

## **Integrating Backcasting and Eco-design for the Circular Economy: The BECE Framework**

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### **Summary**

Circular economy is essential for decoupling economic growth from resource consumption and environmental impacts. However, effective implementation requires a systemic change across supply chains, involving both technological and non-technological innovations. Frameworks are beginning to emerge to foster circular-economy thinking in organisations. However, literature review carried out as part of this research has revealed gaps in their ability to fulfil circular economy requirements. Furthermore, few frameworks provide support on how circular economy requirements may be implemented. To address these issues, this article presents a new framework “BECE” (Backcasting and Eco-design for the Circular Economy), to ensure businesses can implement circular economy requirements more readily. BECE empowers organisations to tackle the circular economy holistically, by embedding the concept into corporate decision-making and by bringing operational and systems thinking together, thus increasing the likelihood of successful implementation. The potential of the BECE framework was tested through a pilot workshop focusing on the development of a CE business model through re-design of products and supply chains. Using vacuum cleaners as an illustrative case study, several product design and supply chain alternatives were identified, including the development of scenarios and action plans for their implementation at the business level. Although the case study focuses on a particular product, the BECE framework is generic and applicable across different products and business sectors.

### **Introduction**

The concept of circular economy (CE) has emerged in recent years in response to the need for decoupling economic growth from resource consumption and environmental impacts (EC 2011; EMF 2014). Aiming to maximise resource efficiency, it represents an alternative to the current linear ‘take-make-use-dispose’ economic model. The CE concept rests on the following three fundamental principles (EMF 2012): 1) preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows; 2) optimising resource yields by circulating products, components and materials at the highest utility and value at all times within technical and biological cycles; and 3) fostering system effectiveness by revealing and designing out negative externalities. The move towards CE is fully supported by the European Commission as a vital pathway to delivering the resource-efficiency agenda (EC 2011; 2014a; 2014b; 2015) established under the European 2020 strategy for smart, sustainable and inclusive growth (EC 2010).

As the CE concept mimics the way resources flow in natural systems, it takes insights from different nature-inspired schools of thought (EMF 2013). These include natural capitalism (Hawken et al. 1999), regenerative design (Lyle 1994), industrial ecology (e.g. Graedel and Allenby 1995; Ayres and Ayres 2002), performance economy (Stahel 2006), biomimicry (Benyus 1997) and cradle-to-cradle design (Braungart and McDonough 2002). By implication, it also integrates inputs from sustainability-based approaches aimed at reducing environmental impacts by improving resource productivity. Examples include decoupling of resource use and economic growth (UNEP 2011), eco-innovation (OECD 2009), eco-efficiency (WBCSD 2000), design for sustainability (Crul and Diehl 2006; 2009), lean manufacturing (Shah and Ward 2003) and life cycle management (Remen et al. 2007). Thus, CE is a multidisciplinary field that brings together different approaches, methods and tools with the purpose of fostering a shift towards a more sustainable society.

The shift towards the CE will require radical changes in the way we produce and consume so that both producers and consumers as well as other stakeholders will have a significant role to play. Focusing on producers, it will be essential to move away from incremental solutions that encourage business-as-usual thinking and instead build sustainable business models congruent with the principles of CE (Schaltegger et al. 2012; Boons and Lüdeke-Freund 2013; Bocken et al. 2014). As Wells (2013) states, incremental changes within established systems do not have the capacity to “challenge the essence of the business models that underpin much unsustainable activity”.

Sustainable business models aim at improving the economic, environmental and social effectiveness of companies by corporate strategy planning, effective stakeholder management and enhanced operational efficiency (Geissdoerfer et al. 2016). According to Bocken et al. (2014), sustainable business models can serve as a vehicle to coordinate technological and social innovations with systems-level sustainability. Consequently, they have the potential to bridge the gap between systems level sustainable innovation and a firm’s economic performance (Boons et al. 2013). Thus, the adoption of sustainable business models can enable companies to adapt better to complex environments and achieve sustainable competitive advantages (Geissdoerfer et al. 2016). One of the ways that sustainable business models could help towards the CE is through innovative product design and manufacturing processes as they have a significant impact on sourcing, resource consumption and waste generation over time (BEDA 2015; De Groene Zaak and ETHICA 2015; EC 2014a; EC 2015; EMF 2013). For example, the product design stage determines over 80% of a product’s life cycle environmental impacts (EC 2012). Sustainable business models for the CE must also consider whole supply chains and related stakeholders, including consumers, to be able to identify and address relevant economic, environmental and social sustainability issues (Azapagic 2003; Azapagic and Perdan 2000; Bocken et al. 2014).

Backcasting and eco-design are multidisciplinary methods that can help with the development and implementation of sustainable business model innovations congruent with CE principles. Backcasting is a top-down approach that aims to move a company from current practice towards an ambitious future vision and, through scenarios (or roadmaps), establish how such a vision might be achieved at a systems level (Holmberg 1998; Natrass and Altomare 1999; Broman and Robert 2015). Eco-design, on the other hand, is a bottom-up approach that aims to minimise resource requirements and life cycle environmental impacts at an early stage of product design (Brezet and van Hamel 1997; Lifset and Graedel 2002). If coupled together, backcasting and eco-design can be used as powerful symbiotic tools, with the former helping to set long-term targets and identify practical steps to achieving them and the latter enabling realisation of the targets for product and service performance. According to Lieder and Rashid (2016), only a comprehensive framework that takes a top-down and bottom-up strategic approach and that is jointly supported by relevant stakeholders is able to

support a successful realisation of the CE concept. Backcasting and eco-design are such approaches but a framework that combines them with the aim for aiding implementation of CE principles is currently lacking.

Thus, in an attempt to fill this gap, this article presents a novel framework that integrates backcasting and eco-design with the aim of aiding business in implementing CE requirements more readily. First, we present a literature review of existing CE frameworks to examine their congruence with CE principles, actions and requirements, as well as to inform the development of our framework. Then we describe the proposed framework, followed by its application to an illustrative case study. Key conclusions and future research needs are discussed in the final section.

## **A review of circular economy frameworks**

The literature review was performed by considering research papers and practice-based publications (reports from industry, associations and consultants), identified through the use of ScienceDirect, Google Scholar and Google search engines. The following keywords were used in various combinations to identify CE frameworks: circular economy, circular business, circular products, circularity, framework, closed-loop, industrial symbiosis, industrial ecology, product-service systems, performance economy, biomimicry, cradle-to-cradle, business model innovation, product innovation, methodology, method, design, tool and toolkit.

The identified frameworks summarised in Table 1 were classified into four categories corresponding to key strategies that can contribute to building CE business models: sustainable business model innovation, sustainable product design, closed-loop supply chains and product-service systems. The scope of each framework was analysed using the ReSOLVE checklist proposed by the Ellen MacArthur Foundation (EMF 2015a; 2015b; 2015c). The reason for choosing ReSOLVE for analysing the frameworks is that it was identified through the literature review as a leading CE tool used by businesses for building CE business models, which is the focus of this work. ReSOLVE consists of six actions, underpinned by the three principles of the CE mentioned earlier. These actions are: REGENERATE, SHARE, OPTIMISE, LOOP, VIRTUALISE and EXCHANGE (EMF 2015a). Each action represents a CE business opportunity that reinforces and accelerates the performance of the other actions. The result is a strong compounding (systemic) effect that can have a profound impact across different economic sectors (EMF 2015a). Each action has a number of underpinning requirements listed in Table 1 which businesses can use to build a CE business model.

However, while ReSOLVE facilitates idea generation at a conceptual level, it lacks guidance on implementation of these ideas in business practice. To address this gap, we have added the action IMPLEMENT to ReSOLVE, resulting in the ‘iReSOLVE’ checklist. IMPLEMENT has a number of underpinning requirements taken from project management, as detailed in Section S1 in Supporting Information. These requirements aim to facilitate and increase the likelihood of implementing the ReSOLVE actions.

Following the above-mentioned classification of the CE frameworks, the next sections discuss how they integrate various iRESOLVE actions and requirements; for a summary of the findings, see Table 1.

