and staff feedback after the completion of each version of the course.

Results

This section describes the results from a format and content perspective. The "course design" sub-section elaborates on the format and interactions with and among students as well as the key activities expected from them at each step of the course. The "methodology" sub-section describes the TCP methodology in detail throughout the CIRCULAR acronym.

Course design

The course is designed for 4 weeks full-time with a study load of 5 ECTS. The group is divided into smaller teams of 4–6 students. Each team is assigned one case study (case studies can be the same across teams). Each case study has a project description, either provided by a company or developed by the educational team. The project description should give students a challenge and background on the industry without giving them a proposed or desired outcome. A summary of key activities and their correspondence throughout the eight steps of TCP is shown in Table 2 and detailed in Annex 1. Details on each step of TCP are provided in the results section.

Methodology

This section describes the TCP methodology in detail. It follows the CIRCULAR acronym, and the overall methodology is divided into three main blocks: *problem definition, idea exploration, and consolidation*. Table 3 summarizes the steps and blocks, as well as the expected outcomes and learning goals. Further details of each step are provided throughout the results section of this paper. Additionally, each step is complemented by a set of guiding questions to support the students' discovery process throughout the project development without restricting the exploratory nature of the methodology. These questions are provided in Annex 2.

The eight steps of the CIRCULAR pathway

Step 1. Co-define

This step is either performed together with the company or using the company's project description. The goal is to understand the challenge as in-depth as possible; identify a key product, its function, group target, and performance requirements. Using this, students must define a *functional unit (FU)*. In Life Cycle Assessment, a FU is a quantified description of a product's function, and it is used as the basis for all calculations (Arzoumanidis et al., 2020). This means that students must identify the key function that the product is providing, including the lifetime and quality parameters required to provide it. Any other relevant information for the company, the product, or the project is gathered in a brief of requirements or project brief. This is the "birth document" of the project. A template is provided in Annex 3.

Step 2. Identify

During this second step, the students zoom inside the product to see its components, material compositions, and the source of these materials. They then zoom out to consider the product's retail, delivery, use, and final destination(s) at the end of life. Students are then requested to map the product's value chain from extraction to end-of-life.

A value chain map must have information on five main areas: (1) The **product composition** is the exploded view of a product with details on its components, materials, assembly elements (such as glues and screws), coloring, or performance-enhancing elements (dyes, flame retardants, coatings, etc.), and packaging (boxes, bags, and tags). (2) The **supply chain description**

TABLE 2 Distribution of TCP methodology and milestones across a 4-week project period.

Week	1	2		3		4
Key activities	Introduction, initial lecture, kick-off meeting, Q & A 1	Company visit, Q & A 2		Mid-term assessment, Q & A 3		Q & A 4, Final presentation, Final report
Steps in the method	Co-define, identify	Recognize	Create, uncover	Level-up	Analyze, reflect	Summarize and report

TABLE 3 Description of the three phases and eight steps of the circular pathway.

	Step		Description	Main outcome	Key learning goal
Problem definition	1	**C**o-define	Determine product, functional unit, and performance properties	Brief-of-requirements with clear functional unit	Understand the challenge and case study
	2	**I**dentify	Map value chain, system, and boundaries	Map with the value chain of the current system from extraction to end of life	Recognize the processes throughout the life cycle of products
	3	**R**ecognize	Evaluate challenges of linearity in the value chain	Three to five "hotspots" where linearity is a problem	Identify priorities and challenges of linear value chains
Idea exploration	4	**C**reate	Systematic ideation at different levels using the circular matrix	Matrix of solutions	Practice using the 8Rs and 5 system levels to brainstorm ideas
	5	**U**ncover	Filter ideas and chain them into solutions	Two to three circular value chain proposals	Practice systems thinking to interconnect ideas
	6	**L**evel-up	Feedback solutions and turn them into visions	Improved value chain proposals for two solutions	Practice iteration and feedback for improving ideas
Consolidation	7	**A**nalyze	Consider assumptions, barriers, and risks of the visions	List of assumptions and limitations	Critically reflect on the limitations and scope of the solutions
	8	**R**eflect	Embed the visions in the global context of the environment, society, and the economy	Reflection paragraph	Critically reflect on the social, economic, and environmental consequences of the solutions

identifies the processes that enable the product's manufacturing, from the extraction of raw materials to the production and assembly of components and products. (3) The **use chain** considers the processes happening after the product is manufactured and before its end of life. This includes the purchasing and business model strategies, the length and intensity of use, and any potential re-use, repair, or resell activities at a product level. (4) The **retrieval chain** considers the processes after the use phase of a product, such as breaking down the product into different components for refurbishment and remanufacturing, and the separation and sorting of materials, their recycling, and the final destination of the product, components, and materials when no more value is extracted from them. (5) The **logistics** aspect of a value chain includes the strategies used to move products, components, and materials across the chains mentioned above, considering different geographies and scales, as well as considerations specific to a product, such as packaging and specialized transport.

