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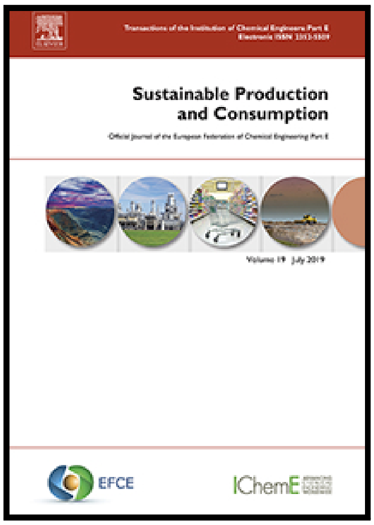

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An expert system for circular economy business modelling: advising manufacturing companies in decoupling value creation from resource consumption

Marina P.P. Pieroni[1*], Tim C. McAloone[1], Yuri Borgianni[2], Lorenzo Maccioni[2], Daniela C.A. Pigosso[1]
[1]Technical University of Denmark (DTU), Department of Mechanical Engineering, Nils Koppels Allé 404, DK- 2800 Kgs, Lyngby, Denmark
[2]Free University of Bozen-Bolzano, Faculty of Science and Technology, Universitätsplatz 3 - piazza Università, 3-39100, Bozen-Bolzano, Italy

*Corresponding author: mdpp@dtu.dk

Abstract: Shortcomings in manufacturing companies' capabilities to execute circular economy business modelling have delayed a broader dissemination of circular business models beyond the stage of pilot projects in niche markets. Circular economy poses additional uncertainties for innovation that are not common for manufacturing companies' traditional activities and business as usual. To cope with such challenges, they lack systematised practices and proactive advice, which are scant in available literature and approaches. The paper presents the development of the tool Circular Economy Business Modelling Expert System within manufacturing companies, intended to address these limitations. Based on systematised business modelling practices for circular economy and proactive advice on potential circular business model configurations, the expert system enhances strategic thinking for circular economy, supporting companies to come up with varied alternative business models with reasonable and viable value propositions to deploy circular benefits accordingly. The expert system was streamlined based on literature review, development, testing and evaluation with 12 practitioners from 10 companies. The paper discusses the main functionalities of the expert system and the results of its application into varied manufacturing companies. The application of the expert system has demonstrated to benefit companies with: inspiration for best practices on circular business modelling, a structured framework for confirming assumptions and a logic structure that prompts decision-making and reduces uncertainties.

Key-words: circular economy, sustainability, business model, innovation, tool

1. Introduction

Circular economy (CE) promises to slow down the exploitation of resources to respect Earth's capacity, whilst enabling economic development. By promoting a vision of decoupling resource consumption from value creation, CE can contribute to a series of goals related to the green transition (e.g. the European Green Deal) and sustainable development (e.g. achievement of Sustainable Development Goals) (European Commission, 2019; Schroeder et al., 2019).

CE implementation requires fundamental changes in the societal, industrial and consumption foundations (Böhringer and Rutherford, 2015). Manufacturing companies have a driving role in CE implementation due to their influence in the definition of value offerings and products' life cycles (Blomsma et al., 2019; Lieder and Rashid, 2016; McAloone and Bey, 2009). To be able to achieve ambitious targets, companies will need to innovate their business models (BM) for CE, to promote disruptive changes able to generate higher impact on consumption, as opposed to acting solely on reactive and end-of-life strategies (e.g. recycling).

Circular economy business models (CEBMs) have hitherto limited penetration within the manufacturing sector and are still covering a niche market (OECD, 2018). The vast majority of CEBM initiatives in the European Union have focused on recycling or the development of circular supplies, with minimal contributions to more impactful solutions able to shift consumption systems at their core (i.e. such as products-as-services) (Mhatre et al., 2021). Moreover, CEBMs are currently only at a pilot level in the manufacturing industry. There is a need to systemically align CEBMs with the manufacturing companies' core corporate strategies to reach all the potential benefits (Khan et al., 2020; Urbinati et al., 2017).

Several external barriers have contributed to this limited dissemination of CEBMs (e.g. customers' preferences for 'new' products, regulatory restrictions, lack of infrastructure) (de Jesus and Mendonça, 2018; Kirchherr et al., 2018; OECD, 2018). Shortcomings in manufacturing companies' capabilities and skills to execute circular economy business model innovation (CEBMI) are within the most relevant bottlenecks (Bocken and Geradts, 2019; Chiappetta Jabbour et al., 2019; De los Rios and Charnley, 2017; Guldmann and Huulgaard, 2020; Khan et al., 2020; Kirchherr et al., 2018). CEBMI comprises the process of designing CEBMs (e.g. finding opportunities, configuring and implementing viable and promising CEBMs), the influencing aspects on the process (e.g. transformation, ecosystem), and the outcomes of the process (i.e. the innovative CEBMs) (Foss and Saebi, 2017). The process of designing CEBMs is called circular economy business modelling (CEBMn) in this paper, and deals with elements such as activities, methods and tools to promote innovation within organisations (Bocken et al., 2013; Rohrbeck et al., 2013). Manufacturing companies require knowledge and science-based approaches to conduct CEBMn (Bocken and Geradts, 2019; Khan et al., 2020; Lieder and Rashid, 2016), since designing CEBMs lead to additional uncertainties when compared to traditional BMs, such as changes in financial value creation and enhanced operations complexity (Bocken et al., 2018; Lieder and Rashid, 2016).

CEBMI body of knowledge is still in a conceptualisation stage and is characterised by fragmented and sometimes incongruent literature (Merli et al., 2018; Nußholz, 2017; Pieroni et al., 2019a). As pointed out by systematic reviews in the field, the varied CEBMn approaches developed so far present challenges in their current format for practical and systematic application within organisations (Bocken et al., 2019; Khan et al., 2020; Pieroni et al., 2019a). For example, they are still scattered and lack systematisation of managerial practices in a holistic structure (i.e. set of management activities to support the execution of a business process with varied methods and tools). In particular, they have an atomistic discussion level with focus on the early development stages of CEBMs in detriment of processes that cover all innovation stages from ideation to implementation. Moreover, existing approaches lack support to enable companies to cope with increased uncertainties of CEBMn, since they are heavily based on abstract workshop-based tools and activities, thus hindering documentation, iterations and repeatability of the CEBMn process. Additionally, analytical and decision-support activities are not explicitly considered (Ünal et al., 2019b). Finally, CEBMn approaches remain conceptual and essentially descriptive, with limited empirical demonstration and limited potential to offer advice for independent application by practitioners (Bocken et al., 2019; Kirchherr and van Santen, 2019; Lieder and Rashid, 2016; Pieroni et al., 2019a).

In summary, to bridge the existing gap between scientific knowledge and action (Lüdeke-Freund et al., 2019a), CEBMn approaches need to provide systematised knowledge and proactive advice to support companies in their decision-making and configuration of CEBMs. To fulfil this need, this paper presents a tool for CEBMn within manufacturing companies able to offer systematised CEBMn practices and proactive expert advice for CEBM design. The tool, developed in the format of an expert system, aims to enhance strategic thinking for CE by supporting companies to come up with alternative CEBMs. Those are to be featured by reasonable and viable value propositions to deploy CE benefits (e.g. long-term value creation and resource consumption reduction), and are built upon recommendations provided by the expert system according to the specific companies' sector and other contextual factors, which advances the status-quo of existing tools.

This article focuses on illustrating how this tool called Circular Economy Business Modelling Expert System (CEBMES) was conceptualised (i.e. based on previously systematised CEBMn practices and proactive advice that serve as foundations for the expert system) and thoroughly evaluated regarding its applicability and usefulness within ten manufacturing companies.

After an overview of the literature and conceptual foundations for the CEBMES (section 2), this paper describes the methods (section 3), the proposed CEBMES with its elements and the evaluation results of its application within manufacturing companies (section 4). Finally, the applicability, limitations, contributions, and future research possibilities are discussed (section 5), followed by conclusions (section 6).

2. Literature Review: Circular Economy Business Modelling

The conceptualisation of the tool CEBMES relied on the identification of previously systematised CEBMn practices and proactive advice that can serve as content for the CEBMES. Hence, this paper builds on CEBMn frameworks previously developed in CE literature. This section provides an overview of available CEBMn approaches (section 2.1) and frameworks used for the conceptualisation of the CEBMES (section 2.2).

2.1. *Overview of circular economy business modelling approaches*

CEBMI has attracted increasing interest from industry and academia since 2013 (Diaz Lopez et al., 2019). Seminal publications focused on arguing for the relevance of the topic (Linder and Williander, 2017;

Schulte, 2013) or on outlining the concept of CEBMs and CEBMI (Lewandowski, 2016; Nußholz, 2017). Subsequently, different systematic literature review studies were published exploring multiple perspectives such as definitions and conceptual framing of CEBMI and CEBMs (Geissdoerfer et al., 2020; Rosa et al., 2019); different types of CEBMs and their adoption by industry (Diaz Lopez et al., 2019; Lüdeke-Freund et al., 2019b; Mhatre et al., 2021; Pieroni et al., 2020a; Reim et al., 2019; Rosa et al., 2019); and available approaches for CEBMn in academia and practice (e.g. managerial activities, methods and tools) (Bocken et al., 2019; Centobelli et al., 2020; Pieroni et al., 2019a).

According to these studies, the most recurrent CEBMn tools available in literature are mainly focused on guiding the early stages of ideation for CEBMs, relying on workshop-based application (Bocken et al., 2019; Pieroni et al., 2019a). Examples of such tools comprise visualisation frameworks/canvases (Antikainen and Valkokari, 2016; Bocken et al., 2018; Lewandowski, 2016; Mentink, 2014; Nußholz, 2018), or archetypes and morphological boxes (Bocken et al., 2016; Diaz Lopez et al., 2019; Lüdeke-Freund et al., 2019b; Moreno et al., 2016; Pieroni et al., 2020a; Planing, 2018; Whalen, 2019; Yang et al., 2018). As a consequence of their abstract workshop-based approach, these tools frequently demand external facilitation. Moreover, they are limited in the extent that they allow proper documentation, iterations and repeatability of the CEBMn process by companies, which is fundamental to enable companies to explore and manage intrinsic uncertainties of CEBMn. Lastly, these tools lack continuity or a holistic overview of the CEBMn processes that cover innovation stages beyond ideation (i.e. detailing, evaluation, implementation).

Similarly, available tools from practice proposed by think-tanks or consultancies do not yet holistically address the identified limitations and gaps. For instance, the tools *Circulab* (Wiithaa, 2018) and the *Circularity Canvas Methodology* (Sustainn, 2017) envision stages beyond the ideation, however, they are still based on workshops and limited in providing advices and flexibility for iterations/simulations. The *Circular Economy Toolkit* (Evans and Bocken, 2013), the *Circulator (or Circular Business Model Mixer)* (EIT Raw Materials, 2016) and the *Smart Business Modeler* (Lüdeke-Freund et al., 2019a) provide advice for the ideation stages with recommendations of CEBM alternatives (i.e. based on cases or CEBM patterns) and enable iteration or repeatability to some extent. However, they are limited or lack analytical and decision-support tasks for assessing and implementing CEBMs (i.e. assessment of the CEBM economic or resource decoupling potential). Moreover, the *Smart Business Modeler* was not originally developed for CEBMn. In summary, these tools still miss an effective systematisation of CEBMn practices able to support decision-making for CEBMn.

2.2. *Expert systems to support decision-making*

An expert system uses databases of expert knowledge to offer advice and decision-making support in specific areas (Liao, 2005). Similar to a human consultant, an expert system can also contextualise and explain the advice provided. Usually presented as a computer-based system (or software), an expert system is designed to simulate the decision-making ability of a human expert to solve complex organisational problems by reasoning through bodies of knowledge (Liao, 2005).

Expert systems have been used successfully in diverse domains and for multiple purposes ranging from Medicine (supporting medical planning/diagnosis) to Management (supporting decision-making in complex organisational problems) (Liao, 2005). Beyond the varied types of applications, multiple methodologies are available as a means to underpin the development of expert systems. For example, Im and Cho (2013) proposed an expert system based on morphological analysis and integrated fuzzy approach to support companies with developing, evaluating and selecting BMs to meet their business objectives. However, this approach was limited to traditional business modelling and lacks CE focus, which is, conversely, explicitly targeted in this research.