### *Sustainable business model innovation*

Sustainable business model innovation (SBMI) frameworks are aimed at creating significant positive and/or significantly reducing negative impacts for the environment and/or society (Bocken et al. 2014). This can be achieved through changes in the way the organisation and its value chain create, deliver and capture value or change their value propositions. As indicated in Table 1, each framework can help companies address some of the ReSOLVE actions, including their implementation. However, no framework covers all the actions and the implementation requirements as defined here by iReSOLVE.

As can be noticed from Table 1, the most comprehensive SBMI framework is that proposed by Bocken et al. (2014) which includes all six ReSOLVE actions and two IMPLEMENT requirements (stakeholder engagement and systems thinking). By taking a value-network perspective, the framework describes mechanisms and solutions which can assist companies in embedding sustainability in their business model. Similarly, the value-mapping tool for sustainable business modelling (Bocken et al. 2013) can help companies design value propositions by analysing sustainable value-creation opportunities from a multi-stakeholder perspective. Both frameworks, however, lack structured (top-down and bottom-up) guidance on how a company can identify, evaluate and implement CE opportunities by aligning strategically business model innovation with product design requirements. This lack of alignment was acknowledged by Bocken et al. (2016) who proposed a CE product and business model strategy framework which uses future visioning and goal setting to guide circular product designs, concurrently with CE business model strategies. Doing so helps to ensure that designed products are supported by effective business models (increasing the likelihood of their commercial success) and, importantly, that developed business models are themselves congruent with CE principles. However, this framework does not contain step-by-step guidance on how companies should define an overarching vision based on CE principles and develop effective action plans to address the necessary business and product design changes to realise the vision.

The only two frameworks that address all five requirements of the IMPLEMENT action are those developed by Gaziulusoy et al. (2013) and Broman and Robert (2015); see Table 1. The former uses a double-flow approach to system innovation, combining backcasting and forwardcasting. This ensures that barriers that may make a future vision difficult to implement are identified at an early stage. To do so, they take a systems view of sustainability but relate this to a company, using scenario mapping to bring about a future vision. The second framework (Broman and Robert 2015), termed Framework for Strategic Sustainable Development (FSSD), is also driven by the concept of backcasting. Following four steps, it first develops a future vision that is compliant with a sustainable society and which may include company's core purpose or values. Drivers and barriers to this future vision are then identified and, through brainstorming, solutions are proposed that may help the company move from current practice towards the future vision. Finally, strategic guidelines are set to prioritise solutions into a strategic plan and to provide a roadmap of actions that will facilitate organisational change. However, neither of these two frameworks satisfy any of the ReSOLVE actions.

**Table 1.** Analysis of how the iReSOLVE actions and requirements are integrated in various circular economy frameworks (adapted from EMF 2015).

Circular economy principles <sup>a</sup>		Principles 1,2,3	Principles 2,3	Principles 2,3	Principles 2,3	Principles 1,3	Principles 1,3	Principles 1,2,3	
iReSOLVE actions		REGENERATE	SHARE	OPTIMISE	LOOP	VIRTUALISE	EXCHANGE	IMPLEMENT	
iReSOLVE requirements		Shift to renewable energy and materials Reclaim, retain, restore health of ecosystems Return recovered biological resources to biosphere	Share assets Reuse, second-hand use Prolong product life (durable design, maintenance, repair) Increase product performance and efficiency Remove waste in production and supply chain Leverage big data, automation, remote sensing, steering	Remanufacture products or components Recycle materials Digest anaerobically Extract biochemical from organic waste	Dematerialise directly Dematerialise indirectly	Replace old with advanced non-renewable materials Apply new technologies Choose new products/services	An ambitious vision/target A scaled-up business plan with a roadmap Stakeholder engagement Systems thinking (value chain, cross-cycle, cross-sector) Specific step-by-step guidelines and supporting tools		
Frameworks <sup>b</sup>	<b>SBMI</b>	Bocken et al. (2013) Bocken et al. (2014) Bocken et al. (2016) Green and Vergragt (2002) Quist et al. (2001) Hallstedt et al. (2010) Gaziulusoy et al. (2013) Broman and Robert (2015) Smolders et al. (2013) van Renswoude et al. (2015) Mentink (2014) Evans and Bocken (2013)	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	
	<b>CLS</b>	Chertow and Ehrenfeld (2012) Krikke et al. (2003) Guide et al. (2003) Rashid et al. (2013)	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	
	<b>PSS</b>	Brezet et al. (2001) Maxvell et al. (2006) Ny et al. (2012)	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
	<b>SPD</b>	Braungart et al. (2007) Baumeister et al. (2013) Tempelman et al. (2015) Crul and Diehl (2009) Poppelaars (2014) van den Berg and Bakker (2015)	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓

<sup>a</sup>Principles: 1 – Preserve and enhance natural capital, 2 – Optimise resource yields by circulating products, components and materials, 3 – Foster system effectiveness by revealing out of negative externalities. <sup>b</sup> SBMI: Sustainable Business Model Innovation; CLS: Closed-Loop Systems; PSS: Product-Service Systems; SPD: Sustainable Product Design.

### *Closed-loop systems*

These frameworks focus on resource conservation by aiming to close material loops and as such contribute to several ReSOLVE actions (see Table 1). In this respect, they are also congruent with the industrial ecology principles (Allenby and Cooper 1994; Graedel 1996; Lifset and Graedel 2002). However, they do not satisfy any of the REGENERATE requirements. An example framework in this category is Resource Conservative Manufacturing that considers resource conservation and closed-loop systems as key aspects of product design and development (Rashid et al. 2013). However, its implementation is challenging as it requires radical changes in business models, product design and configuration of supply chains but step-by-step guidance on how to achieve this is missing.

### *Product-Service Systems*

In the Product-Service Systems (PSS) frameworks, selling service rather than goods is a key business strategy. This concept was first proposed by Stahel (1994) to encourage a shift to a more sustainable economy. Today, the implementation of PSS is considered one of the most effective instruments to support the CE (Bocken et al. 2016; Tukker 2015; Bakker et al. 2014). PSS that can be grouped into product-, use- and result-oriented business models (Tukker 2004). Reim et al. (2015) point out that linking strategic- with operational-level decisions is essential for successful implementation of PSS. Baines et al. (2007) also argue that the PSS approach needs to be implemented at the systems level because it requires changing the organisational structure and early customer engagement.

Due to the nature of PSS frameworks (Table 1), they are mostly focused on supporting the development of the SHARE and VIRTUALISE actions in ReSOLVE as well as relevant IMPLEMENT requirements. They can also assist in the development of OPTIMISE and LOOP actions, depending on the PSS business strategy. However, like the closed-loop systems frameworks, they do not address the REGENERATE action in ReSOLVE nor do they support the EXCHANGE requirements. Furthermore, the implementation of PSS business model is not well studied and understood (Baines et al. 2007; Reim et al. 2015). In particular, there is a need for strategic tools and methodologies that can provide companies with business-wide guidance for the implementation of PSS, providing assistance on the configuration of products, technologies, operations and supply chain to support value creation.

### *Sustainable Product Design*

One of the frameworks in this category is cradle-to-cradle design (Braungart et al. 2007) which aims to assist designers in the development of eco-effective products and industrial processes following three natural principles: waste equals food, use solar energy and celebrate diversity (McDonough and Braungart 2002; McDonough et al. 2003). It does this by encouraging optimal material flow within technical and biological cycles (Braungart et al. 2007). Cradle-to-cradle (C2C) products should be made of biodegradable materials that can be safely returned to the environment to feed biological processes, or technical materials with the potential to be safely reused in closed-loop systems. Consequently, the C2C approach is mostly focused on supporting the development of REGENERATE and LOOP actions. It also encourages designers to formulate a vision and roadmap of eco-effective strategies to IMPLEMENT the vision at the product, brand or enterprise levels (MBCD 2012).

The biomimicry approach (Benyus 1997) encourages designers to innovate by taking direct inspiration from organisms, biological processes and ecosystems (de Pauw et al. 2015).

Following this approach, Baumeister et al. (2013) developed a framework which provides step-by-step instructions for applying biomimicry thinking in product design by scoping, discovering, creating and evaluating. Thus, like C2C, biomimicry is also inspired by nature and helps to develop similar ReSOLVE actions (Table 1). However, Volstad and Boks (2012) highlight that biomimicry should not be used without consideration of whether nature actually holds the most suitable solution for overcoming a particular problem. Similarly, de Pauw et al. (2014) highlight that using biomimicry to mimic only forms and processes does not necessarily render more sustainable outcomes. Thus, biomimicry can reach its full potential only when used in a holistic, system-level way (Montana-Hoyos 2008; Volstad and Boks 2012).

