Resources, Conservation & Recycling 184 (2022) 106344

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Implementing circular economy strategies during product development

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ARTICLE INFO

Keywords:
Sustainable product development
General morphological analysis
Strategy implementation
Strategic product planning
Circular product design

ABSTRACT

Although recent circular economy literature has emphasized the strategic role played by circular product design in private sector organizations, strategic management literature has so far overlooked the management implications of integrating circular economy strategies into new or existing products. As a result, the implementation of circular product design in private sector organizations remains unclear. The present paper aims to describe the managerial factors necessary for the implementation of value retention strategies during design and to designate a range of conditions under which each factor may arise. Examples of implementation processes ($n = 24$) were collected via expert interviews and compiled within a comprehensive framework based on general morphological analysis. Hence, implementation processes are represented as a combination of a limited number of process conditions. The framework is also used to describe a taxonomy of process configurations using hierarchical clustering, which indicates a strong influence of corporate sustainability maturity profiles in the implementation configurations observed. The contents of the present work help bridge the gap between strategic management and circular product design literature by providing the building blocks necessary for the integration of value-retention strategies during product planning and development.

1. Introduction

Current rates of population growth and consumption threaten the planet's carrying capacity. If left unchecked, quantitative thresholds for nine key biophysical indicators are going to be surpassed, implying an end to the sustainable functioning of our planet (Rockström et al., 2009). One important underlying force in this context is the inefficient management of natural resources. Such management has historically followed a linear pattern based on the sequence take-make-use-dispose (Boulding, 2013). Even though better technology has improved natural resource use and lowered pollutant emissions, the benefits gained have so far have been outweighed by the pressures emerging from increasing global consumption (Wiedmann et al., 2020). It has thus proved necessary to integrate how societies produce and consume into relevant global policy agendas such as the Sustainable Development Goals (SDGs), specifically in SDG 12: Responsible consumption and production. In recent years, the idea of a circular economy (CE) has also become a policy goal (Schroeder, 2019). The CE is intended to provide socio-technical systems with a set of strategies for slowing, closing, and narrowing material flows (Bocken et al., 2016). These strategies are based on the Inertia principle proposed by Stahel (2010) and seek to preserve the multiple values embedded in products for as long as possible. This has also led to the development of value-retention strategy (VR strategy) frameworks. These include short-loop strategies (where products remain close to their users and functions) such as 'Refuse', 'Reuse', 'Resell'; medium-loop strategies (where products are upgraded and producers are again involved), such as 'Repair', 'Remanufacture', or 'Refurbish'); and long-loop strategies (where products lose their original function), such as 'Recycle', 'Recover energy' and '*Re*-mine' (Reike et al., 2018). These strategies are mostly intended to guide corporate agents' actions (e.g. through value chain interventions at the beginning and end of product life-cycles) (Schöggl et al., 2020). Among corporate activities, product design and development are considered leverage points as the decisions made during these processes have an effect on the entire product (multiple) lifecycle(s) and account for 80% of products' sustainability impacts (IRP, 2018).

As CE practices have become increasingly documented—especially in manufacturing industries (e.g. individual mobility vehicles, consumer electronics), fast-moving consumer goods, and raw material industries (Stumpf et al., 2021)—knowledge on circular product design features

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https://doi.org/10.1016/j.resconrec.2022.106344
Received 30 November 2021; Received in revised form 10 March 2022; Accepted 5 April 2022
Available online 18 May 2022

have now become quite advanced in the academic domain. Prominent publications provide frameworks for defining the circular functionalities of products (den Hollander et al., 2017; Moreno et al., 2016; Tukker, 2015), offer circular product design guidelines (Shahbazi and Jönbrink, 2020; Willskytt and Brambila-Macias, 2020) and provide product-level metrics enabling the evaluation of circularity and sustainability performance (Kravchenko et al., 2019; Niero and Kalbar, 2019; Saidani et al., 2019). Very often, such product circular economy features entail the consideration of intangible design traits and requires reconfigurations of the material, value, and information exchange networks surrounding the physical product. In the academic literature, circular product design is often linked to business model innovation (Schöggl et al., 2020), user-centered design (Selvefors et al., 2019), and digitalisation (Antikainen et al., 2018). Thus, as the implications of adopting circular product designs often interfere with elements of an organisation's competitive strategy, the design process often acquires a strategic role in CE-oriented organisations (Diaz et al., 2021). Despite this, the management implications of adopting circular product design practices remains relatively unexplored. Baldassarre et al. (2020) point to a knowledge gap around implementation issues in sustainable design theories; similarly, a lack of clarity concerning the implementation process has been pointed out in business model innovations for a CE (Hofmann and Jaeger-Erben, 2020); and Hazen and colleagues (2020) emphasize the need for managers to understand how companies approach CE practices. In order to address this issue, the present study analyses product design and development activities through the lens of strategic management and aims to answer the following research questions:

RQ1: Which strategy implementation factors are needed in circular product design and what factor conditions can these take?

RQ2: Which strategy implementation process configurations emerge and, in terms of corporate sustainability, what is their strategic intent?

This research is based on primary data drawn from 15 interviews with designers and engineers engaged with circular economy-oriented product development activities. General morphological analysis (GMA) (Ritchey, 2011) and hierarchical clustering (Oleksy, 2018) are used as the main synthesis methods to present an abstraction of product development processes for circular product design. This information covers the main necessary implementation factors (*process factors*), the range of conditions under which these factors can appear (*factor conditions*), and the emerging process implementation roadmaps (*process configurations*). Hence, the framework presented here aims not only at exploring the strategic nature of circular product design activities, but also provides implementation guidance to practitioners. The following sections include an overview of strategic management and product development practices (Section 2); a description of the methods used in conducting the research (Section 3); the research results (Section 4), containing insights on the managerial factors observed for circular product design and emerging clusters of factor conditions observed across our sample; a discussion of the results from a strategic management perspective (Section 5), and a brief summary of relevant conclusions (Section 6).

2. Theoretical background

This section presents an overview of the main factors determining strategy implementation and the extent to which these have been considered during the integration of VR strategies in circular product design practices.

2.1. Strategy implementation research

At the corporate level, CE is implemented through VR strategies, definitions of which have already been thoroughly discussed in the literature (Kirchherr et al., 2017; Reike et al., 2018). The strategic management literature points at strategy implementation as being the bottleneck to strategy deployment. This possibly explains why researchers have found that the large majority of strategic initiatives are never properly implemented (Aaltonen and Ikävalko, 2002). Several definitions for implementation activities exist, such as the "operationalisation of a clearly articulated strategic plan" (Wind and Robertson, 1983) or a "focus on operational task execution and a scheduled allocation of resources" (Noble, 1999). A few contextual considerations surrounding implementation have also been documented. For instance, Mintzberg distinguishes between two distinct views on strategy generation: an explicit view which usually implies carrying out a predetermined strategic plan; and an emergent one, where a strategy unfolds and evolves without interventions by strategic planners, or even in spite of them (Mintzberg, 1978). In practice, as is well-known, both planned and emergent strategies interact and evolve hand in hand (Aaltonen and Ikävalko, 2002). The conditions in which strategies evolve follow a *planning school* view – a stable organisational environment, centralised and top-down communication flows and formal, standardised decision-making processes; a *learning school* view – decentralised, informal bottom-up communication flows, flexible planning), and a *configurational school* view –, one which assumes that both stable and dynamic organisational structures exist (Okumus, 2003).