To fulfil the need explored in this research (i.e. effective tools in providing systematised knowledge and proactive advice to help companies with CEBMn), the format of an expert system was selected to guide the development of the tool CEBMES.

2.3. *Conceptual foundations for building an expert system for circular economy business modelling*

Two frameworks available in literature were selected as foundations for the conceptualisation of the CEBMES due to their enhanced methodological robustness that included systematisation of already available knowledge (presented in section 2.1) followed by detailed studies with complete evaluations across a considerable number of manufacturing companies (Bocken et al., 2019; Kirchherr and van Santen, 2019; Rosa et al., 2019). These frameworks are the *CEBMn Process Model* (Pieroni et al., 2019b) and the *CEBM Patterns* (Pieroni et al., 2020b).

The *CEBMn Process Model* (Pieroni et al., 2019b) was developed from systematisation of CEBMn practices from CE literature and testing with seven companies through action research (A-G in Table 2). The practices comprised by the CEBMn process are organised in three stages (i.e. sense, seize and transform) and include 14 deliverables (e.g. CEBMI opportunities, CEBM ideas), 14 activities (e.g. map CE characteristics in current BMs and estimate circularity potential), 8 decision gates (e.g. screen value propositions according to CE gains), 10 change enablers/catalysers (e.g. ability/willingness to question linear dogmas) and 14 tools (e.g. Circular Strategies Scanner, SWOT). These practices were used as foundations for the deployment of the modules and steps of the CEBMES (explained in section 4).

The *CEBM Patterns* (Pieroni et al., 2020b) were developed from multidimensional scaling analysis (Amshoff et al., 2015) of 180 cases of companies that implemented CEBMs. Moreover, they were complemented by insights from industrial experts (companies H-P in Table 2). The patterns were used in the CEBMES as a means to provide advice about possible configurations of CEBM for different contexts and sectors (explained in section 4).

The following section 3 explains how these frameworks contributed in the conceptualisation of the CEBMES.

3. Methods

The research approach adopted was the Design Research Methodology (Blessing and Chakrabarti, 2009) and comprised four stages (Figure 1), which are described in the sub-sections 3.1 to 3.4.

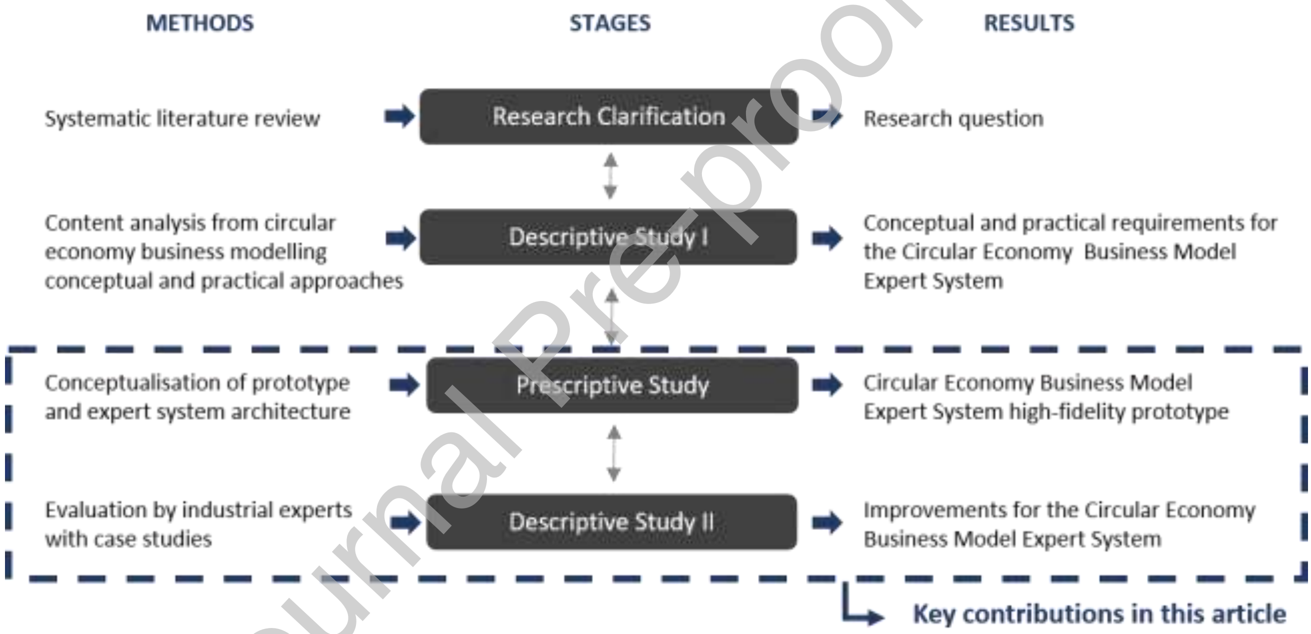

Figure 1 - Research approach.

3.1. *Research Clarification*

By means of a systematic literature review (Pieroni et al., 2019a) the research gap was identified as: *the lack of a structured approach able to provide guidance and advice to manufacturing companies for CEBMn, beyond the level of ad hoc workshops and discussions available in existing tools*. This gap led to the need for scientific investigation in the format of a research question: *How can an expert system be developed to provide advice to manufacturing companies on CEBMn?*

3.2. *Descriptive Study I*

Descriptive Study I identified and prepared the foundations to build the CEBMES. First, 21 conceptual and practical development requirements were compiled (Pieroni et al., 2020c). Conceptual requirements (R1-R11 in Table 1) were collected based on content analysis (Dresch et al., 2015) from previous systematic literature reviews about best practice CEBMI (i.e. including CEBMn) methods or tools; gaps of methods or tools in providing advice to companies; and recommendations for developing new methods or tools (Bocken et al., 2019; Pieroni et al., 2019a; Rosa et al., 2019). Practical requirements (R12-R21 in Table 1) were collected from a previous detailed practical study that applied the *CEBMn Process Model* (section 2.2) with seven manufacturing companies from varied sectors (Table 2) (documented in Pieroni et al. (2019b)). The conceptual and practical requirements were prioritised in 'must-be' or 'attractive' depending on their degree of importance according to literature and users (companies A-G in Table 2) (Kano et al., 1984).

Based on the requirements, the foundations for the CEBMES development were selected, i.e., the *CEBMn process model* (Pieroni et al., 2019b) *and the CEBM patterns* (Pieroni et al., 2020b) (described in section 2.2). Table 1 illustrates how these frameworks fulfil the requirements for the CEBMES development, and highlights which requirements will be created or enhanced by functions developed within the CEBMES.

Table 1 – Requirements for the expert system. Adapted from Pieroni et al. (2020c). Legend: CEBM - circular economy business model; CEBMn - circular economy business modelling; CEBMES - Circular Economy Business Modelling Expert System.

Code	**Requirements (R)**	**Relevance**	**Fulfilment of requirements**		
			CEBMn Process model	**CEBM Patterns**	**Created/ enhanced by CEBMES**
R1	Simple and not too time-consuming	Attractive			✓
R2	Enables adaptations to different contexts	Must-be	✓	✓	
R3	Provides advice – i.e. prescriptive tool	Must-be		✓	✓
R4	Provides a transparent procedure and application guidance	Must-be	✓		✓
R5	Enables low requirement of external facilitation - i.e. knowledge embedded in the tool	Attractive			✓
R8	Inspires or triggers business change	Must-be	✓		
R9	Safeguards circular economy/broader sustainability objectives	Must-be	✓	✓	✓
R10	Guides ideation with different types of CEBMs	Must-be	✓	✓	✓
R11	Envisions all elements of a business model	Must-be		✓	
R12	Supports decision-making with focus on business value – i.e. quantification of economic/resource decoupling gains	Must-be	✓		✓
R13	Enables a holistic approach - i.e. from design to implementation	Must-be	✓		✓
R14	Provides suggestions to inspire new CEBMs with cases	Attractive		✓	
R15	Focuses on specific sectors	Must-be		✓	
R16	Supports a logic flow of decisions	Must-be	✓		✓
R17	Supports communication and teamwork	Must-be			✓

R18	Considers the ecosystem and collaborations	Attractive		✓	
R19	The value proposition definition follows an iterative process with explicit guidelines	Attractive	✓		
R20	Enables comparison of CEBMs	Attractive			✓
R21	Enables a repeating process, with data storage and migration	Attractive			✓

3.3. *Prescriptive Study*

Based on the requirements, key CEBMES' functions were identified and organised according to an overall architecture by describing:

- Specific modules and steps, i.e., what users need to accomplish;
- Functionalities, i.e., what the CEBMES can do for users to support them with the steps within the modules;
- Logic and content for the different levels of information, i.e., front-end, back-end and databases.

The architecture was deployed into a high-fidelity prototype hosted on a spreadsheets software.

3.4. *Descriptive Study II*

The usefulness and applicability of the CEBMES was evaluated with case studies for theory testing with industrial experts, which were carried in three steps (Dul and Hak, 2008): *case selection; data collection;* and *data analysis.*

Case selection comprised manufacturing companies (Table 2) from varied sectors, with pre-existing intention to innovate their BMs for CE, limited experience in CE and availability or willingness to provide data as feedback and to be trained and apply the CEBMES independently. In order to fit the overall project scope and enable physical events/workshops, the companies were located in Northern Europe (i.e. Denmark, Finland, Germany, Iceland, Norway, and Sweden). Geographical proximity enabled the control of some contextual variations (e.g. cultural similarities; acknowledgement of sustainability as a relevant topic).

Data collection occurred during and after the training (i.e. three-hour webinar) and the independent application of the CEBMES high-fidelity prototype by the companies. The application of the CEBMES to supported innovation, strategic planning or corporate social responsibility activities and occurred within six weeks subsequent to the webinar training. The time dedicated by companies to apply the CEBMES within the six weeks was on average eight hours. The application was led by varied roles in the companies (see Table 2). Most of the companies engaged teams during the application of the CEBMES, including a number of functional areas (e.g. operations & logistics, corporate social responsibility, finances, sales, product design & engineering, and manufacturing), with exception of companies H and P, whose facilitators applied the system independently due to the limited size of the organisations. The collection of data for the research was based on structured standard questionnaires, which included four-point Likert scale questions and open-ended questions to evaluate 48 performance criteria about the CEBMES and identify company-(e.g. size) and user-related aspects (e.g. self-assessed experience in CE) (see Appendix A in the Supplementary Material). To enable triangulation for data consistency (Yin, 2006), an interview to clarify the provided answers was conducted and recorded, and documents resulting from the CEBMES application were collected.

Data analysis comprised:

- Histograms with quantitative data about the CEBMES usefulness according to multiple performance criteria;
- Statistical analysis to explore the contextual conditions of the companies' and users' characteristics that favoured or disfavoured the application or perception of the CEBMES performance (e.g. willingness to move forward throughout modules) – i.e. this was limited to Module 1, because the sample of those using the subsequent modules was deemed too restricted to infer considerations (see section 4.2);
- Content analysis and clustering (Dresch et al., 2015) of qualitative replies obtained from the questionnaire and comments from interviews, including suggestions of improvements for the CEBMES modules and comments to support or refute the performance evaluation presented in histograms and correlations with contextual factors.

Table 2 - Companies participating in the research. Legend: CEBMES - Circular Economy Business Modelling Expert System; SME - small and medium enterprises; CEO – Chief Executive Officer.

Company	**Sector**	**Size**	**Practical requirements**	**CEBMES evaluation**	**Roles of facilitators**
A	Electrical/electronic equipment/appliances	SME	✓		
B	Heavy machinery	Large	✓		
C	Furniture	SME	✓	✓	
D	Electrical/electronic equipment/appliances	SME	✓		
E	Furniture	SME	✓		
F	Textile	SME	✓		
G	Medical devices	Large	✓		
H	Electrical/electronic	SME		✓	CEO

	equipment/appliances			
I	Heavy machinery	SME	✓	CEO
J	Furniture	Large	✓	Environmental Management Specialist
K	Furniture	SME	✓	CEO & Product Designer
L	Furniture	SME	✓	CEO & Project Manager
M	Agricultural and food products	Large	✓	Business Development Director
N	Outdoor goods	Large	✓	Sustainability Manager & Analyst; External Sustainability Consultants
O	Outdoor goods	SME	✓	Innovation Leader
P	Construction	SME	✓	Sustainability Consultant

4. Results: Circular Economy Business Modelling Expert System

This section is structured in two parts. Section 4.1 describes the proposed CEBMES tool according to its elements and application procedure. Section 4.2 presents the results of the CEBMES evaluation by manufacturing companies in respect to its applicability and usefulness, followed by an overview of improvement opportunities recommended by the companies.