Step 3. Recognize

During this step, students reflect on the key linearity challenges within the value chain map they created. Using a scoring matrix, they assess the current value chain in eight categories as proposed by the literature (Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022), and through literature and consensus, the group provides a circularity score from 0 to 10 for each stage. The scoring matrix is provided as Supplementary material. The aspects of the value chain with the lowest score are considered the project's "hotspots" or "bottlenecks" and will be addressed in the following steps.

Step 4. Create

In this step, students create an inventory of innovations for each identified bottleneck by using a circular matrix and trigger questions, both represented in Figure 1. To use this figure as a tool, students must gather ideas across the eight circularity strategies and on five system levels. In essence, this is a matrix, and the goal is to fill in the intersections (of a given circularity strategy and system level) with as many ideas as they can. Figure 1 shows an example of guiding questions used for the triggering of ideas, which can be used by the tutor to support the students or by the teams themselves. The use of a matrix that combines system levels with circularity strategies aims to promote creative thinking and force the search for ideas beyond the obvious or initial ones.

The five levels are built concentrically to allow students to zoom in and out of the circularity challenge. (1) The **material level** is the smallest unit of analysis and includes the materials of a product. Changes at the material level can consider their sourcing, toxicity, availability, recyclability, and environmental impact. (2) The **component level** uses the materials to build pieces that will conform to the final product. These pieces might be made

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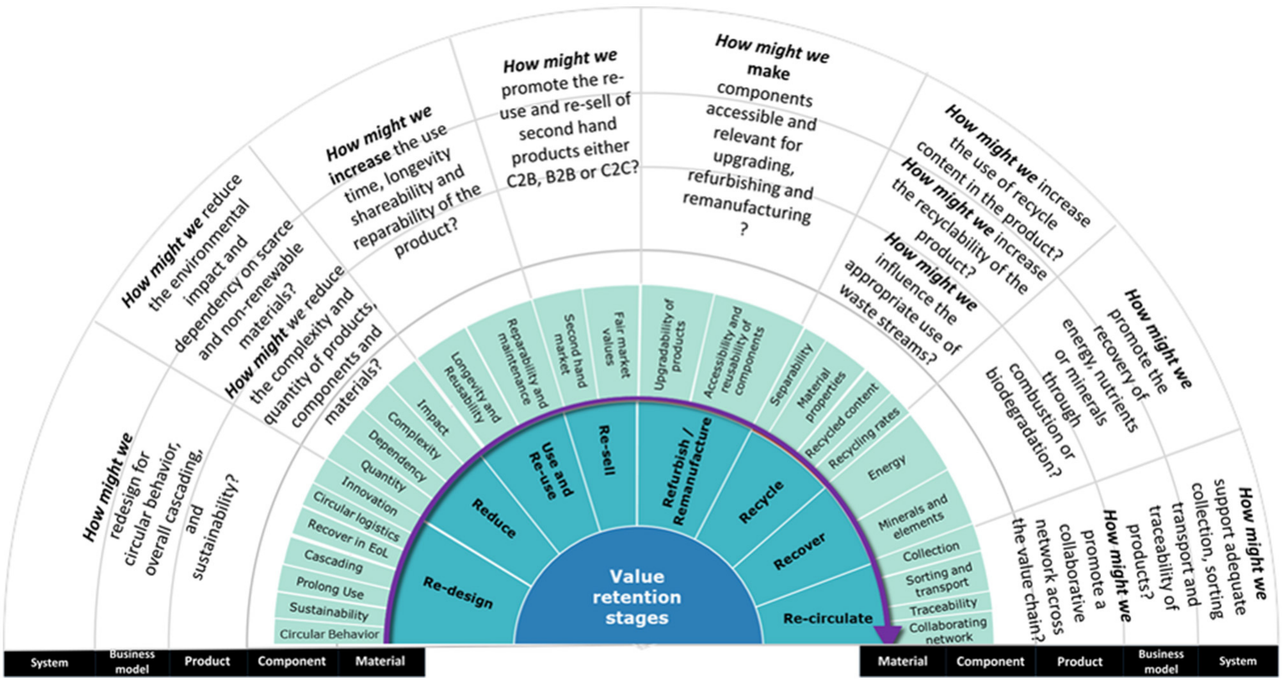