In an organisational context, the factors needed for successful strategic implementation processes are of a structural and an interpersonal nature. Analyses of structural factors indicate that while specific arrangements of organisational charts do not play a major role in implementation effectiveness, management control mechanisms do (Engert et al., 2016). More specifically, a strong alignment between strategic goals, process performance targets, and compensation systems for all company levels is needed so that actors' activities and behavior effectively translate strategic plans into action (Gębczyńska, 2016). Besides structural factors, interpersonal factors are of prominent importance. In particular, effective communication appears to be an important factor in strategy implementation, as it is the main driver for strategic consensus and coordinated action. This is crucial in the case of sustainability strategies (Engert and Baumgartner, 2016). Thus, two-way communication (bottom-up and top-down), as well as lateral communication (across business functions), are both necessary (Bamford and West, 2010). Here, middle-managers have been appointed as key communication facilitators across different company levels and departments (Baumgartner, 2014; Stone, 2006). Additional interpersonal topics influencing implementation relate to autonomous strategic behaviours, leadership, and openness to change (Aaltonen and Ikävalko, 2002; Noble, 1999). Even though implementation processes are considered too complex to be explained through a generally agreed-upon prescriptive model, many frameworks identify essential implementation process constituents. These elements are generally grouped into four categories: elements that relate to the strategic content (why and how the strategy is initiated); elements that relate to the strategic context (belonging to the external and internal environments of the company); operational process elements (planning, resource allocation, communication and control activities); and implementation outcomes (the implementation process results) (Okumus, 2003). Thus, these elements need to be supported by an organisational management base that can guide normative (organisational culture, shared values), strategic (long-term goal-setting), and operational decisions (execution of the appropriate activities and guidelines to pursue organisational goals) (Baumgartner, 2014).

Reviews of design research studies identified a thematic change in the design literature, e.g. entailing a move from simple product add-ons towards greater emphasis on management strategy integration (Erichsen and Christensen, 2013). Process models are important tools in depicting the various activities involved in integrating strategies during product development. The activities included are often a sequence of steps related to product planning, process monitoring, organization communication flows, IT support implementation, and the provision of guidelines to direct, evaluate and improve team acting and thinking

(Blessing and Chakrabarti, 2009). Process models emerged following initial design methodologies, including systemic inventories of design working principles and cataloging of physical product components. Relevant work contributing to the systematization of design and development activities and process models subsequently emerged, e.g., the VDI 2221 guidelines, the works of Pahl & Beitz (1977), and contributions from the Danish schools (Andreasen and Hein, 1987). Digitalisation strongly influenced design routines and since the late 1980s, process models have been shaped by information and software systems (Boehm, 1988). Besides the stronger vertical integration of company levels within design activities, designers are also increasingly regarded as cultural intermediaries who play a significant role in shaping the production and consumption relations of capitalism (Negus, 2002). This makes their activities crucial when attempting to meet the complexity of global challenges such as climate change (Fleischmann, 2013).

2.2. Strategic management perspectives on circular product design

Design for Sustainability (DfS) has contributed considerably to the conceptualization of circular products. The idea of integrating sustainability aspects into design was first put forward by the publication of "Design for the Real World: Human Ecology and Social Change" (Papanek, 1972). Since then, several design movements have attempted to integrate sustainability principles into product design. According to the review of Ceschin and Gaziulusoy (2016), early Green design principles aim at improving products' environmental performances through the modification of discrete qualities of individual products. The Green design field evolved into Eco-design as it progressively accounted for products' environmental impacts throughout the entire lifecycle – supported by Life-cycle Assessment – gradually acknowledging the need to integrate eco-design operational activities with tactical and strategic organisational goals. The social dimension of sustainability then became somewhat integrated into Green design and value-retention was pursued by means of a stronger user focus in disciplines such as Emotionally durable design (Barnes and Lillford, 2009) or Design for sustainable behavior (Lilley, 2009). The notion of what a product is has progressively evolved from it being a mere physical artefact to it being a complex value-delivery system composed of physical and non-physical components. This systemic view has been crystallized in the concept of Product-Service Systems (PSS), incorporating principles of both eco-efficiency and sustainable PSS design (Mont, 2002). In parallel, the societal aspects of design have moved from an early focus on individual user engagement to the targeting of entire societal groups in disciplines such as 'Design for the Base of the Pyramid' and 'Design for Sustainable Social Innovations' (Vezzoli et al., 2017). Finally, the work of Geels (2002) on sustainability transitions was also adopted by design scholars, and led to approaches such as 'Design for Sustainability Transitions' (Ceschin, 2012, p. 94). Circular product design, built upon these pre-existing paradigms, focuses on developing products able to pass through multiple life cycles (Moreno et al., 2016). This is enabled through design strategies that allow the preservation and recovery of products' functionalities, physical integrity, and embedded materials or energy for use in subsequent product lifecycles. In other words, design strategies that allow the retention and recovery of products' value so that they are kept in economic systems for as long as possible. These design strategies are made explicit through Design for X (DfX) guidelines proposing improvements in particular product traits that are key enablers of value retention.