4.1. *Circular Economy Business Modelling Expert System*

The Circular Economy Business Modelling Expert System (CEBMES) contains a step-by-step approach to support manufacturing companies in designing, configuring and evaluating BM alternatives that, when implemented, will meet business and CE needs. The CEBMES is composed of four modules and seven steps with the objectives:

- Module 1: sensing and identifying opportunities for CEBMs (steps 1/2);
- Module 2: designing CEBM alternatives (step 3);
- Module 3*:* configuring the detailed elements of CEBM alternatives (step 4);
- Module 4*:* evaluating, selecting and optimising CEBM alternatives based on their economic and resource decoupling potential (steps 5/6/7).

The steps of the CEBMES were deployed from activities embedded on the *CEBMn Process Model*, and focus primarily on the *Sense* and *Seize* stages of the *CEBMn Process Model*. Furthermore, the CEBMES can provide inputs for the execution of the stage *Transform* with the support of additional tools (Pieroni et al., 2019b), such as an experimentation roadmap and test cards.

The steps correlate with three levels of the CEBMES architecture (Figure 2):

- Front-end*:* spreadsheets or interfaces visible for the users and tailored for each step. Address 14 core functionalities to fulfil 21 requirements (Table 1). In each spreadsheet/interface, user inputs serve as basis for the provision of advices for CEBMn (i.e. outputs).
- Back-end*:* spreadsheets for calculations or knowledge processing to generate advice that emerge as outputs in the front-end. The back-end logic relies on methodologies (Liao, 2005) of rule-based system for Modules 1 and 4 ('i' in Figure 2); and case-based reasoning for Modules 2 and 3 ('ii' in Figure 2).
- Databases*:* knowledge bases that provide scientific and empirical foundations about CEBMn to support the generation of advices at the back-end.

The following subsections (4.1.1 to 4.1.5) explain the CEBMES modules, including details of the required steps, functionalities and logic of modules. Additionally, examples of results from applications of the CEBMES in manufacturing companies are provided. The CEBMES is freely accessible from the Technical University of Denmark's (DTU) repository (https://doi.org/10.11583/DTU.11798655).

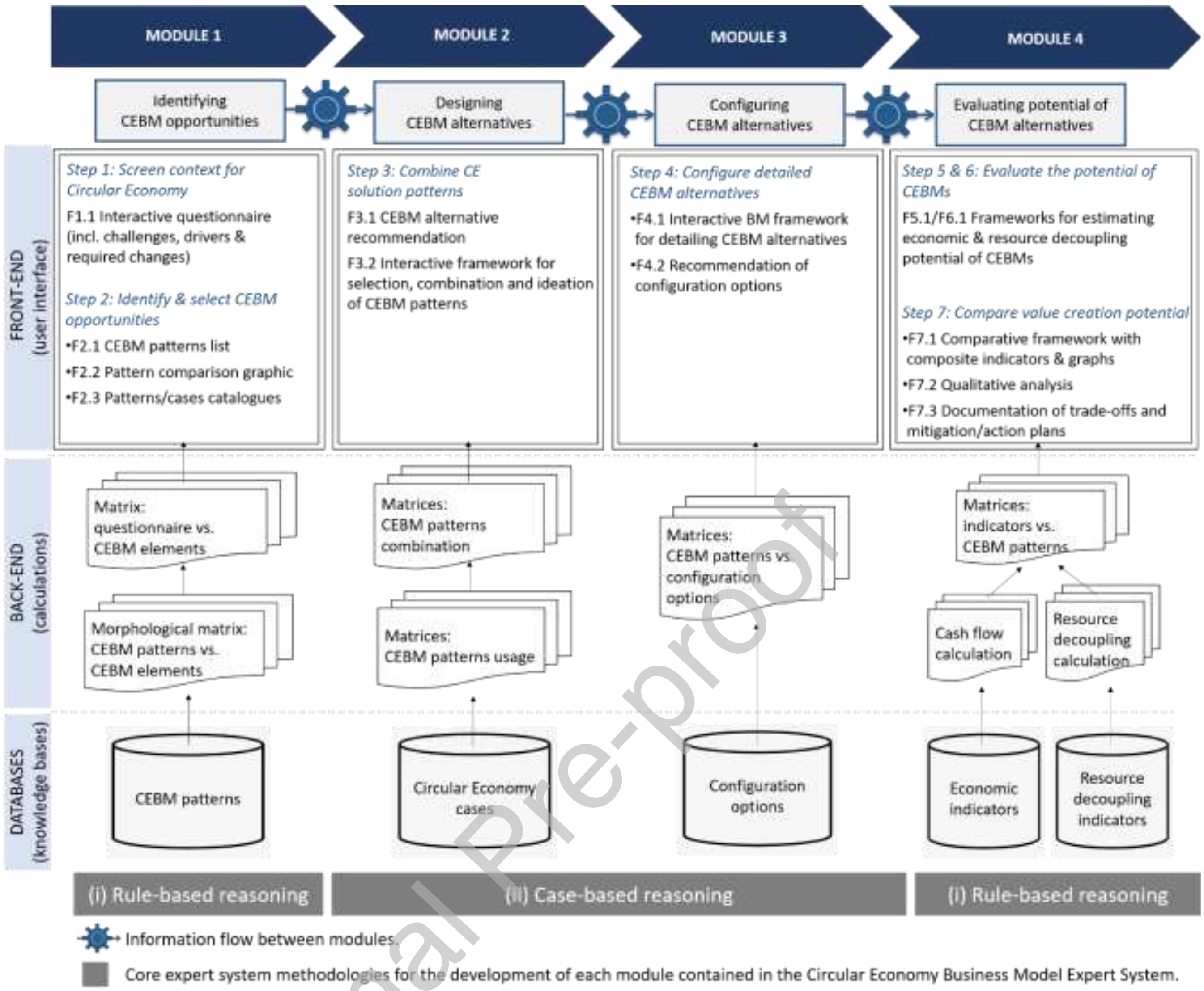

Figure 2 – Architecture of the Circular Economy Business Modelling Expert System. Adapted from: Pieroni et al. (2020c). Legend: CEBM - circular economy business model; F – functionalities in the expert system.

4.1.1. Module 1- Sensing and identifying opportunities for circular economy business models

This module includes two steps that foresee screening of companies' context, CE challenges and drivers and advice and selection of CEBM opportunities. As outputs, companies obtain the characterisation of their CE challenges (Step 1, described in the subsection 4.1.1.1) and potential opportunities for designing CEBMs (Step 2, described in the subsection 4.1.1.2).

4.1.1.1. Step 1 – Screening context, CE challenges, drivers and required business model changes

The front-end comprises one core functionality (F1.1): *an interactive and structured questionnaire to support the evaluation of company's context and characterisation of CE challenges and opportunities.* Companies shall answer 20 questions that screen four categories: (i) product and sector of current BM; (ii) challenges and weaknesses of current BM; (iii) trends and drivers for CE; and (iv) strategic intentions with

CE and enablers in the company's ecosystem. An example of question in the category (i) is "3 - What is the level of complexity of the offerings, i.e. product or services?". The complete questionnaire can be accessed on the second spreadsheet of the CEBMES.

At the back-end, Module 1 (i.e. Steps 1 and 2) relies on rule-based reasoning to represent information in the form of rules (e.g. IF-THEN) that can be used to process the answers to the questionnaire (Liao, 2005). The set of rules for Step 1 is recorded on a *matrix that relates the answers in the questionnaire with affected BM elements*. This enables the identification of the elements of the company's BM that require changes for CE.

The questions and relationship with changes in BM elements were developed based on previous research that proposed similar screening approaches to characterise existing BMs in companies (Kwon et al., 2019; Remane et al., 2017). They were adapted to the context of CE based on insights identified with the application of CEBMn in companies (A-G in Table 2), e.g., key aspects that drove companies to change their BMs for CE collected through a SWOT analysis and qualitative screening of their circularity based on implemented CE strategies (Blomsma et al., 2019). The CEBMES considers a BM framework that contains 12 elements: overall benefits (i.e. E01-economic, E02-environmental and E03-social); E04-target customers; E05-benefits for customers; offerings (i.e. E06-products and E07-services); E08-revenue mechanisms; E09-value delivery processes; E10-value creation processes; E11-partnerships and collaborations; and E12-benefits for partners (adapted from Kraaijenhagen et al. (2016) and Biloslavo et al. (2018)). For example, question 3 (mentioned above) affects the elements E06 and E07.

4.1.1.2. Step 2 - Identify and select circular economy business model opportunities

The front-end comprises three functionalities:

- A list with six *recommended CEBM solution patterns for* companies *(F2.1)*, based on outputs from Step 1. The CEBM solution patterns represent best-practice configuration alternatives for BMs to solve a specific identified and repeatable CE challenge (Amshoff et al., 2015). Each CEBM pattern is described by: its name; an explanation of the CE challenges and the CEBM solution; inspirational cases; and potential resource decoupling and economic benefits. Companies can use the list to prioritise up to three CEBM patterns for exploration.
- A *graph to support companies in comparing and prioritising the six recommended CEBM patterns (F2.2)* according to their adherence to the screening questionnaire (Step 1) and the degree of change promoted in BMs (i.e. from linear to circular).
- Access to *the complete database of CEBM patterns (F2.3)*, which contains further detailing and references to original cases.

At the back-end, the CEBMES relies on another *morphological matrix relating CEBM solution patterns with corresponding affected BM elements*. This matrix was developed according to Remane et al. (2017). Based on outputs of Step 1, different BM elements are diagnosed as requiring changes to enhance circularity. Based on these elements, different CEBM patterns can be identified as relevant in the morphological matrix and recommended by the CEBMES (Figure 3).

At the databases level, Step 2 relies on *CEBM solution patterns databases* (development explained in section 2.2 and documented in Pieroni et al. (2020b)). The databases are available for four specific manufacturing sectors (i.e. heavy machinery; electrical and electronic equipment and appliances; furniture; agriculture and food) and in a generic version applicable for any manufacturing sector. The complete list of patterns can be accessed in the CEBMES.

	Questions	1 - What the company expects to solve or achieve with circular economy implementation?							...	7 - What is the customer's core reason for changing or stopping the use of products?				
	Affected BM elements (E)	E02 - Environmental benefits promoted by the BM							...	E04/E05 - Target customers/ Benefits for customers				
Pattern	**Code for pattern**	**Absolute decoupling** Strive for 'zero' resource intake	**Narrow or reduce** Optimise and reduce directly resource intake for production or	**Intensify** Reduce product idleness and indirectly resource intake	**Slow or postpone** Extend product lifetime and indirectly resource intake	**Close or recover** Reduce pollution, waste and landfilling	**Multiple effects**	**Not specified or no direct impact on resource decoupling**	...	**1- Sensible to aesthetics changes** E.g. product becomes old-fashioned	**2- Sensible to technological changes** E.g. product becomes outdated	**3- Seasonal needs** E.g. product becomes small, not necessary	**Multiple effects**	**Not specified or no direct relevance**
Collaborative services in sharing or pooling platforms	P6			x						x		x	x	
Product as a service in customized temporary contracts	P7			x							x			
Product as a service in pre-configured packages	P8			x							x		x	
Lifetime products sales	P9		x		x									x
Products with through-life care services	P10				x						x			
Incentivized buy-back of products	P11				x									x
Additional services to add 'new life cycles' for products	P12				x					x	x			
...	...	...												

Figure 3 - Extract of morphological matrix at the back-end of Module 1. Legend: BM – business model; P - pattern.

Figure 4 exemplifies the result presented by the CEBMES after the completion of Module 1. In this example, the CEBM pattern P08 ('Product as a service in pre-configured packages') was recommended as the most favourable opportunity to solve the challenges of the company (i.e. highest adherence to screening), while contributing to CE targets for resource decoupling (i.e. highest degree of change from linear logic). The CEBM pattern P12 ('Additional services to add new cycles for products') can also tackle challenges identified by the company regarding its current BM, however they will probably cover fewer challenges (i.e. lower adherence to screening) and with lower potential to disrupt the linear logic than P08 (i.e. resource decoupling benefits might be more modest).