FIGURE 1
The circular matrix template and trigger questions (based on Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022).

suitable for refurbishment or remanufacturing. The component level also considers the effects of dematerialization, modularity, and reassembly of products. (3) The **product level** is made of different components and acts as the centerpiece, connecting producers to consumers and end-of-life. Changes at a product level might include increasing or decreasing the use time, repair properties, and overall design to increase circularity and circular consumer behavior. (4) The **business level** considers the strategies and mechanisms by which the product reaches the consumer's hands. It includes elements of the consumer experience, such as shifting product ownership for product-as-a-service, rental, or rewards for circular behavior. (5) The last level is the **system level**, and it considers the relationships beyond the business model toward suppliers, consumers, and cascading industries. It also considers improvements in how the system's set-up might be made more circular as a whole at an industrial park or city level.

Step 5. Uncover

This step supports the processing and organization of the ideas generated during the exploratory phase. The students must build three scenarios as new value chains by grouping the solutions they have found. The goal is to sketch three new value chains by chaining several ideas into one value chain. An example of this diagram is shown in Figure 2. This step places particular emphasis on the systemic nature of product redesign by encouraging students to consider how any solution would affect and be affected by processes occurring during extraction, manufacturing, use, cascading, and end-of-life.

Step 6. Level-up

During this step, the last one in the idea creation phase, students use the same scoring matrix as in step 3 (Recognize) to evaluate their alternatives in terms of circularity. Using these results and through collaborative discussions, students iterate two solutions to increase their circularity score by looking again at their inventory of ideas and the lowest scores from the score matrix. This step reinforces the concept of iteration and continuous improvement of ideas, a fundamental activity in product redesign using systems thinking.

Step 7. Analyze

Students analyze the potential risks and barriers for their two final solutions during this step. First, they reflect on the circumstances under which the two final redesigned products might work and what would happen if the assumptions made (e.g., available recycling facilities, use of advanced materials) were not in place. These risks can be supplier-related, technology availability, component, materials, or consumer-related. Secondly, students are asked to elaborate on barriers that could be expected for these scenarios in terms of distance and geography, organizational structure and culture, availability of resources, and existing systems surrounding the enterprise as established by Khan (2019).

Step 8. Reflect

At this stage, students have explored alternatives, converged them into plausible scenarios, and analyzed their circularity, risks, assumptions, and potential barriers to implementation. They are