The strategic character of design has become even more prominent when circular product performance is sought (Baldassarre et al., 2020; Diaz et al., 2021). Hence, this is increasingly recognised in circular product design frameworks. Besides explicit DfX guidelines, circular products need to integrate additional design traits fulfilling operational excellence, product leadership, and customer intimacy goals to further prevent obsolescence (Asif et al., 2021). Mesa *and colleagues* (2019) propose to leverage an open architecture strategy through the modularity, standardization, and reconfiguration design features of products. Hapuwatte & Jawahir (2021) propose a circular product design framework that integrates the values of primary company stakeholders into products' architecture, material, or process. Additionally, the identification of product ecosystem partners has been included in the conceptual design framework for circular products of Brown et al. (2021). Finally, Subramoniam et al. (2021) provide insights into the intrinsic digitized lifecycle strategy of circular products undergoing reverse supply chains and remanufacturing. Here, a strong digital infrastructure is necessary for original equipment manufacturers to obtain information regarding the amount and condition of returned products so that the competitive advantage of remanufacturing operations can be seized. Despite the increasingly transformational implications of circular products for organisational activities, the management needs required for its implementation have still not been thoroughly explored (Dokter et al., 2021; Fernandes et al., 2020). Hence, the present paper adopts a strategic management perspective on design activities and proposes a process model focused on facilitating the adoption of VR strategies during product development.

3. Methods

This section introduces the methodological foundations of the proposed process and the steps involved in its development (Sections 3.1., 3.2, and 3.3). An overview of the approaches is represented in Fig. 1.

A design research methodology approach (DRM) (Blessing & Chakrabarti), intended to formulate and validate models and theories about the phenomenon of design as well as to provide support for improving design practice, is adopted here. DRM provides a framework for research projects composed of 4 different stages: Research Clarification (RC), Descriptive study I (DS-I), Prescriptive study (PS-I), and Descriptive Study II (DS -II). The outcomes of RC and DS-I have been reported in Diaz et al. (2021), which provided an overview of the implications of circular product design for sustainable product development processes. The study identified strategic management activities as a key determinant for the VR strategies being integrated during circular product design. Therefore, the present study (PS-I) focuses on the company-wide management implications of adopting VR strategies and introduces a framework to support these.

3.1. Data collection methods

The data used for this work belongs to the interview dataset collected in Diaz et al. (2021). Recruitment of interviewees concerned the following inclusion criteria: a) to be working for a large enterprise (250 employees or more) belonging to high-quality value chains operating in industrialised economies; b) have at least three years of experience in a product developer or sustainability expert role executing sustainable product development routines; c) have executed sustainable product development routines within engineering teams or research and development departments (Diaz et al., 2021). The interview sample size was decided based on saturation point identification for theory-based