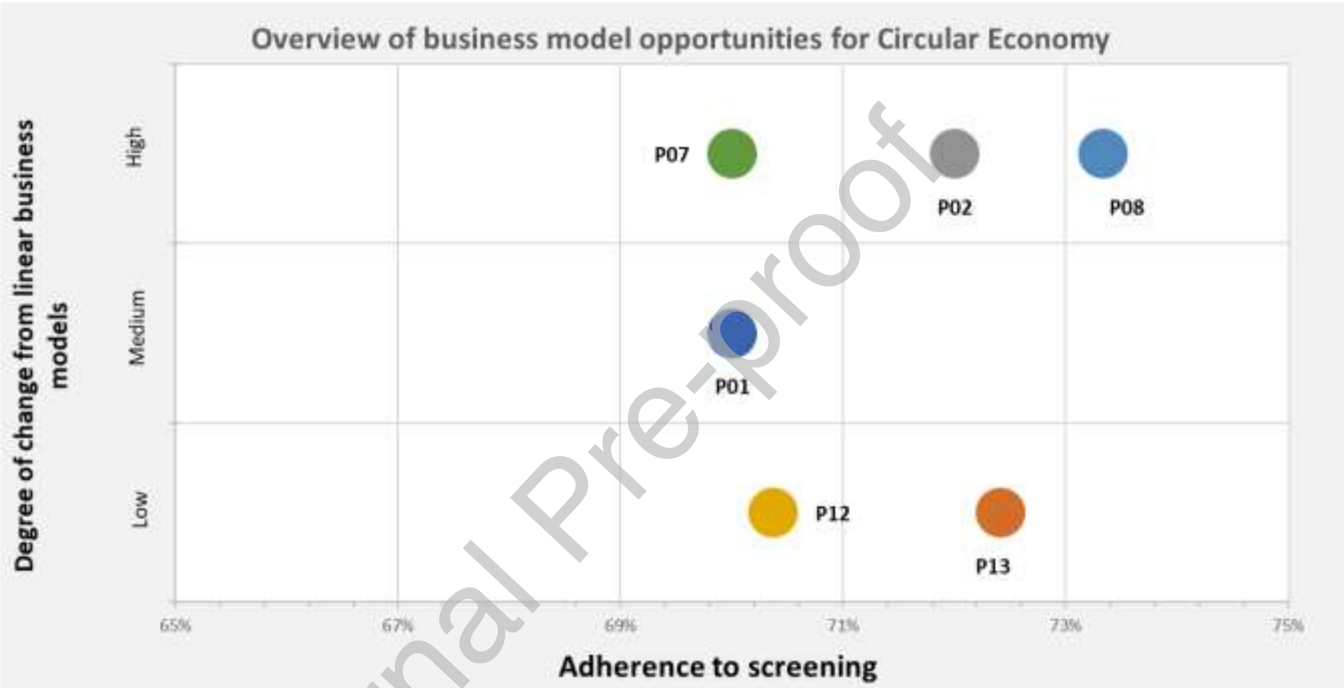

Figure 4 – Example of results for Module 1. Legend: P – pattern.

4.1.2. Module 2- Designing circular economy business model alternatives

Module 2 supports the further detailing of selected patterns from Module 1 into complete CEBM alternatives, through suggestions of potential synergies among different CEBM patterns and a framework that enables the adaptation of pattern combinations to the company's context. Module 2 comprises one step, as described next.

Step 3 – Combine patterns to design circular economy business model alternatives

The front-end of Step 3 comprises three functionalities:

- *Advice on potential CEBM alternatives (F3.1), which are based on likely combination of solution patterns* for the upstream and downstream architectures. The CEBM patterns are divided into downstream (i.e. affecting offerings; target customers; value delivery processes;

revenue mechanisms) and upstream (i.e. affecting value creation processes; partnerships/collaborations). Therefore, different types of patterns shall be combined to enable the configuration of complete CEBMs. Up to three CEBM alternatives can be generated based on patterns selected in Step 2.

- A framework that enables exploration of CEBM alternatives based on the *selection of CEBM pattern combinations for the upstream and downstream architectures and support to ideation and documentation of details (F3.2)*, with definition of key stakeholders (e.g. customers, suppliers), value proposition, and key benefits for stakeholders and CE (i.e. economic, resource decoupling).

At the back-end, Module 2 relies on case-based reasoning, which adapts solutions that were used to solve previous CE problems and use them as sources of inspiration to create CEBMs addressing similar problems (Liao, 2005). The advice on the combination of CEBM patterns for a specific company relies on *matrices of usage and of potential combinations of CEBM patterns in previous cases*. The likelihood of a CEBM pattern (selected in Step 2) being related with another pattern is calculated based on their recurrence in the *sample of 180 CEBM cases*, which composes the knowledge base for the databases level of Module 2. The usage and combination matrices and the cases' knowledge base were developed as explained in section 2.2 and documented in Pieroni et al. (2020b).

Figure 5 illustrates the results presented in the CEBMES after the completion of Module 2 by an electrical equipment manufacturer. The red rectangle under the block 'downstream architecture' indicates the CEBM pattern originally selected in Step 2 (EPD0202). The green rectangles represent the advice provided by the CEBMES regarding synergistic patterns to enable the configuration of a complete CEBM based on previous cases within this sector (e.g. EPD0102 for the downstream and EPU0301 for the upstream architecture). The outer columns entitled 'Select' show the CEBM patterns chosen by the company (i.e. yes) among the recommended ones after their ideation session. The company used the 'value generation box' (i.e. the central block) to outline specific customers; potential suppliers and partners that will need to be engaged; what benefits customers or partners will receive; and how the new CEBM could benefit the company and contribute to CE targets.

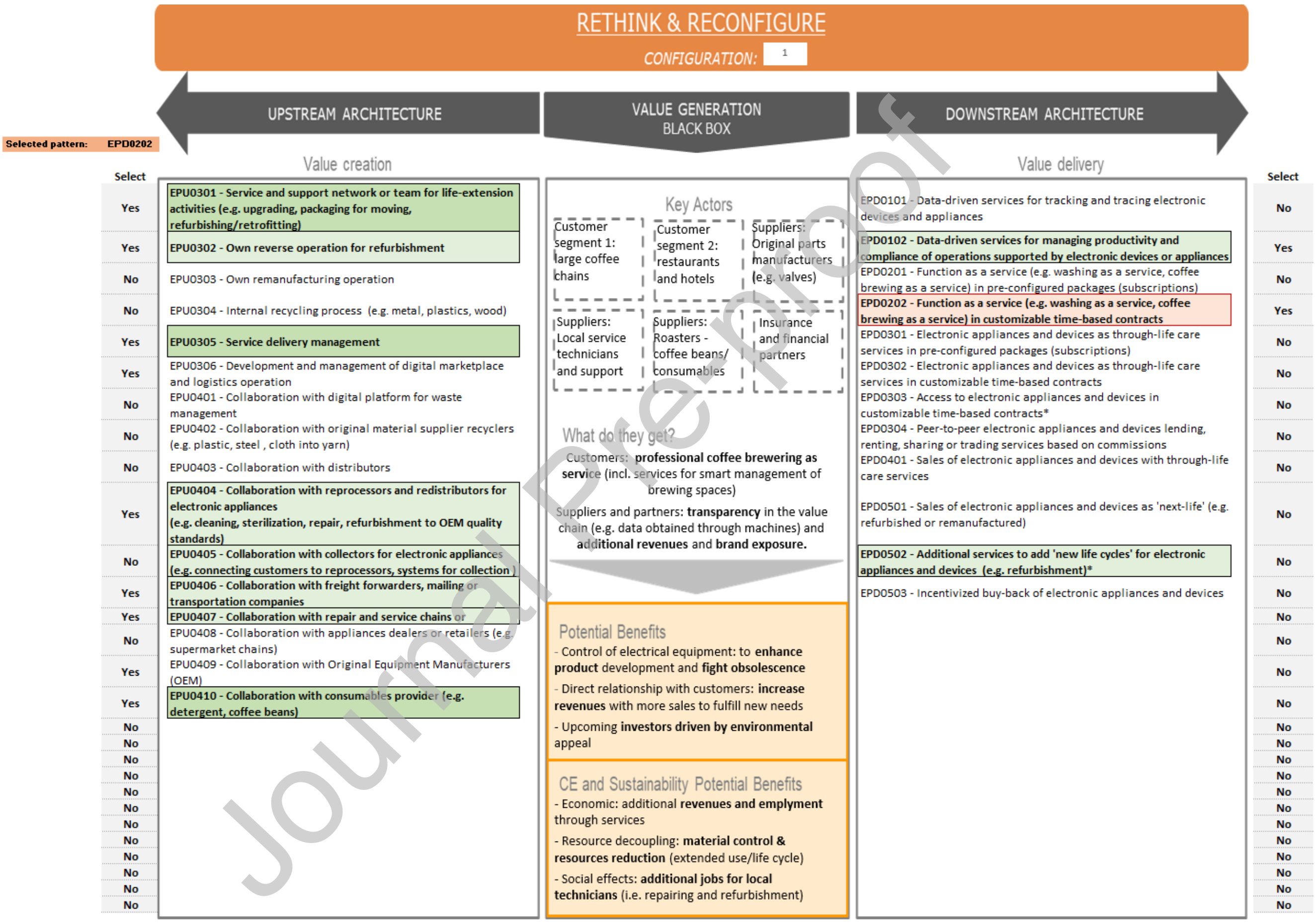

Figure 5 – Example of results for Module 2.

4.1.3. Module 3- Configuring detailed circular economy business models

Module 3 enables the configuration of detailed CEBMs. As output, companies receive suggestions of configuration options for all elements of the CEBM. This module comprises one step, as described next.

Step 4 – Configure detailed circular economy business model alternatives

At the front-end, Step 4 comprises two functionalities:

- A *BM framework that enables documentation of the ideation process for checking the viability and detailing of the CEBMs (F4.1).* The BM framework comprises 12 elements, which were previously described in section 4.1.1.
- *Advice on potential configuration options (COs) (F4.2)* for each CEBM element, in which COs are the available alternatives for shaping the 12 elements of a CEBM (Amshoff et al., 2015).

At the back-end, Module 3 also relies on case-based reasoning (Liao, 2005). A *matrix relating the selected combination of CEBM patterns (from Step 3) to correspondent common practice COs present in CEBM cases* enables the advices. The *complete list of COs* is available in the databases level. Both the matrix and knowledge base of COs were also developed as explained in section 2.2 and documented in Pieroni et al.(2020b).

Figure 6 illustrates partial results presented in the CEBMES after the completion of Module 3 by the previously mentioned electrical equipment manufacturer. The CEBMES suggested two COs of 'Revenue Mechanisms' (E08) for the chosen CEBM alternative based on the core pattern 'Function as a service' (EPD0202): (i) subscription with a pay per use fee (e.g. priced according to volume of brewed coffee); or (ii) subscription with a monthly/annual fee (e.g. priced according to duration). The recommended COs are not intended to be the final COs adopted by companies because adaptations to each organisational context are required. Instead, they are meant to remind and inspire companies about minimum required capabilities to implement CEBMs (e.g. reprocessing infrastructure and procedures; service level formalised in contracts). The additional lines (empty on Figure 6) on each block allow users to include or modify COs.