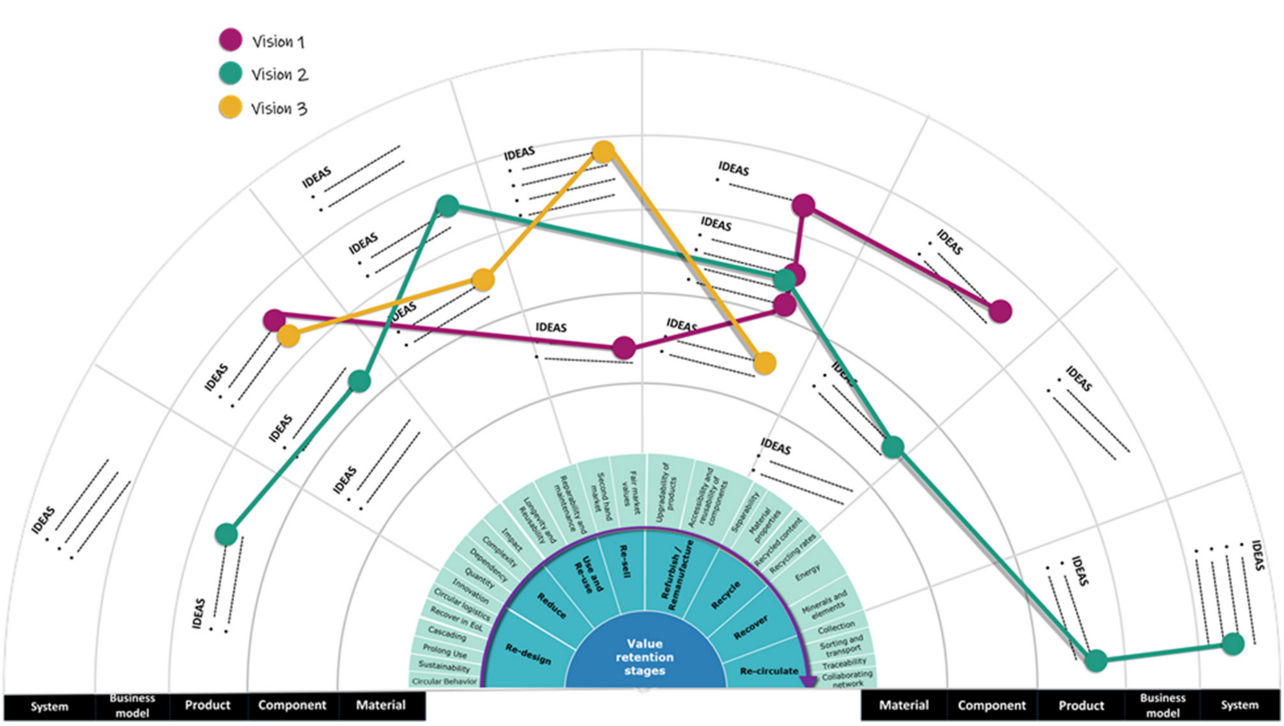

FIGURE 2
Representation of three visions created by coupling different alternatives into one value chain.

now asked to take a step back and reflect on how each solution contributes (or not) to the *key pressing challenges of the company* and the global goals and challenges, such as the Sustainable Development Goals, the planetary boundaries, and the Social Ceiling through critical thinking and discussion with peers.

Discussion

The following section discusses the strengths and limitations of this methodology in the domains of CE, LCT, ST, and soft-skills development. The discussion is based on the anecdotal evidence collected from the two courses given in the 2020–2021 and 2021–2022 academic years. Illustrative samples are included throughout the discussion, and the total of collected evidence is supplied in Annex 4. Overall, we argue that this methodology is a valuable tool for the development of LCT and skills for identifying, understanding, mapping, and prioritizing the challenges that different value chains have when transitioning to a circular economy. As one of the student teams pointed out:

> *We have learned that to achieve a sustainable product, one must not only think in the recycling part of the chain rather than each different step of the circular product. Therefore, to make a [product] sustainable, the company had to find a way to tie the different aspects of the chain in order to have a flowing circular product. [Y1T01]*

As signaled by Clark et al. (2009), this capacity of thinking in systems and across the value chain is an essential skill to redesign products beyond "superficial sustainability' to meet consumers" needs in a more holistic, sustainable, and socially responsible way. Furthermore, the students' feedback indicates that this methodology is a helpful tool to move deeper from the general challenges of circularity to the wicked issues in complex systems and ST. Two examples of this increased awareness are provided below:

> *Finding a circular alternative to a problem has been more complex and challenging than only replacing one product by another one. Redesigning a value chain is a whole organization with many aspects to think about that can affect each other. The whole process needs to be seen as a holistic view. We also saw that a problem does not always have one ideal solution. In the real world, something is rarely one hundred percent advantageous or disadvantageous. Often, a potential solution offers counterparts too. However, these counterparts have to be weighed against their benefits by the help of a score matrix. [Y1T19]*
>
> *It is important to mention that the circular economy is a complex system that is closely related to the socioeconomic context and that focuses on the value of sustainability and its impact on the environment and society. [Y2T08]*

The usefulness of ST for the design of circular products has been contested by Sumter et al. (2020), who did not find evidence of the use of ST by circular design practitioners, even when its importance has been highlighted before (Iacovidou et al., 2020; Robinson, 2022). We argue that in the context of ECE, understanding CE through the lens of ST allows students to (1) contextualize the interconnected nature of products and how redesigning one element of the system will require adaptive responses in other parts of the system as well, and (2) gain a more practical understanding its relevance to sustainability, society, business, and innovation. Moreover, the development of ST skills fosters a deeper understanding of the relationships between humanity and the environment, while raising awareness of the influence that elements outside the business unit such as inequality, global disparities and economic development have when designing for sustainability (Pandey and Vedak, 2010; Frantz and Mayer, 2014). This contribution is closely connected to the principles of EES and ESD as well.

Specific to the course design and the use of PCL, research has argued that working in teams on a project with an outsider company or client and adequate educational support can strengthen the students' individual and collaborative learning capacities and build communication, collaboration, and project-management skills (Wiek et al., 2014). Evidence from the student's reports signals that the course allowed them to practice several soft skills, including communication, and teamwork, as exemplified below.