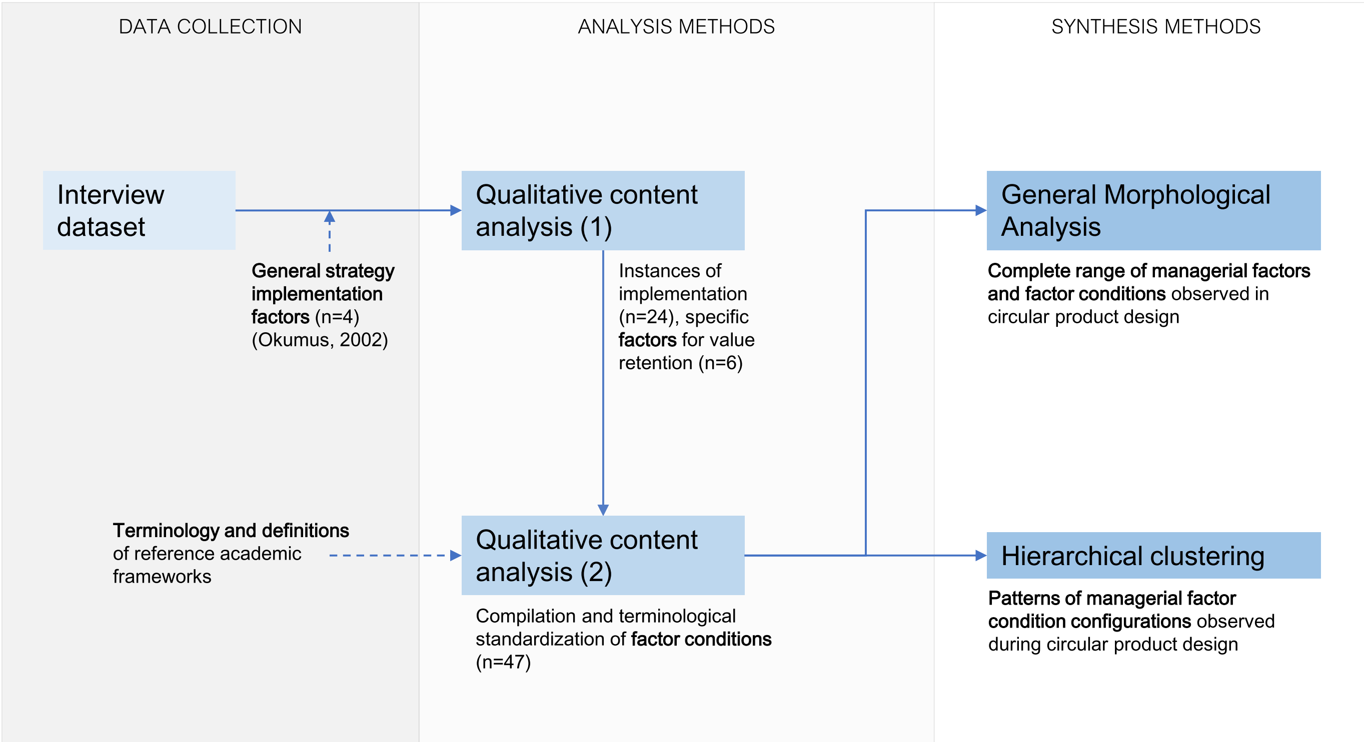

Fig. 1. Overview of research approach.

content analysis (Francis et al., 2010). This required two rounds of interviews: the first round of analysis was set for 10 interviews, where spurious data saturation due to homogenous sampling was discarded based on the preliminary content analysis results. During the second round, new interviews were added to the sample until no new themes emerged for three consecutive interviews, which in our case occurred at interview 15.

Further details on the interviewees (Table A1) and the interview questions (Table A2) are given in the Appendix.

3.2. Analysis methods

The first step consisted in identifying examples of VR strategy implementation which involved strategic management activities. For this, theory-driven categories of necessary factors for strategy implementation were developed. This first generic categorization included generic strategy elements proposed by Okumus (2003) — strategic content, strategic context, strategic process, strategic outcomes — and its definitions. The data was analysed using a deductive content analysis approach (Elo and Kyngäs, 2008). After an initial round of analysis, 24 instances of VR implementation with strategic management

Table 1
Details on the instances of VR strategy implementation extracted from the interview dataset.

OBSERVATION CODE	VR STRATEGY	TYPE OF PROJECT	INDUSTRY
OBS 1	Recycle	Product ecosystem design	Not disclosed
OBS 2	Recycle, Recover energy	Sustainable material selection	Not disclosed
OBS 3	Recycle, Recover energy, remine	PSS design	Telecommunications
OBS 4	Resell, Reuse, Recycle	PSS design	Automotive
OBS 5	Recover energy	Energy-efficient design	Built environment
OBS 6	Repurpose, Recycle, Remine	Modular design	Built environment
OBS 7	Refuse, Reduce	Product passport	Built environment
OBS 8	Repair, Refurbish	Predictive maintenance	Built environment
OBS 9	Repair	Design for repair	Measurement systems
OBS 10	Refurbish	Design for remanufacture	Aviation
OBS 11	Refuse, Reduce	Nature-inspired design	Energy sector
OBS 12	Refuse, Reduce	Energy-efficient design	Energy sector
OBS 13	Repurpose, Recycle, Recover energy	Product passport	Energy sector
OBS 14	Recover energy	Energy-efficient design	Energy sector
OBS 15	Repair, Refurbish	Predictive maintenance	Energy sector
OBS 16	Recycle, Recover energy	Sustainable material selection	Automotive
OBS 17	Recycle, Recover energy	Sustainable material selection	Automotive
OBS 18	Recover energy	Product ecosystem	Automotive
OBS 19	Resell, Reuse, Repair, Refurbish	PSS design	Not disclosed
OBS 20	Repurpose	Product ecosystem	Automotive
OBS 21	Recycle	Product passport	Automotive
OBS 22	Repair	PSS design	Measurement systems
OBS 23	Recycle	Sustainable material selection	Aviation
OBS 24	Reduce	Energy efficient design	Energy sector

Table 2
Overview of factors and factor conditions enabling the integration of VR strategies during circular product design.