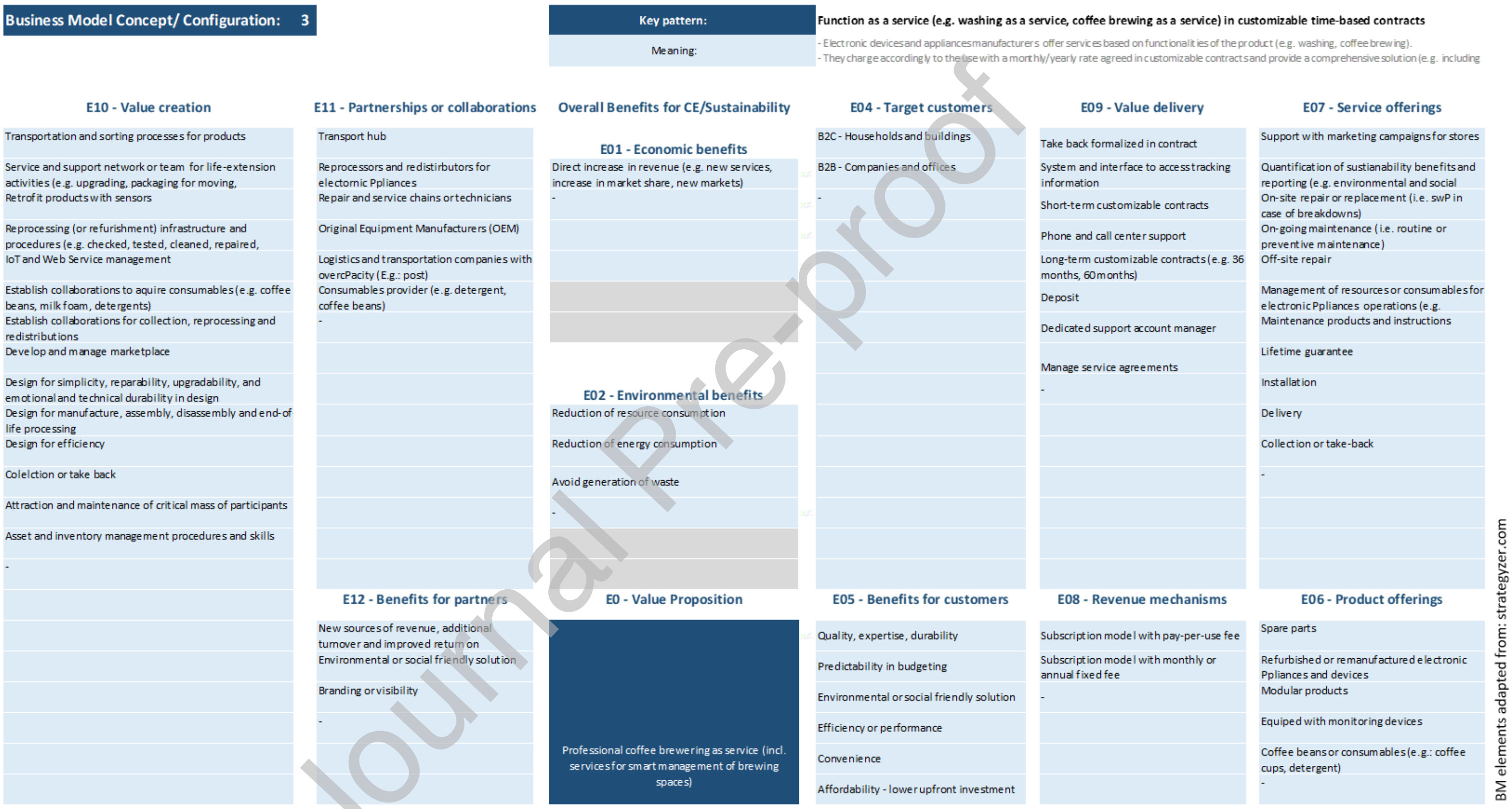

Figure 6 - Example of advice for possible COs provided in Module 3.

4.1.4. Module 4- Evaluating the potential of circular economy business models

Module 4 focuses on the preliminary assessment of the economic, resource decoupling and customer value potential for CEBMs. As output, users receive calculations of indicators and comparative frameworks of scenarios to guide decision-making. The module comprises three steps (5, 6 and 7), described in the subsections 4.1.4.1 to 4.1.4.3.

4.1.4.1. Step 5 – Evaluate the economic potential of circular economy business model alternatives

One core functionality (F5.1) is presented at the front-end: *support to the evaluation of the economic potential of CEBMs based on cost-benefit analysis with a dynamic business case framework.* The recommended indicators to calculate the business case vary according to the specific CEBMs proposed in Step 4. Indicators in five categories are recommended:

- Financial factors - e.g. corporate income tax; depreciation, interest rates;
- Market and demand assumptions – e.g. sales forecast, use cycles;
- Revenue sources – e.g. pricing;
- Development costs – e.g. refurbishment hubs, tracking and tracing devices;
- Operational costs – e.g. average maintenance and repair interventions per contract;
- Intangible benefits – e.g. price growth from improved reputation with customers, brand value.

To enable presentation of results and comparison among CEBMs, five composite indicators are calculated: *return on investment; net present value; payback; gross margin; and cash flow (graph format).*

The back-end of Module 4 also relies on rule-based reasoning. In Step 5, *a matrix relating CEBM configurations (e.g. combination of CEBM patterns) and economic indicators* enables the advice on a dynamic business case structure. Moreover, the back-end hosts the calculation rationale for the composite indicators. The databases level hosts the *database of economic indicators to assess CEBMs.*

The indicators and their calculation rationale were obtained from state-of-the-art systematic literature reviews about indicators to assess CE initiatives available in literature (Kravchenko et al., 2019; Rodrigues et al., 2017). They were complemented by insights from the application of the CEBMn process with seven companies (A-G in Table 2).

4.1.4.2. Step 6 – Evaluate the resource decoupling potential of circular economy business model alternatives

At the front-end, Step 6 has one core functionality (F6.1), i.e. *support to the evaluation of the resource decoupling potential of CEBMs based on eight indicators*: *average utility (also in the format of graph); longevity; virgin resource consumption; energy consumption; fuel consumption in logistics; fuel consumption in product operation; waste output; and land/facilities usage/productivity.*

The CEBMES suggests the adequate indicators from the overall pool depending on the CEBM configurations proposed in Step 4. To establish a reference point for comparisons among different CEBMs, information of existing BM from the company or competitors is requested. Based on that, results about improvement/regression in resource decoupling of each CEBM compared to the existing scenario can be presented.

At the back-end, the rules are recorded in a *matrix relating CEBM configurations (e.g. combinations of CEBM patterns) with adequate indicators from the pool*. The correlations in this matrix were based on advices for evaluating resource decoupling in BMs by Kjær et al. (2019). The *resource decoupling indicators* hosted on the databases level were selected from Kravchenko et al. (2019). Only eight indicators were selected to enable the high level assessment required at this stage (Figure 7).

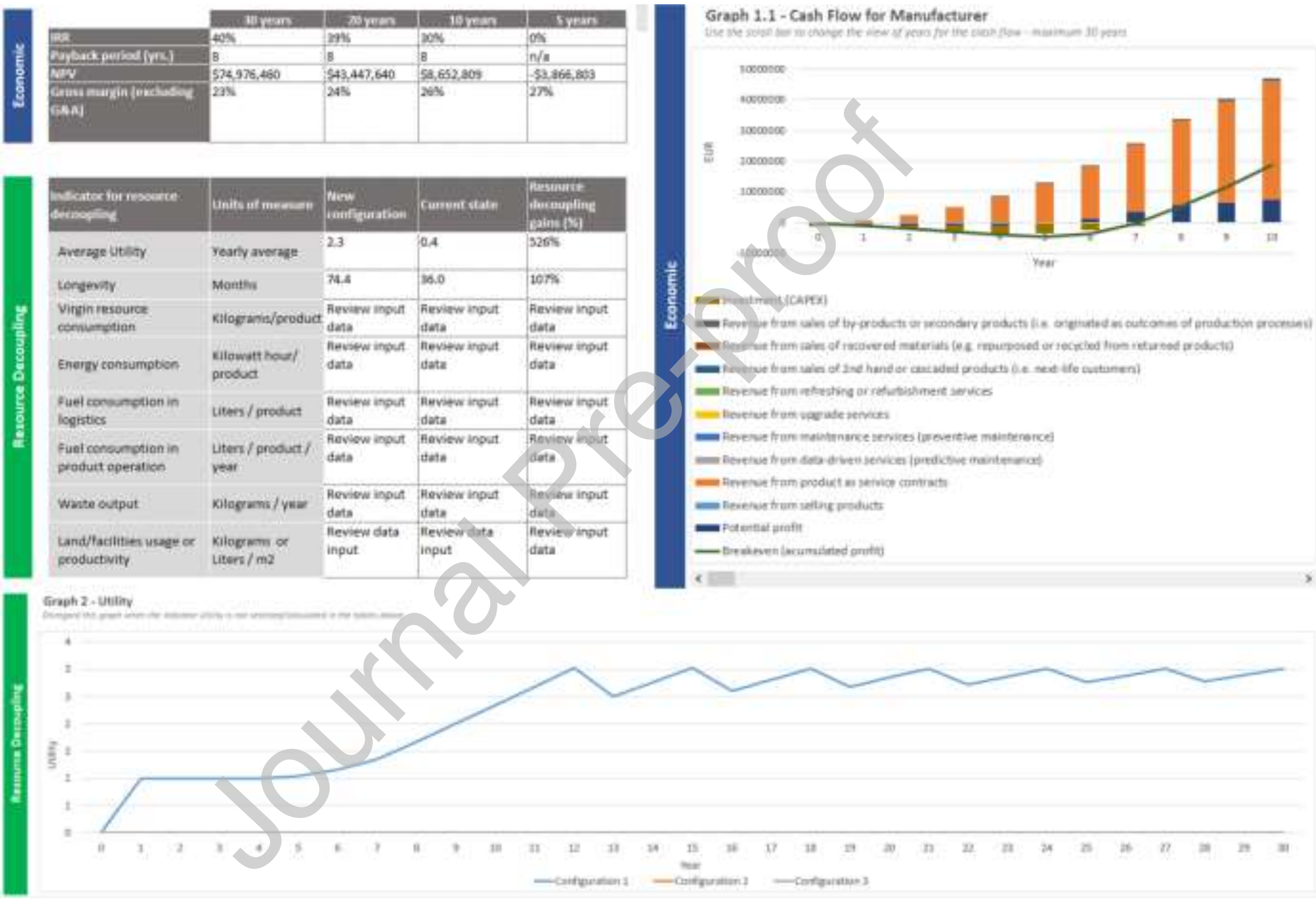

Figure 7 - Example of results for Module 4, Step 7A. Legend: IRR – Interest rate of return; NPV – Net present value.

4.1.4.3. Step 7 – Compare overall value creation potential

Step 7 comprises only the front-end, which contains 3 functionalities that were developed as responses to practical requirements (Table 1):

- A *framework that enables comparing the composite indicators for economic and resource decoupling potential (F7.1)* of up to three CEBM alternatives;
- A framework that supports consolidation of the economic and resource decoupling quantitative indicators with: *complementary qualitative indicators to provide an overview of the overall*

value creation potential criteria for CEBMs; indication of *targets/thresholds for the evaluation criteria to enable interpretation* of results according to each company; and space for *documentation of mitigation and action plans to optimise and improve CEBMs (F7.2)* (Figure 8). The qualitative indicators enable assessing the CEBM potential regarding (Figure 8):

- Superior customer value, i.e., based on the fulfilment level of customer benefits and the market potential/volume;
- Economic growth, i.e., based on the composite indicators (Step 6), analysis of required investments and scaling-up conditions, and;
- Resource decoupling, i.e., based on net reduction analysis through indicators, burden shifting mitigation possibilities, and rebound effects.

		Requirement is fulfilled when...			
Circular Economy Targets	Requirement	Conditions for the company	Value for the bold condition on the left	Scenario 1.1	Mitigation plan
Superior customer value	Perceived added benefits >= perceived added sacrifices	Minimum margin for customers >= **current margin for customers** **Tip:** use the learnings from the exercise with the Customer Journey Map to identify at least one critical requirement for customers, in the example, the customers, which is a business, expected to maintain the margins they had when	50%	!	Verify whther disposal costs are considered in
	Market potential (representativeness/volume)	Expected market share for the German market is achieved in... **years**	10	✓	
Economic growth	Positive net profit	Gross margin of created business models>= **long-term gross margin of current business model (in 10 years)**	65%	!	Review channels and pricing considerations.
	Available investment options	Payback period of **... years** is acceptable	3	✓	
		External financing options are necessary and available (e.g. bank loan, investment groups, subsides/ funded public projects/ grants)	No	✓	
	Favourable upscaling conditions	Volume of returning products justifies pay-off investments, i.e., **ROI of at least...is expected after 5 years**	100.00%	✓	
Resource decoupling	Positive net resource reduction	Longevity >= **current longevity**	1	✓	
		Utility >= **current utility**	N/A	N/A	
	Absent burden shifting between life cycles stages	Burden shift to manufacturing is avoided	Yes	✓	
		Burden shift to end-of-life is avoided	Yes	✓	
	Mitigated rebound effects	Business model is **able to substitute for benchmark alternatives** (i.e. current options in the market)	Yes	✓	
		Price of offering in for business model is >= **substitute price**	$39	✓	
		current business model poses **risks to shifting consumption** (e.g. incrasing consumption due to lower prices)	No	n.a	
Adherence of scenario to Circular Economy Targets:				69%	

Figure 8 - Example of results for Module 4, Step7B. Legend: ROI – return on investment.