Nature-inspired design (NID) has emerged as an alternative design approach to creating products with a positive impact across value chains (de Pauw et al. 2010), which is congruent with the systems-thinking requirement of IMPLEMENT. Tempelman et al. (2015) propose a practical guide towards positive impact products through NID. For any product to be sustainable, designers should consider six basic NID principles formulated by merging the biomimicry and C2C principles. Consequently, the NID approach can contribute to the development of the same ReSOLVE actions as C2C and biomimicry, as indicated in Table 1. However, de Pauw et al. (2014) argue that if NID strategies are applied in isolation there is a risk of unforeseen environmental impacts due to the lack of quantitative tools for their evaluation.

The Design for Sustainability (DfS) framework is the result of the evolution of product eco-design (Brezet and van Hemel 1997) with the purpose of helping designers to meet consumer needs by considering three pillars of sustainability (people, profit and planet) during product development (Crul and Diehl 2009). Companies using DfS strive to alleviate negative environmental, social and economic impacts of products and services throughout their life cycle. This framework combines various methods and tools that can be applied in product re-design, new product development and product-service systems. In this way, the DfS framework can contribute to development of most of the ReSOLVE actions listed in Table 1, except for REGENERATE.

Many studies have demonstrated the usefulness of C2C (Rossi et al. 2006), biomimicry (Baumeister et al. 2013), NID (de Pauw et al. 2012; de Pauw et al. 2014) and DfS (Crul and Diehl 2006; Crul and Diehl 2009), including eco-design (Fiksel 2012), in improving the environmental performance of products systems and companies. However, this does not mean that the applications of these approaches have contributed or led to creating new business models. Rather, they are usually applied to improve the performance of a particular product category or production line. However, the move to a CE model requires radical changes, including a new way of thinking and doing business, where a combination of multiple business models and design strategies, approaches, methods and tools are required (Bocken et al. 2016). Thus, rather than choosing one particular design approach to guide product development and support business model innovation for CE, there is a need to integrate best practices from different fields of research and practice.

To this end, several frameworks focusing on circular product design for the CE have been proposed recently. For instance, Bocken et al. (2016) categorise product design and business model strategies into slowing and closing resource loops as two fundamental actions needed for the cycling of resources in the CE. Product design strategies for closing resource loops include design for a technological cycle, design for a biological cycle and design for dis- and re-assembly, which are C2C design strategies. Product design strategies for slowing resource loops include design for long-life products (attachment and trust, reliability and durability) and design for product-life extension (ease of maintenance and repair, upgradability and adaptability, standardisation and compatibility and dis- and reassembly), which are also eco-

design strategies (Holt and Barnes 2010). Similarly, Poppelaars (2014) and van der Berg and Bakker (2015) propose a product design framework for the CE based on the consideration of eco-design elements where design for disassembly is a key first step for encouraging material circularity, as specified in the EMF butterfly diagrams (EMF 2012). Design for easy disassembly can facilitate product reuse (maintenance and reparability), parts reuse (remanufacturing and component upgrading) and material reuse (closed-loop recycling).

As Holt and Barnes (2010) state, design is, by definition, purposeful. Consequently, all the design strategies mentioned above can be categorised as Design for X (DfX), where X stands for a particular product design goal. DfX strategies can be divided into those that seek to optimise product's features (e.g. simplicity, functionality, modularity, longevity, reparability or recyclability) and those that optimise a particular life cycle stage (e.g. manufacturing, assembly, distribution, use or end-of-life) (Holt and Barnes 2010). Accordingly, a diverse set of DfX tools and metrics exist to help designers develop sustainable products (e.g. Rose 2000; Knight and Jenkins 2009; Ramani et al. 2010; Allwood 2011; Sanye-Mengual 2014). Nevertheless, most DfX approaches and techniques required to design sustainable and circular products, such as design for product life-extension (slowing resource loops) and design for product recycling (closing resource loops), are not routinely applied in product development practices (Bakker et al. 2014). Some relevant limitations include the lack of robust DfX guidelines based on life cycle thinking to prevent conflicts between DfX strategies (e.g. remanufacturing vs manufacture and assembly) (Hatcher et al. 2011). The inability of some DfX tools to address fully the needs of product designers (e.g. because of tools' complexity and knowledge and time requirements) is another constraint. Additionally, practical design knowledge on product life extension, remanufacture and end-of-life management (material reuse and recycling) is currently underdeveloped (Bakker et al. 2014). Thus, Hatcher et al. (2011) states that no design is fully holistic taking all aspects of a product life cycle into account, something which is compounded by the insufficient provision of appropriate DfX tools for designers or the provision of information to guide early design decisions in areas where designers may not have expertise.

Concurrent engineering demands from designers to think beyond form and function and consider the implications of their choices at wider product development levels (Holt and Barnes 2010). Nevertheless, current DfX guidelines and techniques do not provide guidance on how product design information should be used in wider business planning and systems-level decision making. Additionally, DfX tools are usually developed by applying a reductionist, bottom-up approach to support design decision-making processes (Holt and Barnes 2010). Consequently, the isolated application of DfX tools to meet a specific design goal goes against the concepts of concurrent engineering and life cycle thinking. Likewise, the development of integrated approaches for applying multiple DfX techniques in product development has been limited. Even though methods based on the use of TRIZ contradiction matrix and life cycle planning have been proposed as a way to rank DfX strategies for development of eco-innovative products (e.g. Kobayashi 2005, 2006), they rely on the application of bottom-up approaches without integrating business models or stakeholder value network considerations comprehensively. According to Bakker et al. (2014), the most relevant challenge for the design of circular products is the selection of appropriate DfX strategies by understanding how to optimise products on sustainability. Finding business models that support those DfX strategies is also challenging. Consequently, the application of top-down (systems-level) business considerations in circular product design is crucial for evaluating the trade-offs between DfX techniques and select and implement those product design strategies that can contribute effectively to a CE. van den Berg and Bakker (2015) suggest building a circular product design vision to strategically guide the design process. Similarly, Bocken et al. (2016) state that companies should define a CE vision before



analysing circular business model and product design opportunities in order to fully capture the business potential of pursuing a CE.

### *Summary of the analysis of the CE frameworks*

As indicated in Table 1 and discussed in the previous sections, while most frameworks satisfy some of the iReSOLVE actions and requirements, none satisfies all of the criteria. Most are focused on supporting the SHARE, OPTIMISE, LOOP and IMPLEMENT actions, while REGENERATE, VIRTUALISE and EXCHANGE are mainly excluded. Two out of four requirements in the LOOP action (“digest anaerobically” and “extract biochemical from organic waste”) are missing in almost all of the frameworks; however, this is due to the nature of the case studies to which they were applied.

Theoretically, all the frameworks reviewed here have the potential to incorporate all the iReSOLVE requirements. However, no instances of this were found in the literature; indeed, some of the frameworks satisfied only a small number of requirements. It should be noted, however, that the iReSOLVE checklist is not intended as a means by which to critique or criticise the CE frameworks. Rather, it acts as a useful lens through which the different focus of existing frameworks can be appreciated. For example, it highlights that different frameworks aim to address different aspects of the CE, as required by the sector, type of product, or phase in product development in which they are applied. Nevertheless, the structured integration of the iReSOLVE checklist as part of business decision-making processes can guide companies in identifying and prioritising profitable CE opportunities.

The analysis of existing CE frameworks raises questions on how the CE can be brought about effectively, given that implementation aspects are often missing and that few of the frameworks consider innovation at a systems level. The question must, therefore, be asked as to how implementation can be fostered by such frameworks, to ensure that business models and ‘circular’ products are not just designed but also are implemented in practice. Therefore, integrative top-down and bottom-up strategies taking a systems view are essential. The integration of backcasting and eco-design approaches into a common framework could address this need and assist companies strategically in building CE business models, as described in the next sections.