> *The project not only cultivated problem-solving skills but also contributed to improvements in individual and teamwork, together with brainstorming and communication skills. [Y1T06]*
>
> *The project was a great source of experience and knowledge for the research team. They learned what a value chain and circularity are, how research can be conducted efficiently and how to work as a team to get through the project in an effective and precise way. [Y1T19]*

Additional to the students' feedback, the companies involved in these projects have demonstrated their interest in collaborating with students and universities on projects related to sustainability and CE. Based on our experiences and discussions with the companies, their participation allows them to broaden their perspectives through the insights provided by an "outsider team." The methodology, in particular, offers them an exploratory lens to envision the potential benefits of adopting CE practices within their specific business niche. Even if the immediate applicability may not be evident, this serves as an initial screening of alternative approaches. Finally, several companies have expressed their interest in collaborating with students with the outlook of providing them with internships and getting in contact with young professionals interested in the field. Particularly noteworthy is the interest and commitment that start-ups have shown despite the significant time investment required, relative to their available workforce.

Challenges and limitations of the methodology and initial results

We have identified three types of challenges in our ECE methodology: (1) Issues related to the relationship with the companies that supply the case studies, (2) issues related to the short period given to complete the challenge, and (3) issues related to the breadth and depth of knowledge required to complete the assignment.

The use of real-world business cases has been championed as a powerful learning tool to develop critical thinking and problem-solving skills (Kennedy et al., 2001; Baaken et al., 2015). However, the challenge of working with companies seems to be a common issue with PCL (Garousi, 2011; Wiek et al., 2014; Baaken et al., 2015). In our experience, and according to the student's feedback, one of the key blocks in their progress is the relationship with the company. Specifically, the lack of company transparency and data availability limits their access to accurate information and, therefore, the usability of their results. Two examples are provided below:

> *This lack of transparency makes it also significantly harder to understand the magnitude of the issue at hand, and the possible impact of circular products like the one proposed. [Y1T13]*
>
> *During the research the team was faced with a few limitations. This was mainly a result of the lack of information provided by the company, which prompted many assumptions on various topics, such as the composition of the [product]. If further research on the subject is intended, then effective communication with the company is the key to achieving accurate, concise results. [Y2T11]*

An alternative to solve this challenge would be to use existing business case collections (Cases | Harvard Business Publishing Education, 2023) or use data from the literature to make sure students always have access to the required information. This would reduce the dependency on the company and their availability of data, but it would also reduce the real-life experience for the students.

The second challenge, as reported by some teams, was the short time assigned for the execution of the projects (4 weeks in total), which limited the scope and depth of the results they were able to obtain. A possible solution to this would be to shift the course to the 8-week periods of the academic year, which would potentially give students more time to settle into the project and its execution, although the study load would be comparable in the 8-week period, as this period covers two parallel courses. However, no literature has been found to argue that a longer period to execute the project with the same study load would be better or worse than a 4-week full-time period.

Finally, and related to the second challenge, some teams perceived their knowledge gap on CE and the company's industrial field to be too big for the short period given. While we acknowledge their concerns, the depth of the student's reports was sufficient and analyses were complete. This indicates that perhaps more effort is required to manage the students' perception of the required depth of knowledge. Two examples of this are provided:

> *The limited time 1 month limits the possible depth in which the topic can be explored and restricts the amount of resources that could be evaluated. [Y2T18]*
>
> *One major limitation of this report is the time our team had to do thorough research. If we would have had more time we could have given better and more exact advice on how to get rid of the waste. [Y2T09]*

Overall, we contend that these challenges, and the potential alternatives here suggested, would not significantly affect the learning outcomes for this course, as the methodology still allows them to (1) demonstrate the ability to plan and perform a group-led scientific research project in the Circular Economy field; (2) develop teamwork and communication skills; (3) critically reflect on research work quality, group work, and scientific ethics; and (4) effectively communicate science both in writing and orally.

Considering the limitation that this methodology was developed specifically for PCL environments, one of the methodology's fundamental limitations is the application of results after the design phase, i.e., implementation strategies, change management practices, and process engineering. Additionally, from an educational standpoint, this methodology has been applied to a wide array of group sizes, company types and educational levels. Despite the overall positive response from the student groups and companies, further work could be directed toward fine-tuning the material for different educational levels and group sizes.