Figure 7 and Figure 8 exemplify part of the results presented in the CEBMES after the completion of Module 4.

As indicated in Figure 7, only two resource decoupling indicators (i.e. average utility and longevity) were selected for the electrical equipment manufacturer's case. Based on the cash flow graph (top-right on Figure 7), the manufacturer was able to foresee required investments for scaling-up the CEBM. These would be associated mainly with the manufacturing of machines and installation of infrastructure to enable connectivity for remote monitoring and management of maintenance. Based on these estimations, the company was able to attract investors to co-finance the scale-up of their CEBM. Moreover, the graph for products' utility, enabled identifying when refurbishment operations would be required in a more expressive volume, triggering discussions about the possibility of partnering with existing subcontractors to deal with refurbishment until enough volume is reached to justify investments in internal infrastructure.

Figure 8 illustrates the overall framework for evaluation and improvement of a CEBM potential, based on the case of a medical devices' manufacturer. Their proposed CEBM would offer immobilisation solutions as services for clinics and hospitals, which would enable reuse of medical devices by multiple patients before disposal. Even though this CEBM presented a promising resource decoupling potential (see green checkmarks on Figure 8), the economic benefits for the company and their customers (i.e. clinics/hospitals) were not satisfactory when compared to the existing model. This triggered the company to review channels and pricing considerations.

4.1.5. Application procedure

The average time for application of the CEBMES observed in the case studies was of approximately eight hours spread in a period of six weeks. The effort varied depending on companies and modules: Modules 1 and 2 (2-4 hours each); Module 3: 1-2 hours; Module 4: 2-3 hours.

The recommended application procedures are described on the steps' interfaces. Moreover, a detailed guideline for practitioners was developed to explain the application of the CEBMES to support CEBMn process in parallel to other tools (e.g. interactive frameworks), which are available at DTU's repository (https://orbit.dtu.dk/en/publications/circular-economy-business-modelling-circit-workbook-2).

4.2. *Evaluation*

This section provides an overview of the perceived usefulness of the CEBMES (4.2.1), insights about its applicability according to contextual aspects (4.2.2), and improvement opportunities (4.2.3).

4.2.1. Overall evaluation of applicability and usefulness

Figure 9 illustrates how participants within manufacturing companies (C; H-P in Table 2) evaluated the overall applicability and usefulness of the CEBMES.

For most participants, the CEBMES provided a logic sequence of steps that helped designing and maturing CEBMs (performance criteria 47 and 48). However, most companies could only complete Steps 1-4, which they perceived as relatively easy to use. Three companies that completed all steps, perceived difficulties in Steps 5-7 related to a detailed level of information and extensive requirements for quantitative data (e.g. to estimate economic and resource decoupling potentials). These observations pointed out to a potential variability in applicability of different modules of the CEBMES depending on how advanced companies are in respect to the CEBMs' design stages (see Appendix B in the Supplementary Material for further details).

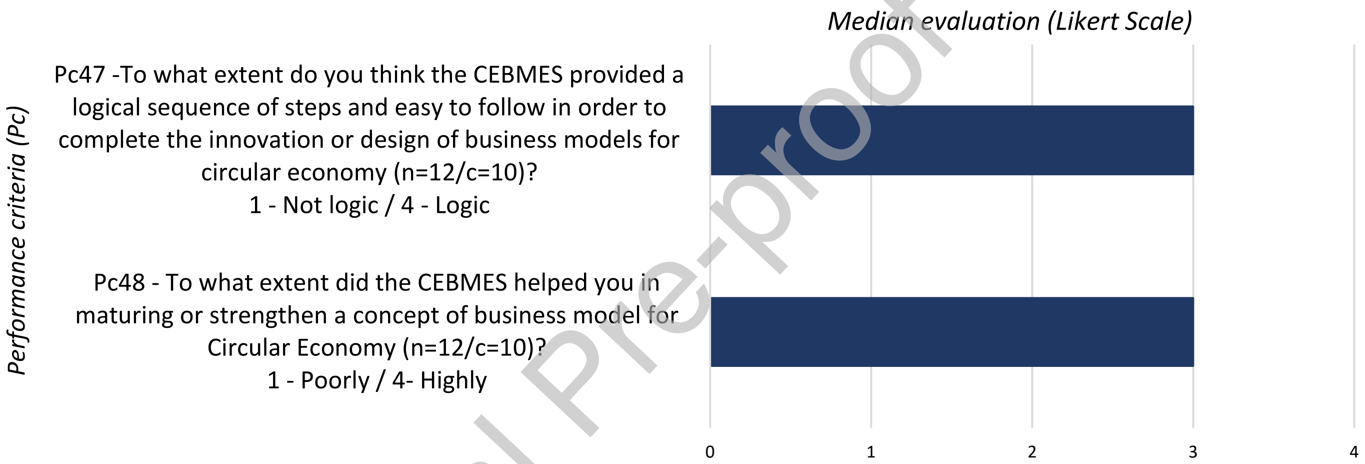

Figure 9 - Overall evaluation by manufacturing companies. Legend: n - number of respondents; c - number of companies; CEBMES - Circular Economy Business Modelling Expert System.

4.2.2. Contextual aspects and implications for applicability

Statiscal analyses enabled exploring contextual conditions that favoured or disfavoured the application or perception of the CEBMES performance. The initial set of perceived performance criteria for Module 1 (see Appendix A in the Supplementary Material) included 11 variables (e.g. comprehensiveness for recommending solutions for CE problems). A process of reduction of variables was required to describe the perceived CEBMES evaluation with fewer non-redundant criteria. Spearman's correlation among the variables demonstrated that some performance criteria were correlated to a certain extent, although not enough to be considered as fully overlapping (no correlation coefficient exceeded 0.8). Hence, Principal Component Analysis (PCA) was applied to build a reduced number of fully independent performance criteria based on Principal Components (PCs). PCs showing an eigenvalue larger than 1 were considered further, as a common rule of thumb, and interpreted based on the most (positively/negatively) impacting initial variables. Four PCs, were achieved and interpreted based on the positive/negative contributions (with absolute value greater than 0.3) of the initial variables (i.e. performance criteria):

- *PC1: Functionality,* i.e. the degree to which the CEBMES performs its expected function of suggesting proper solutions for CE challenges, steering CE-thinking and supporting decision-making throughout the CEBMn process in the perspective of implementing actions targeting CE in a practical/informative way.
- *PC2: Need for detail*, i.e. the degree to which the advices provided by the CEBMES were perceived necessary and useful, although limited to guide users.
- *PC3: Good Black Box-alike*, i.e. the degree to which the CEBMES was perceived as effective to support decision-making, despite the presence of an unclear logic (to the user) behind its functioning.
- *PC4: Supporting newness*, i.e. the degree to which the CEBMES is capable of guiding the user towards solutions or actions that were unimaginable and perceivably creative.

This process considered all initial variables (i.e. performance criteria) at least once in the interpretation process (Figure 10).

Initial performance criteria (Pc) extracted from the Circular Economy Business Modelling Expert System evaluation	Principal Components (PC)			
	PC1	PC2	PC3	PC4
Pc01 - To what extent has Step 1 helped characterisation of circular economy problems and identification of opportunities?			-0.525	
Pc02 - To what extent were the recommended ideas (i.e. circular economy business model solution patterns) in Step 2 comprehensive?	0.466			
Pc03 - To what extent could the recommended ideas in Step 2 address the circular economy problems and opportunities?	0.397			
Pc04 - To what extent were the recommended ideas in Step 2 applicable to your company's context?		0.477		
Pc05 - To what extent did recommended ideas in Step 2 require effort for adaptation?		0.514		
Pc06 -To what extent was the description of circular economy business model solution patterns provided in Step 2 enough?		-0.342	0.327	0.625
Pc07 -To what extent was it necessary to consult the Patterns' Database or the Cases' Database in Step 2?		0.438	0.301	
Pc08 -To what extent was the information available in Step 2 within Patterns' and Cases' Databases enough?	0.346			
Pc09 - To what extent did the graph in Step 2 supported the selection of ideas?	0.376		0.446	
Pc10 - To what extent was the exploration of ideas in Step 2 straight forward (i.e. practical)?	0.323			
Pc11 - To what extent could you discover new ideas for circular economy that you had not seen/heard/thought about before?				0.540

Figure 10 - Determination of Principal Components (PC) for the expert system evaluation aggregated based on impact coefficients ascribable to initial performance criteria (Pc).

Regressions were subsequently used to identify possible correlations among PCs and six contextual aspects of application (i.e. company size; sector; declared experience in CE; declared experience in BM innovation; and declared time of application), in addition to the decision to progress with subsequent modules within the CEBMES (leveraged as a dummy variable). Separate regressions were performed for each PC and regressor, which led to determine regression coefficients and their associated p-values. Three types of relationships were then identified: not significant correlations ($p>0.1$); quasi-significant correlations ($0.05<p<0.1$); and significant correlations ($p<0.05$).

Not significant correlations were observed in relation to sectors or size of companies, which did not affect the perceived performance of CEBMES. This observation enables inferring a broad applicability and flexibility of the CEBMES for varied organisational contexts, indicating the potential ability of the CEBMES to be generalisable within the specific manufacturing sectors that it was developed and tested for (i.e. outdoor goods, furniture, heavy machinery, electrical/electronic equipment/devices).

A quasi-significant positive relationship was observed among the use-time of the CEBMES and the perception of companies regarding the CEBMES functionality (PC1) and ability to support newness (PC4). The more time the companies used the CEBMES, the better their impression regarding its functionality and ability to support ideation. This result was already expected and provided evidence about estimated time required to use the CEBMES, which were incorporated in the CEBMES' instructions. Moreover, a quasi-significant correlation was also observed among the CEBMES' functionality and the users' willingness to advance from Modules 1 to 2. Even though some companies could not fully understand the logic behind Module 1 (i.e. CE characterisation vs. suggestions of solutions), they demonstrated motivation to move forward and appreciated the advices. The same company that mentioned that "sometimes it is difficult to understand how the CEBMES comes from Steps 1 to 2 examples", also mentioned that they "followed the process as a recipe, as far as possible, and it was very helpful to structure the CEBMn approach!"

A *significant positive relationship* was observed among the company's experience in BMI and the perception of effectiveness and clarity/logic to support decision-making (PC3). Companies with experience in BMI encountered logic in the selection of CEBM patterns to tackle CE problems instead of perceiving it as an effective 'black-box'. This might be related to two aspects. Companies that were acquainted with activities related to strategic thinking felt more comfortable with the logic of advices, because this step is related to abstract discussions to transform a vision into ideas. Moreover, these companies might have specific functions and organisational structure that allows creativity and empowerment/autonomy of participants to try to change the status-quo.

4.2.3. Improvement opportunities

The following improvement opportunities were identified based on replies to questionnaires and comments from interviews with companies (detailed in section 3.4):

- Consideration of additional criteria (e.g. customer segment specifications, scope of CEBMI) to refine the logic of advices for CEBM patterns according to the companies' contexts and improve the adherence variable in the graph (Step 1);
- Review of CEBM patterns for specific sectors (i.e. agriculture and food) (Steps 2 and 3);
- Additional explanations about sensitivity analysis for the economic potential assessments (Step 5);
- Clearer guidelines for each step supplemented by use examples;
- More precision in definitions and terminology.

5. Discussion

This section presents discussions about the applicability and limitations of the CEBMES (5.1), contributions to literature and practice, and future research possibilities (5.2).