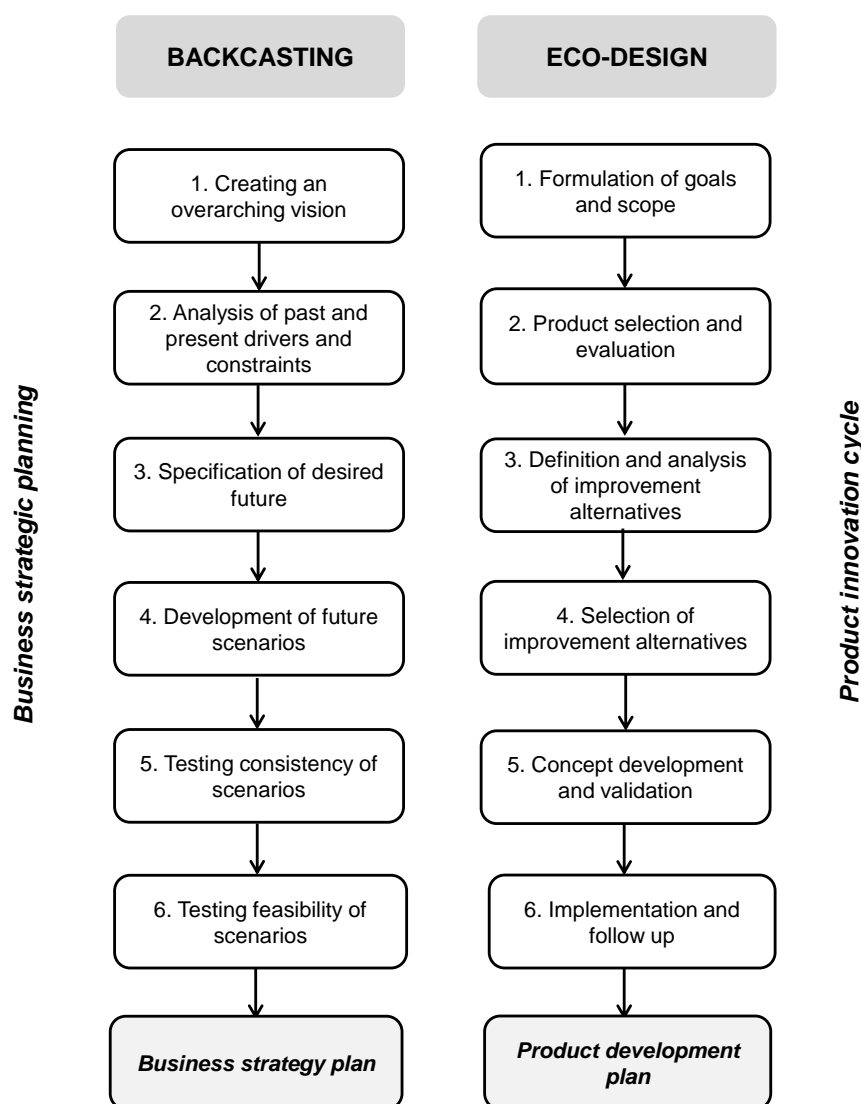
### **Backcasting and eco-design approaches**

This section provides an overview of backcasting and eco-design and the rationale for using them as the underpinning approaches in BECE. Their respective methodologies are outlined in Figure 1 and discussed in more detail below.

#### *The backcasting approach*

Backcasting can be defined as “an approach to futures studies which involve[s] the development of normative scenarios aimed at exploring the feasibility and implications of achieving certain desired end-points” (Robinson 2003). It does not aim to predict; rather, it aims to achieve a particular desirable future state (identified before scenarios are developed), by exploring alternative non-predictive pathways towards it by developing different scenarios. In practice, backcasting is usually combined with foresighting (Gaziulusoy et al. 2013; Sharmina 2013), a scenario method characterised as ‘exploratory’ as it answers the ‘what-if’ questions (Börjeson et al. 2006). Among the three scenario approaches – forecasting, foresighting and backcasting – the latter is the most suitable for exploring complex societal long-term futures, offered by the CE context, where forecasting is unlikely

to be accurate (Börjeson et al. 2006; Holmberg and Robert 2000). Compared to foresighting, backcasting is a more targeted planning tool, while the former is useful for exploring assumptions through a range of ‘what-if’ futures.



**Figure 1.** Outline of the backcasting and eco-design methodologies. The former is based on Anderson (2001), Bows et al. (2009) and Robinson (1990) and the latter on Crul and Diehl (2009), Sanye-Mengual et al. (2014) and Mendoza et al. (2015).

Backcasting has been applied in a range of contexts and sectors, including energy (Anderson et al. 2008; Pokharel 2010; Giurco et al. 2011; Thollander et al. 2013), chemicals (Partidário 2002), agriculture and forestry (Quist and Vergragt 2001), transport (JRC 2008), tourism (Benckendorff et al. 2009), residential sector (Green and Vergragt 2002; Quist et al. 2001; Quist and Vergragt 2006), and business in general (Holmberg 1998; Natrass and Altomare 1999; O’Hare 2010; Broman and Robert 2015).

As indicated in Figure 1, backcasting is used for strategic planning and is carried out following six consecutive steps, based on the approach developed by Robinson (1990) and subsequently amended by Anderson (2001) and Bows et al. (2009). In the first, an overarching vision is defined to determine future strategic objectives. This is followed in step 2 by identification of the past and present drivers and barriers to implementing the defined vision. Step 3 adds detail to the vision by characterising other relevant aspects. Subsequently,

future scenarios that could help achieve the vision are built and discussed in step 4. Their consistency and feasibility is tested in steps 5 and 6, respectively. The process is repeated until the overarching vision is achieved and the scenarios are internally consistent and feasible.

### *The eco-design approach*

Eco-design is a tool that helps incorporate environmental considerations into product (or process or service) design with the aim of minimising life cycle environmental impacts (Brezet and van Hemel. 1997; Lifset and Graedel 2002). Therefore, eco-design is underpinned by life cycle thinking and is usually used in combination with life cycle assessment (LCA) (UNEP/SETACT 2012; Remmen et al. 2007; de Pauw et al. 2014). Because it can help reduce resource use and increase the cycling of materials, it is viewed by the European Environmental Bureau (EEB 2015) and the European Commission (EC 2014a, 2014b, 2015) as a key approach for the development of the CE.

As indicated in Figure 1, eco-design is part of the product innovation cycle (Tukker et al. 2000; Crul and Dhiel 2009; van Boeijen and Daalhuizen 2013) and is, therefore, used as an operational-level tool. The eco-design methodology can be divided into six main steps. First, a set of goals are defined, which includes consideration of drivers and constraints associated with pursuing eco-design. In step 2, a product category (or service) is selected to fulfil the defined goals. The attributes of product(s) to be eco-designed should be clearly defined and their life cycle environmental performance characterised by applying qualitative and quantitative tools (Sanye-Mengual et al. 2014). As a result, in step 3 an eco-brief (Smith and Wyatt 2006) should be built to guide eco-design to overcome the hotspots identified in the previous step and to improve environmental performance. In this way, a series of eco-design strategies can be defined and their technical and socio-economic feasibility for potential implementation can be analysed. Following this, the most interesting and promising solutions are selected in step 4 for the conceptual development and environmental validation of the eco-product, which are carried out in step 5. In the final, step 6, production and marketing plans are developed for the eco-product(s) to be commercialised.