Finally, an important aspect to consider and discuss is the means of application of LCT and ST within the methodology. Our results suggest that students were able to incorporate LCT and ST tools into their projects despite having a limited theoretical background in these fields. Students were required to define a functional unit and its value chain, emphasizing the presence of ST. Additionally, they needed to identify linear challenges using various CE principles. To generate, organize, and comprehend ideas in relation to the status quo of their challenge, other potential solutions, and the entire value chain, students had to utilize both ST and LCT. Lastly, when selecting a scenario and reflecting on the business, environmental, and societal implications, students relied on the interconnected criteria of LCT, ST, and CE principles. This enabled them to present arguments in support of their work and discuss its limitations. While this approach has worked for the scope and timeline of the projects, other applications might require more extensive background information on these subjects and, depending on the case, on frameworks such as Life Cycle Assessment, Life Cycle Costing, or theories such as the planetary boundaries.

Despite these challenges and limitations, we have experienced that the methodology presented here effectively teaches the CE principles, ST, and LCT. This allows students to develop a well-defined set of skills and knowledge on CE and guides them through the iterative process of product and process redesign, which is in line with the learning goals of the course. Overall, the TCP methodology is an engaging and practical entry point to CE, ST, and LCT, whose course design and strategies support the development of teamwork, communication skills, and critical thinking, as intended by the learning outcomes of the course. Most importantly, we contend that developing graduates with the skills to create circular business models, sustainable products and services, and promote circular consumption can facilitate the growth of the CE and the creation of new, meaningful career opportunities for them.

Conclusion

The CE is gaining global significance as an alternative to offset the negative impacts of the linear economy, such as resource depletion, pollution, and climate change. However, the transition from a linear to a circular economy requires significant changes in the way businesses design products, processes, and business models. To succeed in this transition, professionals must be equipped with the knowledge and skills to implement CE principles effectively. However, there is a gap in existing higher education programs on EES, ESD, and CEE for educational resources to help students develop the skills and knowledge required to implement CE principles in real-world settings.

This paper outlines a new methodology to introduce students to the principles of CE, LCT, and ST through hands-on experience and real-world case studies in a project-centered learning environment. Together, these approaches provide a holistic perspective that looks at the system beyond individual parts or stages of a process. The findings from the application of this method at a bachelor's level indicate that students learn to identify and address complexity, linearity, and the importance of systemic change across the entire value chain, which supports their critical thinking, problem-solving, and decision-making skills. We also acknowledge that this method has important limitations due to working directly with companies in a short period and the demanding nature of fast-paced project periods. Despite these limitations, we have confidence in the relevance of this paper and method as a well-defined and tested approach for exploratory circular product redesign. We assert that the method is useful to the students' learning journey, but also to other educators, businesses, and professionals who require training in CE for educating others, advancing their careers in the field of sustainability and CE, developing new products and business models or support other industries and regions regarding circularity transitions.

This methodology is built in eight steps that follow the CIRCULAR acronym: (1) With the company, students **co-define** the topic, understand its pressing challenges and develop an initial brief of requirements. (2) Using this brief, students **identify** the product's current value chain, from extraction to use and end of life. (3) Students then use the theory provided on CE and the scoring matrix to **recognize** the critical problems of linearity regarding value retention and sustainability. These first three steps comprise the *problem definition* phase. (4) Afterwards, students **create** multiple alternatives to the identified problems at different levels and sort them to (5) **uncover** three value chains that converge multiple solutions. (6) Afterwards, students **level up** their solutions to improve them and turn them into two visions of change. These three steps cover the *idea exploration phase.* (7) Finally, students **analyze** their solutions' risks, limitations, and opportunities and compare them to the original product. (8) In closing this process, they **reflect** on these visions' impact on the business, environment, and society, which is the *consolidation phase* of the process.

Based on the empirical evidence gathered through the application and iteration of this methodology, we contend that its strong focus on systems and life-cycle thinking for CE and application to real-world sustainability business challenges contributes to and complements the existing frameworks of

Education for Environmental Sustainability (EES), Education for Sustainable Development (ESD), and Education for Circular Economy (ECE). Finally, we argue that fostering graduates equipped with the ability to create circular business models, design sustainable products and services, and promote circular consumption can contribute to the growth of a CE and the creation of new, meaningful job opportunities. As such, incorporating CE principles into higher education programs is crucial to driving the transition to a more sustainable and circular economy.

Data availability statement

The original contributions presented in the study are included in the article's Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

CG-S, YM, and AG contributed to the initial design of the methodology and its application. CG-S wrote the first draft of the manuscript. YM and AG provided feedback and guidance for improvement. All authors revised, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1197659/full#supplementary-material

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