5.1. *Applicability and limitations*

Satisfactory use of the CEBMES by varied organisations points towards the applicability of this research to different manufacturing companies' sizes and sectors. Beyond the influencing contextual aspects explored in Section 4.2 (i.e. degree of experience in BMI and time of application), recurrent characteristics that favoured the CEBMES applicability were (Khan et al., 2020; Ünal et al., 2019a):

- Users were usually business developers, sustainability managers and product managers;
- Companies/users were willing to be trained to use the CEBMES independently;
- Companies/users were willing to steer a change of mindset towards CE-thinking within their organisations by engaging multifunctional teams;
- Companies had a pre-existing scope (e.g. a selected product or initial CEBM ideas) for which they wished to strengthen proposals of CEBMs.

Despite the positive uptake by companies, the research presents limitations. Even though the evaluation of the CEBMES was solid compared to other tools in the field (i.e. assessing varied performance criteria with quantitative analysis), the results are restricted to four manufacturing sectors and Northern European companies. Further testing is required to confirm applicability to other sectors (e.g. textile, agriculture) and geographical regions. Moreover, further testing with more companies within a single sector completing all modules could strengthen the analyses of correlations of CEBMES' applicability regarding contextual aspects.

Additionally, the thorough evaluation of the CEBMES with the companies was limited to exploring its applicability and usefulness. Initial interviews carried with Company C fifteen months after their application of the CEBMES pointed out to positive effects of the CEBMES use regarding the implementation of the proposed CEBMs. According to Company C, the results deployed from the CEBMES application supported the generation of substantial arguments and evidence that encouraged the implementation of CEBM pilots. Moreover, they continued to rely on and refine the outcomes obtained through the CEBMES. Finally, this company was successful in planning and implementing a spinout to scale-up a CEBM configuration in partnership with Company E. However, the timeframe of fifteen months was not yet enough to evaluate the success of the implemented CEBM in respect to its effectiveness in decoupling resources while enabling economic gains. Hence, further longitudinal studies with companies are necessary to evaluate the success of the implementation of the CEBMs designed with the support of the CEBMES, and explore whether and how companies continue to use the CEBMES and its results during the *Transform* stage of the CEBMn process.

Lastly, the knowledge databases within the CEBMES (e.g. CEBM patterns, cases, indicators) require a procedure for frequent updates to guarantee that the provided advices reflect innovations in the field.

5.2. *Contributions to practice, literature, and future research avenues*

This research contributes to CEBMI literature by systematising practices and knowledge for action in the format of suggestions to guide the CEBMn process within manufacturing companies. The systematised practices and the process followed to develop the CEBMES go beyond available publications and fulfil expectations for holistic approaches for the strategic management of CEBMI and CE implementation (Khan et al., 2020; Ünal et al., 2019a).

The CEBMES was proposed based on a comprehensive evaluation methodology involving (i) development and testing with multiple practitioners (12 users within 10 companies); (ii) structured evaluation of its performance with multiple criteria (>40); and (iii) detailed analysis based on qualitative and quantitative (i.e. histograms, PCA, regressions) approaches. Available CEBMI works in literature tend to be limited to qualitative evaluations, based on unstructured approaches (i.e. observations/interviews), and with single or few case studies (<5) (Bocken et al., 2019; Pieroni et al., 2019a). Although a straight comparison of approaches is not possible due to significant differences in the level of evaluations or considered performance criteria, a reference checklist for CEBMI tool development (Bocken et al., 2019) confirms the solidity and value added by this research and the proposed CEBMES to literature, as explained in Figure 11.

Regarding practical contributions, this research can support facilitators or process champions within manufacturing companies to trigger a change of mindset towards CE-thinking within their organisations.

The CEBMES can support manufacturing companies to strengthen proposals of CEBMs before seeking for funding or sponsorship for their implementation. The CEBMES will benefit its users by: inspiring best practices on CEBMn; confirming assumptions with a structured framework; offering a logic structure that prompts decision-making; and helping to keep an accounting of decisions. The CEBMES can function as a 'side consultant', providing information that can be used to populate interactive frameworks that are suitable for group discussions and flexible to ‘live changes'.

The work presented in this paper sheds light on three research avenues. First, implementing the identified improvement opportunities could improve the CEBMES usefulness. Even though the evaluation was not focused on usability due to the CEBMES stage of the development (i.e. high-fidelity prototype), participants saw potential and provided feedback about how interfaces/transitions could become more flexible in a web-based format. In association with this format, an automated procedure grounded on artificial intelligence could be developed for updating the databases in the CEBMES by sourcing knowledge from external/open-source CE expert platforms. Second, exploration of how companies beyond manufacturing (e.g. raw materials extraction, services, construction) deal with CEBMn could enable expanding the CEBMES’ scope (e.g. allowing multiple companies with different positions within/across value chains to collaborate and work on simultaneous solutions of how their own CEBMs can converge for closing loops). Third, the integration of this research with works that investigate dynamic capabilities to boost CEBM innovation performance/maturity (Khan et al., 2020) could advance knowledge on how to overcome barriers for the implementation/scale-up of CEBMs.

6. Conclusion

This article presented the conceptualisation and evaluation of a tool to support circular economy business modelling (CEBMn) within manufacturing companies. The tool called Circular Economy Business Modelling Expert System (CEBMES) contains four modules and seven steps. Compared to other available tools, the CEBMES enhances the support to CEBMn process by providing systematised knowledge and proactive expert and contextualised advice to companies regarding activities along the whole process, ranging from design, detailing and assessment of CEBM alternatives prior to their implementation.

The key contributions of this article to literature are: (i) the systematisation and organisation of CEBMn practices and knowledge for action in the format of recommendations to guide the CEBMn process; and (ii) the identification of requirements, deployment of functions and definition of an architecture (i.e. front-end, back-end and databases levels of information) for a novel expert system based on the systematised CEBMn practices.

For manufacturing companies, the key contributions of the article and CEBMES are: (i) enhanced inspiration for best practices on circular business modelling contextualised to varied sectors and organisational conditions; (ii) a structured framework for confirming assumptions; and (iii) a logic structure that prompts decision-making along the stages of CEBMn and reduces uncertainties.

By providing guidance (i.e. systematise knowledge) and proactive expert advice for CEBMn, the CEBMES represent a concrete proposal to steer manufacturing companies in the direction of CE-thinking. This new strategic way of thinking and doing business for CE needs to become a reality as soon as possible if CE is expected to continue to play a major role in realising the ambitious targets for sustainable development in our society. However, on top of adequate tools, several conditions need to be in place to encourage manufacturing companies to dare to change. Further research avenues could explore how to expand the rationale of this research beyond manufacturing and how conducive dynamic capabilities and external drivers or barriers for CEBMn can affect the use of tools such as the CEBMES.

Checklist of criteria	Fulfilment	Comments and testimonials
1. The tool is purpose-made for CEBMI 2. The tool is rigorously developed from both literature and practice insights 3. The tool is iteratively developed and tested with potential users	+++	The development of the CEBMES comprised: • Systematisation of conceptual requirements for CEBMn from systematic literature reviews (section 2.2); • Collection of practical requirements for CEBMn and knowledge foundations for the CEBMES were based on empirically developed frameworks with 7 manufacturing companies (A-G in section 2.1 and Table 2 of section 2.2).
4. The tool integrates relevant knowledge from different disciplines	+++	• The systematic literature reviews from which conceptual requirements for the CEBMES were extracted comprised knowledge from CE, sustainability, and management disciplines (section 2.2). • Practitioners from different functional areas and related to different disciplines were engaged in the collection of practical requirements or testing of the CEBMES (e.g. marketing and sales, procurement, operations, services excellence, digital technologies, business innovation, corporate social responsibility) (section 2.1).
5. The final tool version has then been used by practitioners, preferably multiple times, and an evaluation of this process is done to assess tool use and usefulness	+++	• The CEBMES was tested with 10 companies in case studies (H-P in Table 2). • The evaluation comprised qualitative (i.e. clustering of feedback, benchmarking with checklist for CEBMI tool development described in section 4.3) and quantitative analyses (i.e. histograms, PCA, regressions described in sections 4.1 and 4.2).
6. The tool provides a transparent procedure and guidance for its application	++	• The CEBMES contains instructions inside the prototypical tool. Moreover, users were trained with a webinar and received a manual – e.g. "Training and materials were good." • The fact that companies were able to apply it independently corroborates with a positive evaluation for this criteria. One company mentioned that they "tried to follow the process as a recipe as much as possible, and it was very helpful to structure [their] approach!." • Nevertheless, improvement opportunities in the instructions were identified, which indicates that this criteria was fulfilled, but could be improved – e.g. "A concise user-guide could be useful, for example, I was reluctant to rewatch the webinar."; "It is too much to consume. I think a process were you can start in a basic level and then dig deeper if you like [would be better]"; "Add small examples in the tool [how to fill it in]."
7. CE or broader sustainability objectives and impact are firmly integrated into the tool and safeguarded when tool application is facilitated by others than the tool developer	+++	• The CEBMES recommends CEBM patterns that rely on best practices for CE (section 3). • Moreover, the CEBMES' Module 4 enables evaluating the resource decoupling potential of the proposed CEBMs. This aims to support the users in refining or guaranteeing the achievement of CE objectives and impact (section 3).
8. The tool is simple and not too time-consuming	+	• According to the evaluation (section 4.1 and Appendix B), the CEBMES was considered simple in Modules 1, 2 and 3. However, companies faced difficulties in applying Module 4, which focused on quantitative assessment of CEBMs – e.g. "It feels a little bit complex and difficult to use for the first time". This was expected due to the nature of the tasks. • Overall, the CEBMES requires significant effort for application (2-4h for Modules 1 and 2, 1-2h for Module 3, and 2-3h for Module 4, summing up to 8h on average). However, this was expected because, differently than other available tools (Bocken et al., 2019; Pieroni et al., 2019a), its objective is to guide the CEBMn holistically and not solely with individual tasks of ideation. Moreover, only one company reported time as a restriction to the use of the CEBMES – e.g. "Comprehensive and impressive tool which is also holistic. Might overwhelm companies in how much time they need to spend". In general the number of companies being able to use the CEBMES up until the Module 3 (i.e. detailing the CEBMs) indicates acceptance of the effort required. Companies that could not apply Module 4 associated it with: (i) lack of readiness to pursue this module (i.e., they still needed more iterations in the previous modules), (ii) lack of access to data; or (iii) lack of priority by sponsors.
9. The tool inspires or triggers (business) change	+++	Different companies reported that the CEBMES brought an element of newness, providing ideas that can trigger change of companies' status quo (section 4.2). Examples of testimonies were: • "Helpful to reflect upon what the company does today in relation to the CE-concept, also to reflect upon what may be further possibilities in the enhancement of CE-practice." • "We had not considered offering a product or group of products in rented, leased, or subscription based packages. We found this to be a very interesting example for the company as there are many opportunities to offer packages for certain categories of products demanded in seasonal activities." • "The CEBMES provided the company with ideas that they had not considered, e.g. to rent out/lease a package of products from different product categories."
10. The tool is adaptable to different (business) contexts	+++	• The broadness of companies participating in the validation (Table 2) points out to the flexibility of the CEBMES to adapt to different contexts (i.e. sizes, sectors), within the scope that it was developed for (i.e. specific manufacturing sectors). • The PCA showed that the positive performance of the tool was not affected by size or sectors, which corroborates with this criterion (section 4.2).

Figure 11 - CEBMES evaluation according to CEBMI tool development criteria (Bocken et al., 2019). Legend: +++ = very strongly; ++ = strongly; + = moderately; 0 = doesn't meet criterion or only marginally; CE – circular economy; CEBM - circular economy business model; CEBMI – circular economy business model innovation; CEBMES - Circular Economy Business Model Expert System; PCA – principal component analysis.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT author statement

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References

Amshoff, B., Dülme, C., Echterfeld, J., Gausemeier, J., 2015. Business model patterns for disruptive technologies. Int. J. Innov. Manag. 19, 1–22. https://doi.org/10.1142/S1363919615400022

Antikainen, M., Valkokari, K., 2016. A Framework for Sustainable Circular Business Model Innovation. Technol. Innov. Manag. Rev. 6, 5–12.