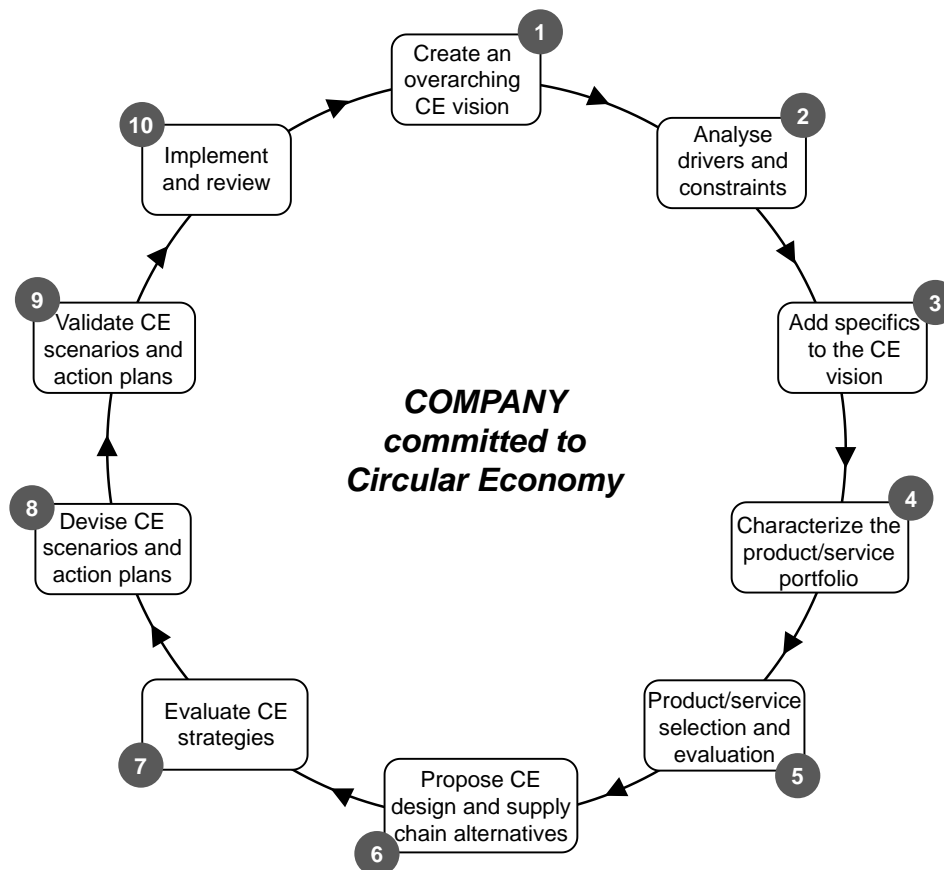
### *The rationale for coupling backcasting and eco-design*

Based on the discussion in the previous two sections, it is evident that both backcasting and eco-design are well suited for aiding businesses in implementing CE requirements. They also have a range of complementary features that lend themselves for a symbiotic relationship. First, backcasting is a top-down, strategic business planning tool that can guide eco-design processes towards the achievement of a business vision defined following CE principles and requirements. Thus, backcasting can facilitate the alignment of successive incremental eco-design improvements into viable development paths towards the development of circular and sustainable business models. Backcasting also brings the potential of stimulating ‘quantum leap’ (radical) eco-innovations in product design, as highlighted by Byggeth et al. (2007). Consequently, it can aid overcoming the relevant challenge of determining which DfX strategies should be implemented in product development, how it can be done and when it should be undertaken to achieve a CE business vision. Eco-design, on the other hand, is a bottom-up, operational approach that can help identify additional opportunities as well as support the development of backcasting scenarios towards CE through better understanding of limitations and opportunities associated with current and new product and service systems. Backcasting can sometimes underestimate the amount of effort required to achieve a strategic vision (Börjeson et al. 2006) which can be

mitigated by the level of detail provided through the eco-design approach. For instance, eco-design can play a relevant role in understanding the factors that influence consumer acceptance of new ownership business models and product-service systems (Bakker et al. 2014). Eco-design outcomes are therefore vital in determining the success of backcasting scenarios towards the CE. Furthermore, whereas backcasting is aimed at identifying strategies for the business as a whole, eco-design is more focused on addressing specific aspects of product development which may not necessarily lead to a significant change in the way business operates unless it is used to support business model innovation processes. Therefore, coupling the backcasting and eco-design approaches can serve as a powerful tool for building and implementing CE business models. This is discussed in more detail in the next section which describes how they are integrated within the BECE framework.

### **The BECE framework**

As outlined in Figure 2, the BECE framework consists of 10 steps, created by combining the relevant steps from backcasting and eco-design that were detailed in Figure 1. BECE starts with the application of backcasting (steps 1-3), helping to formulate a CE vision through consideration of the iReSOLVE set of actions. This is followed by the application of an eco-design analysis (steps 4-7), aimed at achieving the CE vision through strategic (re)design of products, services and supply chains. The framework finishes with the implementation of the vision by defining and validating scenarios and action plans (steps 8-10). In this way, the backcasting steps guide the strategic development of eco-design, whereas eco-design refines and translates the backcasting ideas into concrete solutions.

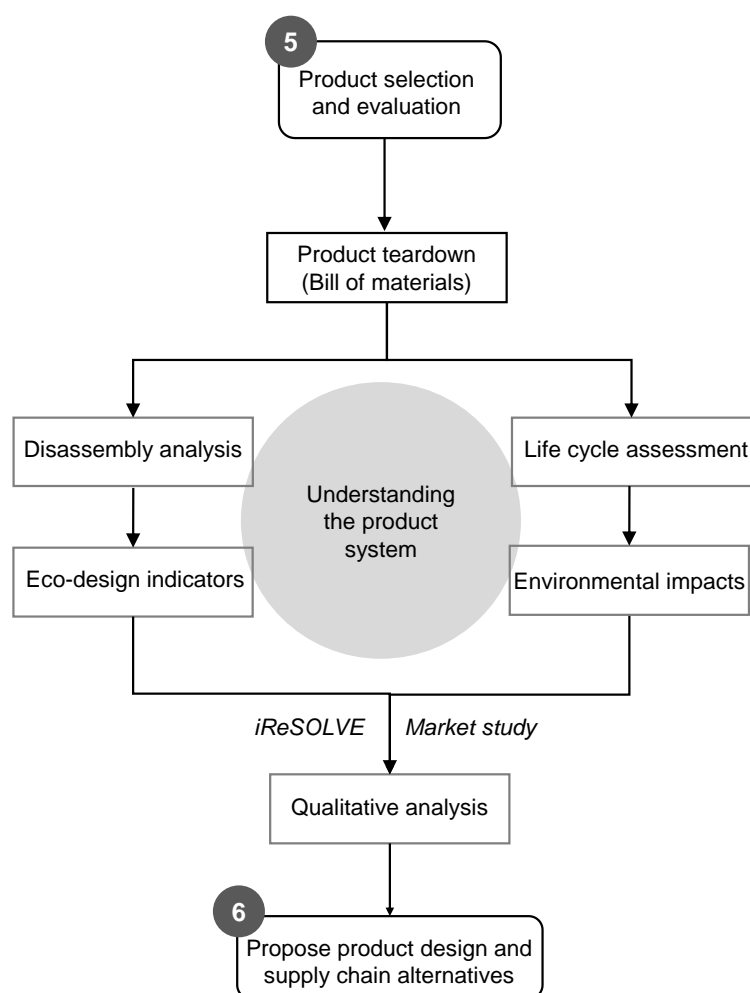


**Figure 2.** BECE framework to support the development of circular economy business models.

The most important aspect before starting the application of the BECE framework is the creation of a multidisciplinary team with knowledge and skills relevant to business model innovation, product design and CE development. The team should participate actively in the application of the framework, starting by building an overarching vision (step 1). This step reflects the strategic objective that an organisation (or a sector) aims to achieve. The defined vision should be congruent with CE principles and guided by the iReSOLVE requirements (see Table 1). This ensures that the participants are encouraged to think creatively (‘out of the box’). This is important because, if a company accepts “less bad” as good enough, then less bad is what it will achieve (Tempelman et al. 2015). Conversely, aspiring to reach an ambitious goal will increase the chances of attaining it.

The next step (2) relies on analysing the internal and external socio-economic, technological, political and environmental drivers and barriers to implementing the strategic vision. As a result, a series of specifications can be added to the overarching vision in step 3 to address all levels of the business model and embrace the CE requirements following iReSOLVE. The vision specifications are used in step 4 as a checklist to characterise qualitatively how well-suited the company’s product or service portfolio is for supporting the development of a CE business model. First, the portfolio should be classified by product or service categories and relevance (e.g. market volume, profits, policy compliance, etc.). Secondly, the degree of implementation of each vision specification to product categories or services should be analysed qualitatively to obtain a first diagnosis of how compliant the entire business model is with CE principles. This latter step allows the company to select strategically a product, or group of products or services, that will be subjected to the eco-design process. However, companies do not necessarily need to build their CE strategies based on their existing product and service portfolio. Companies can start the eco-design process by considering new product categories or services aligned with CE principles. This distinction is relevant as some companies (e.g. established businesses) may benefit from redesigning their entire business models and product portfolio (e.g. moving from selling products to providing services), while others (e.g. start-ups) may prefer to develop business model innovations from scratch.