STRATEGY DIMENSIONS	FACTORS	FACTOR CONDITIONS	TERMINOLOGICAL REFERENCE
Strategic content	Selection of VR strategy	Value-retention strategies ($n = 10$)	(Reike et al., 2018)
Strategic context	Setup of product/service stakeholder system	Network of socio-technical actors facilitating the societal embedding of PSS ($n = 7$)	(Ceschin, 2012, p.198)
	Setup of product/service cross-functional operational teams	Operational level of a sustainability-oriented corporate management ($n = 7$)	(Baumgartner, 2010)
Strategic process	Embodiment of design guidelines	Design focus of circular economy DfX guidelines ($n = 7$)	(Diaz et al., 2021)
Strategic outcomes	Evaluation of technical and economic constraints	Product quality dimensions ($n = 8$)	(Garvin, 1984)
	Evaluation of environmental and social performance	Framework for Strategic Sustainable Development ($n = 8$)	(Broman and Robèrt, 2017)

implications were identified (Table 1). The authors identified six recurring themes emerging from these instances, which were established as the six main factors of value-retention implementation (Table 2). The second step consisted of a second content analysis round throughout the 24 instances of VR implementation, which allowed to compile a range of factor conditions observed for each factor. The factor conditions were renamed in accordance with the frameworks found in the literature in order to overcome terminological differences and to come up with a range of subcategories that were both conceptually and empirically sound (Table 2).

Simplification is often required during the categorization process (Elo and Kyngäs, 2008). In this case, it concerned two sets of factor conditions belonging to 'Embodiment of design guidelines' and 'Evaluation of technical and economic constraints'. The initial range of factor conditions found in the expert interview dataset for 'Embodiment of design guidelines' was composed of 11 different DfX guideline types. Nevertheless, a substantial amount of overlap with regards to the proposed improvements in particular product traits was found, an issue that has been previously reported in the literature (Sassanelli et al., 2020). Accordingly, the correspondence between each DfX guideline type and seven circular product design foci (Diaz et al., 2021) was identified (Tables A3 and A4 in Appendix). Hence, a smaller and mutually exclusive range of factor conditions was compiled. Second, 'Evaluation of technical and economic constraints' was considered a function of product quality, and thus, its corresponding range of factor conditions is based on the product quality framework proposed by Garvin (1984). This allowed us to disaggregate the various forms of compromises met during implementation with regards to sustaining company competitiveness.

3.3. Synthesis methods

3.3.1. General morphological analysis

The main method used, General Morphological Analysis (GMA), is suitable for identifying relationships contained in multi-dimensional, non-quantifiable problems (Zwicky, 1967). Morphological analyses have been used to structure engineering design activities e.g., to set up CAD systems (Belaziz et al., 2000), production systems (Ostertagová et al., 2012), conceptual planning processes (Bezerra and Owen, 2000), and also as a design approach in itself (Kannengiesser et al., 2013). An outcome of GMA is a morphological field, which is built by setting the parameters defining a phenomenon against each other and identifying their co-occurrence, thus marking particular states or configurations. Within the context of the CE literature, the application of GMA has mainly focused on Business Model Innovation (BMI) activities (Lüdeke-Freund et al., 2019; Pieroni et al., 2019). GMA seeks to identify the main parameters (here 'factors') of the issue under investigation and to assign each parameter a set of important values (here 'factor conditions') (Ritchey, 2011). The internal relationships among factor conditions produce configurations (here 'process configurations'), which characterize the different particular states of the phenomenon under study.