Biloslavo, R., Bagnoli, C., Edgar, D., 2018. An eco-critical perspective on business models: The value triangle as an approach to closing the sustainability gap. J. Clean. Prod. 174, 746–762. https://doi.org/10.1016/j.jclepro.2017.10.281

Blessing, L.T.M., Chakrabarti, A., 2009. DRM, a design research methodology, Springer. https://doi.org/10.1007/978-1-84882-587-1

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D.C.A., Hildenbrand, J., Kristinsdottir, A.R.,

Kristoffersen, E., Shahbazi, S., Nielsen, K.D., Jönbrink, A.-K., Li, J., Wiik, C., McAloone, T.C., 2019. Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. J. Clean. Prod. 241, 118271. https://doi.org/10.1016/j.jclepro.2019.118271
Bocken, N., Short, S., Rana, P., Evans, S., 2013. A value mapping tool for sustainable business modelling. Corp. Gov. Int. J. Bus. Soc. 13, 482–497. https://doi.org/10.1108/CG-06-2013-0078
Bocken, N., Strupeit, L., Whalen, K., Nußholz, J., 2019. A Review and Evaluation of Circular Business Model Innovation Tools. Sustainability 11, 2210. https://doi.org/10.3390/su11082210
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124
Bocken, N.M.P., Geradts, T.H.J., 2019. Barriers and drivers to sustainable business model innovation: Organization design and dynamic capabilities. Long Range Plann. 101950. https://doi.org/10.1016/j.lrp.2019.101950
Bocken, N.M.P., Schuit, C.S.C., Kraaijenhagen, C., 2018. Experimenting with a circular business model: Lessons from eight cases. Environ. Innov. Soc. Transitions 28, 79–95. https://doi.org/10.1016/j.eist.2018.02.001
Böhringer, C., Rutherford, T.F., 2015. The circular economy – an economic impact assessment. Rep. to SUN--iza 1–33.
Centobelli, P., Cerchione, R., Chiaroni, D., Del Vecchio, P., Urbinati, A., 2020. Designing business models in circular economy: A systematic literature review and research agenda. Bus. Strateg. Environ. 29, 1734–1749. https://doi.org/10.1002/bse.2466
Chiappetta Jabbour, C.J., Sarkis, J., Lopes de Sousa Jabbour, A.B., Scott Renwick, D.W., Singh, S.K., Grebinevych, O., Kruglianskas, I., Filho, M.G., 2019. Who is in charge? A review and a research agenda on the 'human side' of the circular economy. J. Clean. Prod. 222, 793–801. https://doi.org/10.1016/j.jclepro.2019.03.038
de Jesus, A., Mendonça, S., 2018. Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. Ecol. Econ. 145, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001
De los Rios, I.C., Charnley, F.J.S., 2017. Skills and capabilities for a sustainable and circular economy: The changing role of design. J. Clean. Prod. 160, 109–122. https://doi.org/10.1016/j.jclepro.2016.10.130
Diaz Lopez, F.J., Bastein, T., Tukker, A., 2019. Business Model Innovation for Resource-efficiency, Circularity and Cleaner Production: What 143 Cases Tell Us. Ecol. Econ. 155, 20–35. https://doi.org/10.1016/j.ecolecon.2018.03.009
Dresch, A., Lacerda, D.P., Antunes Jr., J.A.V., 2015. Design Science Research. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1007/978-3-319-07374-3
Dul, J., Hak, T., 2008. Case study methodology in business research, First ed. ed. Butterworth-Heinemann, Oxford, UK.
EIT Raw Materials, 2016. EU Circulator, Circular Business Model Mixer. http://www.circulator.eu/about (accessed 30 June 2018).
European Commission, 2019. The European Green Deal. Brussels.
Evans, J., Bocken, N., 2013. CE Toolkit, Circular Economy Toolkit. http://circulareconomytoolkit.org/Toolkit.html (accessed 30 July 2017).
Foss, N.J., Saebi, T., 2017. Fifteen Years of Research on Business Model Innovation. J. Manage. 43, 200–227. https://doi.org/10.1177/0149206316675927
Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A., Soufani, K., 2020. Circular business models: A review. J. Clean. Prod. 277, 123741. https://doi.org/10.1016/j.jclepro.2020.123741
Guldmann, E., Huulgaard, R.D., 2020. Barriers to circular business model innovation: A multiple-case study. J. Clean. Prod. 243, 118160. https://doi.org/10.1016/j.jclepro.2019.118160
Im, K., Cho, H., 2013. A systematic approach for developing a new business model using morphological analysis and integrated fuzzy approach. Expert Syst. Appl. 40, 4463–4477. https://doi.org/10.1016/j.eswa.2013.01.042

Kano, N., Seraku, N., Takahashi, F., Tsuji, S., 1984. Attractive quality and must-be quality. J. Japanese Soc. Qual. Control 39–48.
Khan, O., Daddi, T., Iraldo, F., 2020. Microfoundations of dynamic capabilities: Insights from circular economy business cases. Bus. Strateg. Environ. 29, 1479–1493. https://doi.org/10.1002/bse.2447
Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the Circular Economy: Evidence From the European Union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028
Kirchherr, J., van Santen, R., 2019. Research on the circular economy: A critique of the field. Resour. Conserv. Recycl. 151, 104480. https://doi.org/10.1016/j.resconrec.2019.104480
Kjaer, L.L., Pigosso, D.C.A., Niero, M., Bech, N.M., McAloone, T.C., 2019. Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption? J. Ind. Ecol. 23, 22–35. https://doi.org/10.1111/jiec.12747
Kraaijenhagen, C., Van Open, C., Bocken, N., 2016. Circular Business Collaborate and Circulate. Circular Collaboration, The Netherlands.
Kravchenko, M., Pigosso, D.C., McAloone, T.C., 2019. Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. J. Clean. Prod. 241, 118318. https://doi.org/10.1016/j.jclepro.2019.118318
Kwon, M., Lee, J., Hong, Y., 2019. Product-Service System Business Modelling Methodology Using Morphological Analysis. Sustainability 11, 1376. https://doi.org/10.3390/su11051376
Lewandowski, M., 2016. Designing the Business Models for Circular Economy—Towards the Conceptual Framework. Sustainability 8. https://doi.org/10.3390/su8010043
Liao, S.H., 2005. Expert system methodologies and applications-a decade review from 1995 to 2004. Expert Syst. Appl. 28, 93–103. https://doi.org/10.1016/j.eswa.2004.08.003
Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042
Linder, M., Williander, M., 2017. Circular Business Model Innovation: Inherent Uncertainties. Bus. Strateg. Environ. 26, 182–196. https://doi.org/10.1002/bse.1906
Lüdeke-Freund, F., Bohnsack, R., Breuer, H., Massa, L., 2019a. Research on Sustainable Business Model Patterns: Status quo, Methodological Issues, and a Research Agenda, in: Sustainable Business Models. Palgrave MacMillan, Herning, Denmark, pp. 1–33.
Lüdeke-Freund, F., Stefan, G., Bocken, N.M.P., 2019b. A Review and Typology of Circular Economy Business Model Patterns. J. Ind. Ecol. 23, 36–61. https://doi.org/10.1111/jiec.12763
McAloone, T.C., Bey, N., 2009. Environmental improvement through product development: A guide. Danish Environmental Protection Agency, Copenhagen.
Mentink, B. a S., 2014. Circular Business Model Innovation A process framework and a tool for business model innovation in a circular economy. Master Theis. Delft University of Technology and Leiden University.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112
Mhatre, P., Panchal, R., Singh, A., Bibyan, S., 2021. A systematic literature review on the circular economy initiatives in the European Union. Sustain. Prod. Consum. 26, 187–202. https://doi.org/10.1016/j.spc.2020.09.008
Moreno, M., De los Rios, C., Rowe, Z., Charnley, F., 2016. A Conceptual Framework for Circular Design. Sustainability 8, 937. https://doi.org/10.3390/su8090937
Nußholz, J., 2017. Circular Business Models: Defining a Concept and Framing an Emerging Research Field. Sustainability 9. https://doi.org/10.3390/su9101810
Nußholz, J.L.K., 2018. A circular business model mapping tool for creating value from prolonged product

lifetime and closed material loops. J. Clean. Prod. 197, 185–194. https://doi.org/10.1016/j.jclepro.2018.06.112
OECD, 2018. Business Models for the Circular Economy RE-CIRCLE. OECD Publishing, Paris.
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2020a. From theory to practice: systematising and testing business model archetypes for circular economy. Resour. Conserv. Recycl. 162, 105029. https://doi.org/10.1016/j.resconrec.2020.105029
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2020b. Circular economy business model innovation: Sectorial patterns within manufacturing companies. J. Clean. Prod. 124921. https://doi.org/10.1016/j.jclepro.2020.124921
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2020c. Defining the requirements for a tool to support Circular Economy business model innovation within manufacturing companies. Int. Des. Conf. - Des. 2020.
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2019a. Business model innovation for circular economy and sustainability: A review of approaches. J. Clean. Prod. 215, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036
Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A., 2019b. Configuring New Business Models for Circular Economy through Product–Service Systems. Sustainability 11, 3727. https://doi.org/10.3390/su11133727
Planing, P., 2018. Towards a circular economy - how business model innovation will help to make the shift. Int. J. Bus. Glob. 20, 71. https://doi.org/10.1504/IJBG.2018.088665
Reim, W., Parida, V., Sjödin, D.R., 2019. Circular business models for the bio-economy: A review and new directions for future research. Sustain. 11, 1–14. https://doi.org/10.3390/su11092558
Remane, G., Hanelt, A., Tesch, J.F., Kolbe, L.M., 2017. The business model pattern database — a tool for systematic business model innovation. Int. J. Innov. Manag. 21, 1750004. https://doi.org/10.1142/S1363919617500049
Rodrigues, V.P., Pigosso, D.C.A., McAloone, T.C., 2017. Measuring the implementation of ecodesign management practices: A review and consolidation of process-oriented performance indicators. J. Clean. Prod. 156, 293–309. https://doi.org/10.1016/j.jclepro.2017.04.049
Rohrbeck, R., Konnertz, L., Knab, S., 2013. Collaborative business modelling for systemic and sustainability innovations. Int. J. Technol. Manag. 63, 4. https://doi.org/10.1504/IJTM.2013.055577
Rosa, P., Sassanelli, C., Terzi, S., 2019. Towards Circular Business Models: A systematic literature review on classification frameworks and archetypes. J. Clean. Prod. 236, 117696. https://doi.org/10.1016/j.jclepro.2019.117696
Schroeder, P., Anggraeni, K., Weber, U., 2019. The Relevance of Circular Economy Practices to the Sustainable Development Goals. J. Ind. Ecol. 23, 77–95. https://doi.org/10.1111/jiec.12732
Schulte, U.G., 2013. New business models for a radical change in resource efficiency. Environ. Innov. Soc. Transitions 9, 43–47. https://doi.org/10.1016/j.eist.2013.09.006
Sustainn, 2017. Circularity Canvas: Methodology to Outline Circular Business Models. http://www.wearesustainn.com/en/2017/03/circularity-canvas-methodology-circular-business-models/ (accessed 30 June 2018).
Ünal, E., Urbinati, A., Chiaroni, D., 2019a. Managerial practices for designing circular economy business models. J. Manuf. Technol. Manag. 30, 561–589. https://doi.org/10.1108/JMTM-02-2018-0061
Ünal, E., Urbinati, A., Chiaroni, D., Manzini, R., 2019b. Value Creation in Circular Business Models: The case of a US small medium enterprise in the building sector. Resour. Conserv. Recycl. 146, 291–307. https://doi.org/10.1016/j.resconrec.2018.12.034
Urbinati, A., Chiaroni, D., Chiesa, V., 2017. Towards a new taxonomy of circular economy business models. J. Clean. Prod. 168, 487–498. https://doi.org/10.1016/j.jclepro.2017.09.047
Whalen, K.A., 2019. Three circular business models that extend product value and their contribution to resource efficiency. J. Clean. Prod. 226, 1128–1137. https://doi.org/10.1016/j.jclepro.2019.03.128
Wiithaa, 2018. Circulab Tools. https://circulab.eu/contact-us/ (accessed 30 June 2018).

Yang, M., Smart, P., Kumar, M., Jolly, M., Evans, S., 2018. Product-service systems business models for circular supply chains. Prod. Plan. Control 29, 498–508. https://doi.org/10.1080/09537287.2018.1449247
Yin, R.K., 2006. Case Study Reserach - Design and Methods. Clin. Res. 2, 8–13. https://doi.org/10.1016/j.jada.2010.09.005