After this analysis, the eco-design process can be initiated (step 5). The aim here is to identify ways of designing the selected product(s) or services in accordance with the vision specifications (defined in step 3). The environmental performance and the potential for improvement of the product(s) or services should be assessed taking a life cycle approach to ensure sustainable outcomes. LCA is typically used to quantify environmental impacts and identify hotspots (ISO 2006), enabling designers to make environmentally sustainable choices. However, LCA is not sufficient to support product or service eco-design as it gives no information about the disassembly complexity of the product or the flexibility of the supply chain to implement the CE principles. A tool such as product teardown (disassembly into elements) is highly effective in helping to identify ways to re-design products fit for the CE, even though it is not commonplace in design thinking (RSA 2013). Furthermore, the outcomes from the disassembly analysis (eco-design indicators) and LCA (environmental impacts) can be used to perform a Qualitative Assessment of Life Cycle Criteria (QALCC) (Sanye-Mengual et al. 2014) to gather information about the flexibility of the supply chain to respond to the product eco-design challenges. A market study may be completed beforehand to detect design trends, which can support and facilitate the eco-design thinking. The vision specifications defined in step 3 should also be considered here to support the QALCC. Figure 3 illustrates a simplified procedure for evaluating current product’s design attributes, environmental performance and opportunities for improvements in accordance with CE principles.



**Figure 3.** Product evaluation procedure to identify circular economy opportunities through eco-design.

Subsequently, product eco-design and supply chain alternatives should be proposed (step 6), consistent with the iReSOLVE actions. Different techniques can be applied here to encourage creative thinking (i.e. van Boeijen and Daalhuizen 2013; Tempelman et al. 2015). Other sources for inspiration might be the CE butterfly diagram and power cycles (EMF 2013; 2014) as well as companies' best practices and examples (e.g. Evans and Bocken 2013; Smolders et al. 2013; Poppelaars 2015; Tempelman et al. 2015; EMF 2016).

The technical and socio-economic feasibility of proposed alternatives should then be evaluated qualitatively (step 7) to select the most feasible and promising options that have the potential to achieve the overarching vision. However, before selecting the promising alternatives, it is important to go back to the results generated in step 2 and identify how the supply chain (and consequently the business mode configuration) could change if those alternatives were implemented. Afterwards, the selected eco-design alternatives should be incorporated into a range of scenarios and action plans towards achieving the vision (step 8), for further analysis considering the CE principles and requirements. It is also essential to ensure that the analysis is scaled up by extrapolating the learnings and outcomes at a product level to the system (supply chain) level.

Once the scenarios and action plans have been defined, including potential supply chain and cross-sectorial opportunities and constraints, their feasibility and consistency can be

validated by simulation, trial tests and/or prototyping (step 9). The most promising set of alternatives, scenarios and action plans should be implemented throughout the business to maximise performance. To facilitate this, roadmaps with specific milestones can be created, with a periodic revision of the outcomes from the different roadmaps, based on the use of suitable performance indicators, helping to identify improvements (step 10). The whole process can then be repeated to ensure successful implementation and continuous improvements. The following section demonstrates how BECE could be applied using an illustrative case study.

### **Application of the BECE framework to a case study**

The BECE framework was tested in a pilot workshop in preparation for a real-life application at a later stage in collaboration with a major retailer. The participants comprised eight sustainability experts working on a range of sustainability topics, including innovative business models, eco-design, LCA and CE. The workshop involved highly interactive activities, starting from co-creating a vision for a circular business model (step 1) and finishing with the identification of corresponding scenarios and action plans (step 8). Given that this was a pilot, the last two steps of the framework (9 and 10) were not considered.

The pilot workshop considered a major retail company that has the ambition of building a CE business model. As the company has the highest level of influence in managing its own products and supply chains, only own-brand products were considered, focusing on non-food categories. The main outcomes from each step of the BECE framework are presented in the next sections.

#### *Step 1: Build an overarching vision*

The iReSOLVE checklist was used to build an overarching vision (see Table 1). For the purposes of the pilot workshop, the vision was defined based on the retailer’s aspirations as “minimising resource extraction and waste generation from non-food products and supply chains by 2025, without worsening other environmental burdens and associated impacts”. The statement had been formulated prior to the pilot workshop, based on the main company’s concerns and helped the workshop participants to identify drivers of and barriers to this vision, which is compliant with the CE principles.

#### *Step 2: Analyse drivers and constraints*

The participants were then asked to identify the drivers and barriers for the adoption of the vision, across the supply chains. Applying the backcasting approach, their analysis helped to inform how the BECE framework satisfies the IMPLEMENT action, i.e., what might get in the way and what might facilitate the required transition.

This process produced a number of outcomes that would impact the company’s ability to comply with the CE principles and requirements. There were clear concerns regarding the cost of implementation, considering the scale of change required. For example, the vision might require a complete re-design of the business model and the involvement of multiple stakeholders (part of the IMPLEMENT action of iReSOLVE), who are likely to have their own goals and strategies, potentially in conflict with those of the retailer. Such stakeholder challenges include customer engagement and education as well as the training of staff across the supply chains. There is also a clear risk of market share loss if customers fail to engage with the CE concept. Another large set of challenges identified during the workshop related to the systems thinking requirement of IMPLEMENT, such as unavailability of reclaimed

and recycled materials for manufacture and difficulties in boundary setting (e.g. identifying how far upstream the supply chains should be considered and transformed).

The participants also identified a number of drivers that may help overcome such challenges, which corresponded to the stakeholder engagement and systems thinking requirements in the iReSOLVE checklist. For example, improved supply chain relationships would be a co-benefit of fostering cooperation. In addition, it is possible that some aspects of the CE may become a matter of legal compliance in the future. Acting early to embed such principles now not only ensures compliance but it also embeds the required skill sets across the company, helps to develop and implement necessary systems and gives the company the opportunity to become a market leader in this area. Importantly, it gives the business the opportunity to shape its own future on its own terms. Delaying action until it becomes a legal requirement may see them having to comply with systems that have been developed externally (e.g. by government or industry bodies) and are thus not optimised for their own needs and requirements.

### *Step 3: Add specifics to the vision*

To make the vision specific, again applying backcasting, the following two aspects were assumed to be important for a ‘desirable future’ in 2025: macro- and micro-economic context, and a business model. The context was informed by the analysis of the barriers and drivers (step 2) and simplified to four variables: competitors, customers and suppliers (cooperative vs. non-cooperative for each of the three groups), as well as the state of the economy (boom vs. bust). From this, the participants were asked to think about an ideal scenario that was free from constraints and barriers, in order to achieve the overarching vision.

The second element of the ‘desirable future’ was a three-part business model including value proposition, supply chain configuration and revenue model (Lehmann-Ortega and Schoettl 2005; Richardson 2008). A three-part business model is preferred here to more complex models for being more concise and thus more suitable for the purposes of the illustration of the framework.

Table 2 presents the details of a CE business model devised by the authors of this article and provided to the workshop participants. This business model builds on the iReSOLVE checklist, excluding sector-specific requirements such as ‘reclaim, retain, restore health of ecosystems’ (part of the REGENERATE action), ‘digest anaerobically’, ‘return recovered biological resources to biosphere’ and ‘extract biochemical from organic waste’ (part of the LOOP action). These requirements were excluded because the focus is on non-food products. The requirement to ‘leverage big data, automation, remote sensing, steering’ (part of the OPTIMISE action) was also excluded as it does not apply in this context. While the IMPLEMENT requirements were not explicitly represented, this ‘ideal’ business model is ambitious by design, requires systems thinking, a scaled-up plan/roadmap and engagement with stakeholders across the supply chain.

The company had already conducted this analysis, selecting different product categories for eco-design. These products represent either a high value-added or a large market volume for the company. Furthermore, they are deemed as having a high potential for integration of CE requirements and could hence contribute to building a CE business model by scaling up the best practices to other product categories. Based on the company’s interests, a product-oriented eco-design approach was applied to identify re-design opportunities for making products more circular. However, the BECE framework is flexible and can be applied to accommodate service-oriented requirements (see Table 2).