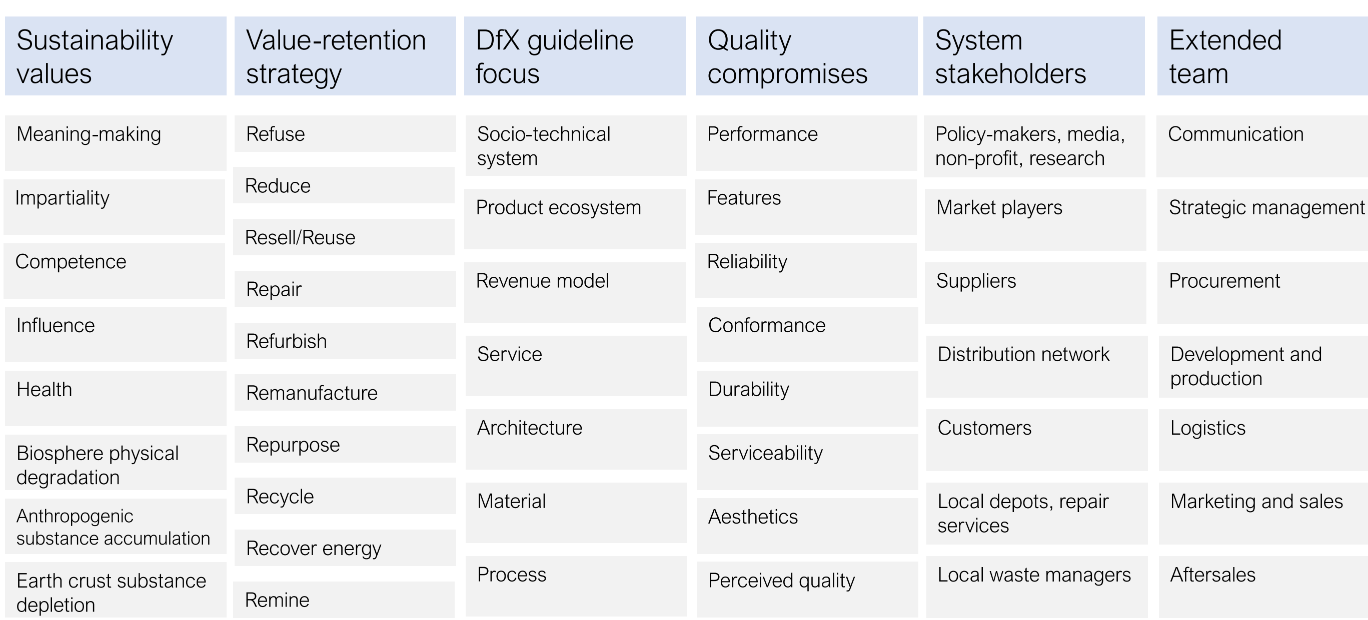

Fig. 2. Complete morphological field. The top row shows the number of managerial factors enabling implementation of VR strategies. The columns display the corresponding range of factor conditions observed.