**Table 2:** A circular economy business model for non-food products

<b>Business model elements</b>	<b>iReSOLVE criteria</b>
Value proposition	<ul style="list-style-type: none"> <li>• A product-as-service (share assets)</li> <li>• Leasing, renting or sharing (re-use, second-hand use)</li> <li>• Take-back (remanufacture)</li> </ul>
Supply chain configuration (product design and manufacture)	<ul style="list-style-type: none"> <li>• Use renewable materials</li> <li>• Share assets</li> <li>• Reuse</li> <li>• Prolong product life</li> <li>• Increase product performance and efficiency</li> <li>• Remove waste in the supply chain</li> <li>• Remanufacture</li> <li>• Recycle</li> <li>• Dematerialise (directly and indirectly)</li> <li>• Replace materials</li> <li>• Choose new products/services</li> <li>• Use new technologies</li> </ul>
Revenue model	<ul style="list-style-type: none"> <li>• Sell a service</li> <li>• Rent and lease product</li> <li>• Provide service of repair and maintenance</li> </ul>

*Steps 4 & 5: Characterise the product portfolio and select product(s) for evaluation*

To illustrate the application of the BECE framework, a vacuum cleaner has been selected as an example product (for product specification, see Gallego-Schmid et al. 2016). To determine the product’s potential for circularity and eco-design, different indicators can be used, including material reuse (Park and Chertow 2014), resource duration (Franklin-Johnson et al. 2016) or material circularity (EMF 2015d). Here, we have used the indicators proposed by Cerdan et al. (2009) because they include a range of requirements for developing circular products (the ease of disassembly, modularity, recycled-content and recyclability) based on different strategies (product reuse, product repair, product remanufacture or product recycling as specified by the EMF butterfly diagram (EMF 2012). Also, these indicators are easy to quantify by companies which reduces time and resource requirements. To quantify the indicators, the vacuum cleaner was disassembled into its constituent elements (see Table S2 in SI for details).

As a general rule, the higher the number and diversity of elements, the more complex the disassembly process. In this case, 150 different elements made of 14 different types of material were used in the design of the product. There were 36 reversible joints that could be disassembled and reassembled without the risk of breaking; however, 57 non-reversible joints were destroyed or damaged during the disassembly process. Nevertheless, the presence of non-reversible joints may not be a problem for product recycling if they are made of the same materials (and 40 joints already satisfy this requirement). Thus, the lower the number of different materials and the higher number of reversible joints, the easier it will be to reuse, remanufacture and/or recycle the product. These joints have to be as simple and as standardised as possible to minimise the number and diversity of tools and disassembly operations. Even though there is no recycled content in the design of the vacuum cleaner, around 79% by weight could be recycled. However, improving product labelling is essential to facilitating the reuse of materials.

The product disassembly also indicated that at least 41 elements of the vacuum cleaner were not theoretically required and could be removed through re-design, without worsening

the product’s performance. Other elements could be reduced in size, such as some accessories or casings. This could contribute to saving over 400 g of materials, reducing resource use and end-of-life waste, thus contributing towards the overarching business vision.

An ideal design of vacuum cleaner should be simple and modular, with standardised and well-labelled elements. It should also be easy to disassemble to enable the circularity of materials through product reuse, maintenance and repair, refurbishment, remanufacture and recycling. These circularity criteria should guide the selection of possible eco-design solutions as indicated in steps 6 and 7 of BECE. However, as the overarching vision is focused on reducing resource use and waste across the supply chains while not worsening other environmental burdens and associated impacts, an LCA has been carried out ensure that circularity is not achieved at the expense of other impacts and to identify further opportunities for improvement through eco-design. For example, it was found that the plastic materials account for 72% of the total weight and contribute 68% to global warming potential (GWP), whereas metals contribute 27% to the weight and 32% to GWP. These materials also contribute most to the other impact categories (for details, see Gallego-Schmid et al. 2016). These results suggest that material substitution (use of low impact materials) and light-weighting may contribute to reducing the product’s environmental impacts. It should be noted that for the purposes of this research a full LCA was carried out but in most business applications, a screening LCA would suffice to help identify the hotspots and inform eco-design.

Next, QALCC was performed to determine the potential for implementation of the iReSOLVE actions and requirements (defined in step 3). This exercise included the consideration of the circularity criteria defined through the disassembly analysis and LCA. For example, the action LOOP included the ease of disassembly to facilitate remanufacture and recycling of products and parts (see Figure 4), which in turn requires design simplicity, modularity and standardisation of parts. Labelling is also an essential requirement to encourage material circularity and was implicitly considered as part of LOOP. Furthermore, as informed by LCA, the use of low impact materials was considered as part of EXCHANGE (replace materials), whereas the requirement to dematerialise, from VIRTUALISE, referred to light-weighting.

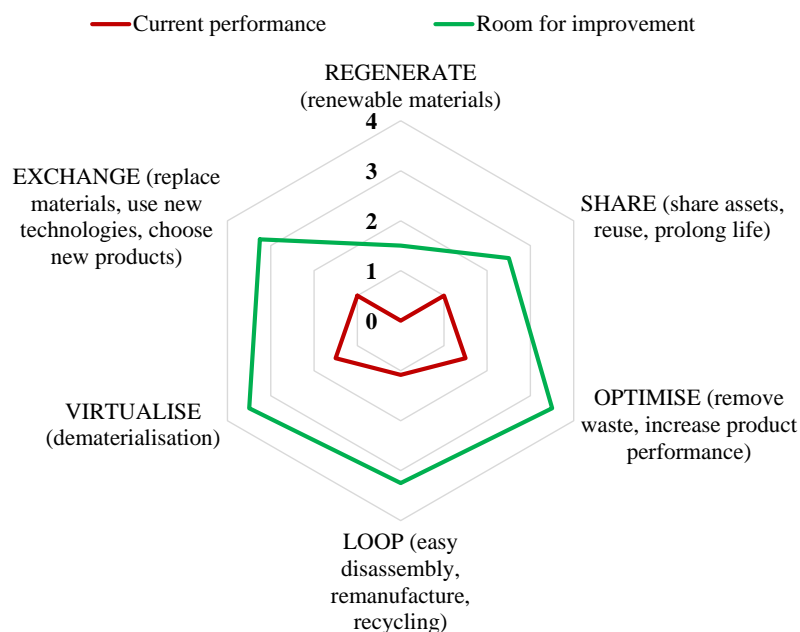
The QALCC results are summarised in Figure 4, with the lower environmental scores denoting a greater potential for improvement. The difference between the “current product performance” and the “potential for improvement” shown in the figure represents the flexibility of the supply chain to implement the CE actions. As can be seen, the requirements with the greatest potential for improvement are those related to the actions of LOOP and EXCHANGE, followed closely by the requirements related to OPTIMISE and VIRTUALISE. Thus, eco-design efforts should focus on development of these actions through product re-design and business model innovation.

#### *Step 6 and 7: Propose and evaluate product design and supply chain alternatives*

After the product evaluation, a series of eco-design alternatives were identified (step 6) and their subsequent technical and socio-economic feasibility evaluated qualitatively (step 7). The eco-design alternatives were labelled as “less feasible” (long-term), “feasible” (mid-term) and “highly feasible” (short-term). Subsequently, feasible eco-design alternatives were classified according to their priority of implementation: “low”, “medium” or “high”. The results are summarised in the next step as part of scenario development within the backcasting approach, which helps to translate eco-design and supply chain alternatives into specific and concrete actions over time, thus aiding the development of a CE business model (as defined in Table 2).

*Step 8: Devise scenarios and action plans*

As mentioned earlier, it is essential that the analysis at a product level be scaled up to the supply chain level and that alternatives for improvements are integrated into the scenarios, following through to the end of the time horizon, in this case year 2025. Informed by the analysis of the vacuum cleaner as an example product, the possible actions that could be adopted at the system level through the different time periods (present, 2020 and 2025) are listed in Table 3. All the eco-design and supply chain actions are aimed at responding to the challenges identified in step 5 in order to build a CE business model. It is important to note that the specific actions in the present are not necessarily a prerequisite for particular actions in the future; instead, they represent a menu of mix-and-match options for the company to choose from. The actions chosen for the present time represent ‘low-hanging-fruits’, such as 24/7 repair services in shops, improving user manuals and parts labelling, standardising screws and fitting easy-to-clean filters. By and large, these correspond to SHARE, OPTIMISE and LOOP of the iReSOLVE checklist but are unlikely to have a major impact on the current business model. By contrast, in the year 2020, a CE business model is assumed to have been put in practice, at least in part. As Table 3 indicates, actions related to SHARE, LOOP and VIRTUALISE are likely to require a transformation of the retailer’s supply chains configuration and value proposition, thereby changing its revenue model (see the CE business model in step 3). The end of the period faces the most challenging actions, including reducing the complexity of manufacturing and the supply chains, use of bioplastics and graphene, replacement of copper as well as reframing the concept of cleaning (e.g. vacuum cleaners are no longer needed) and introducing product multi-functionality (e.g. additional functions for a vacuum cleaner such as drying or blowing).



**Figure 4.** Results of the qualitative assessment of life cycle criteria (QALCC) for the vacuum cleaner

**Table 3.** The results of the pathway mapping up to 2025

<b>Vision specifications (BECE steps 3 and 5)</b>	<b>Potential solutions to implement iReSOLVE actions (BECE steps 4-6)</b>	<b>Feasibility (BECE step 7)</b>	<b>Prioritisation (BECE step 8)</b>
REGENERATE Renewable materials	Use of bioplastics	Low	2025
SHARE Share assets Reuse Prolong life	24/7 repair services in shops Availability of spares Extended warranties Easy to clean filters Vacuum-for-life service	High Medium Medium High Medium	Present 2020 2020 Present 2020
OPTIMISE Remove waste Increase product performance	Buy according to your needs (e.g. accessories) Minimise manufacturing steps and requirements Reduce the complexity of supply chains Improve user manuals	High Low Low High	Present 2025 2025 Present
LOOP Easy disassembly Design simplicity Modularity Standardisation of parts Labelling Remanufacture Recycling	Standardise screws Reduce the number of pieces Use bigger but lighter parts Implement a take-back system Label repairable/upgradable/recyclable elements Avoid mixing materials Increase recycled content and recyclability Partnership/communication with recyclers	High Medium Medium Medium High Medium Medium Medium	Present 2020 2020 2020 Present 2020 2020 2020
VIRTUALISE Dematerialise Light-weighting	Envision a new concept of cleaning Take the wheels off Remove the wiring system (cordless) Encourage multifunction (e.g. dryer/blower)	Low Medium Medium Low	2025 2020 2020 2025
EXCHANGE Replace materials Use low impact materials Use new technologies Choose new products	Use fewer types of plastics Use graphene Substitute copper	Medium Low Low	2020 2025 2025

It is clear that the short-term actions are incremental, while in the future they become increasingly more difficult to implement, requiring a greater level of change compared to the existing product and supply chain. However, some of these actions complement each other and can facilitate the development of other actions. For example, solutions related to VIRTUALISE may have a positive effect on LOOP, OPTIMISE and SHARE if products are not sold but services are provided instead (e.g. through the renting or leasing of products). Furthermore, the LOOP activities, such as the implementation of take-back systems can contribute to the VIRTUALISE actions, as this would reduce material requirements. When combined, these actions can lead to a radical change at the product and supply chain levels, helping to deliver the company’s vision in accordance with CE principles.

## Conclusions

The literature review highlighted that sustainable business model innovation frameworks need to integrate CE principles and requirements consistently and systematically to progress towards a CE. Deploying a CE presents an opportunity to support sustainable development through closed-loop supply chains and product-service systems. Consequently, instead of using sustainability-based decision-support frameworks (e.g. SBMI, CLS, PSS and SPD) in isolation, there is a need to apply holistic CE frameworks integrating top-down (business model) and bottom-up (product-service design). considerations. In response to this

requirement, this article has proposed a novel Backcasting and Eco-design for the Circular Economy (BECE) framework aimed at helping companies to develop sustainable business models that translate CE principles into industrial practice.

The BECE framework goes beyond other CE frameworks in several respects. Firstly, it explicitly integrates CE principles for business model innovation. Secondly, it is underpinned by the CE actions as articulated in the ReSOLVE checklist, with each action representing a relevant CE business opportunity. Thirdly, it emphasises implementation, thereby supporting the integration of CE requirements into business practice. Furthermore, the framework takes a strategic view of a CE, by starting with an ambitious vision. . This CE-compliant strategic vision allows a company to define the direction and scope of its future CE activities upfront and guides the effective implementation of the different steps of the BECE framework to build a successful circular business model.

Thus, BECE takes a systems view, ensuring that identified solutions are sustainable along the product life cycles and supply chains. Moreover, by combining backcasting and eco-design, the framework bridges the gap between the strategic and operational levels, providing tools for both top-down strategic planning and bottom-up product and supply chain design. For instance, LCA, QALCC and product disassembly can be used in a modular fashion and compensate for the top-down orientation of backcasting by providing a detailed analysis of pathways towards a strategic CE vision. Coupling strategy and business model analysis is also needed to protect competitive advantage resulting from new business model design (Teece 2010). Hence, BECE provides a means for translating a strategic vision of CE into specific and implementable step-by-step actions. In this way, the framework can help firms to understand why the CE is important to them and encourage their commitment to it..

The application of the BECE framework was illustrated through a case study focused on product re-design to build a circular business model. However, the framework is generic and flexible and can be applied in different organisations, sectors and contexts, including service provision. This can lead to new, potentially radically different circular business models that may satisfy customer needs in new ways, requiring changes at a strategic level. This consideration is important as there is no one-size-fits-all solution to the identification, analysis and implementation of CE opportunities. The characteristics of different businesses, sectors and regions can vary considerably, therefore requiring toolbox customisation to support decision-making processes aligned with CE principles.

Additionally, user-centric or result-oriented eco-design approaches can be applied to help manufacturers and product-selling companies shift to services (e.g. SHARE and VIRTUALISE) or implement CE principles in service companies. However, products, infrastructure and other physical elements will always be needed to support service provision, whether directly or indirectly. Even if a user-centric, or result-oriented, approach to CE strategies in product- or service-based companies is applied, product design requirements (e.g. OPTIMISE and LOOP) must still be taken into account. However, current DfX techniques are limited in scope. There is a lack of comprehensive guidelines and tools based on life cycle thinking that are able to assist designers in the strategic application of multiple DfX techniques to develop sustainable and circular products. The BECE framework can help overcome this challenge by using an ambitious CE vision to select and apply appropriate DfX techniques. Nevertheless, further research is required to develop innovative DfX tools by embedding top-down business considerations able to guide the strategic development of circular product-service systems.

Although an initial demonstration showed promising results, further research is also required to improve and validate the BECE framework. One of the limitations of BECE is its complexity, which is partly due to its level of detail and comprehensiveness. This can be overcome by using BECE in a modular fashion and streamlining some of the analyses,

including LCA. Applying BECE for different business models, e.g. service-oriented, would also be of value. Furthermore, BECE could benefit from an overarching definition of the CE at the beginning of its application, to ensure that each application produces results that are consistent with this definition. For example, two companies could have different future visions of circularity that are appropriate to them; however, both of these visions should be compliant with an overarching definition of CE. The framework for strategic sustainable development (FSSD) discussed in the article (Broman and Robert 2015) takes a similar approach by defining sustainable development as the framework’s first operational procedure. Another avenue for future research would be to analyse the potential integration of best practices from nature-inspired design techniques, such as cradle-to-cradle and biomimicry (as an alternative to product eco-design) and how more radical approaches in business models based on product-service systems would affect the structure, development and results of the BECE framework. The study of these approaches could include building CE business models both in mature companies based on re-design practices and in start-ups that are more suited to radical innovations. There is also a need to develop generic and sector-specific product circularity indicators to help product developers choose appropriate strategies. Development of analytical models to assess environmental consequences of reconfiguring supply chains towards the CE would also be valuable.

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### **Supporting Information**

The supporting information provides a description of the IMPLEMENT requirements added to the ReSOLVE framework to create the iReSOLVE checklist. Additionally, it presents the eco-indicators used to characterise the circularity and eco-design potential of the vacuum cleaner considered in the case study.