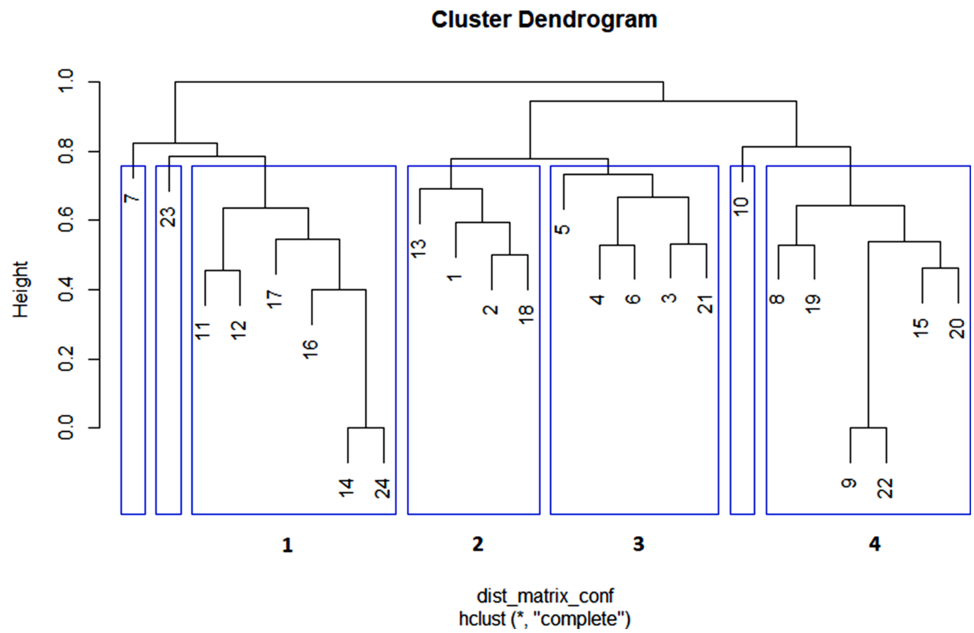

Fig. 3. Dendrogram providing an overview of the hierarchical clustering results. The height axis displays the distance between observations. The horizontal bars indicate the point at which two observations are merged into a cluster. The numbers located at the edge of each dendrogram branch correspond to the observation code. The numbers appearing below each cluster correspond to the clusters discussed in Section 4.2

A morphological field format was used by the main author to translate each instance of VR strategy implementation into a morphological field configuration using the limited number of categorical variables ($n = 47$) set by the range of factor conditions identified (Fig. 2). Cohen's kappa – an indicator for Interrater reliability (McHugh, 2012) – was used to assess the extent to which the resulting configurations were a correct representation of the instances of value-retention implementation. Hence, a second coder independently analysed a third of the total number of implementation instances ($n = 8$) and derived their corresponding morphological field configurations. These were compared to the configurations obtained by the main coder. The resulting Cohen kappa values ranged from 0.75 - 0.91, indicating a strong level of agreement (Table A5 in Appendix). Detailed calculations are contained in the supplementary materials (Equation A1).

3.3.2. *Hierarchical clustering*

Hierarchical clustering (Johnson, 1967) was employed to identify clusters among the morphological field configurations ($n = 24$). Cluster analysis is a form of exploratory data analysis used to solve classification problems. Hierarchical clustering seeks to construct a hierarchy in which some objects are more related to objects that are closer in distance than to objects that are further away. As it is applicable to binary data (Tamasauskas et al., 2012), this method was found to be suitable for the identification of clusters. The analysis was performed using RStudio Version 1.1.456. The steps involved in conducting this method were: a) data preparation; b) building a distance matrix; c) finding groups of similar observations according to calculated distances; d) determining an optimal number of clusters. The data preparation involved the transformation of the coded process configurations into a binary matrix comprising 24 observations of 47 variables each (all the factor conditions included in the morphological field accounted for a binary variable, where TRUE = present condition and FALSE = absent condition). The Jaccard index is a well-known measure of similarity for data sets made up of continuous, discrete, or binary attributes (Fletcher and Isla, 2018) and thus, suitable for construction of a distance matrix. A hierarchical clustering algorithm (hclust()) was applied to the distance matrix using complete linkage criteria in order to identify similar observations. This produces an agglomerative clustering process: each observation is considered a single element, and at each step of the algorithm the two elements that are the most similar are combined into a bigger cluster, a procedure which is iterated until all observations are gathered into one big group. The resulting dendrogram is displayed in Fig. 3. The final step consists in determining the number of clusters. This varies depending on the method used. Since no single objective procedure is available for determining the correct number of clusters, theoretical considerations concerning the 'natural' number of clusters in any particular case need to be drawn upon (Hair et al., 2018, p.221). For practical considerations, the authors decided to cut the dendrogram at height = 0.75 and to dismiss isolated observations from the analysis (Observations 7, 10, 23) (Fig. 3). The remaining observations were then grouped into 4 different clusters and the configurations present within each cluster were contrasted with those found in the sustainability strategy implementation literature (Section 4.2). Hierarchical clustering data is presented in the Supplementary materials.

4. Results

This section describes VR strategy implementation factors enabling circular product design (Section 4.1) and the configurations derived from interview data (Section 4.2).

4.1. *Strategy implementation factors and interdependencies*

This section provides insights on the management factors enabling circular product design at different stages of product planning and development activities (Fig. 4). The interdependencies across these factors are summarized in Table 3.

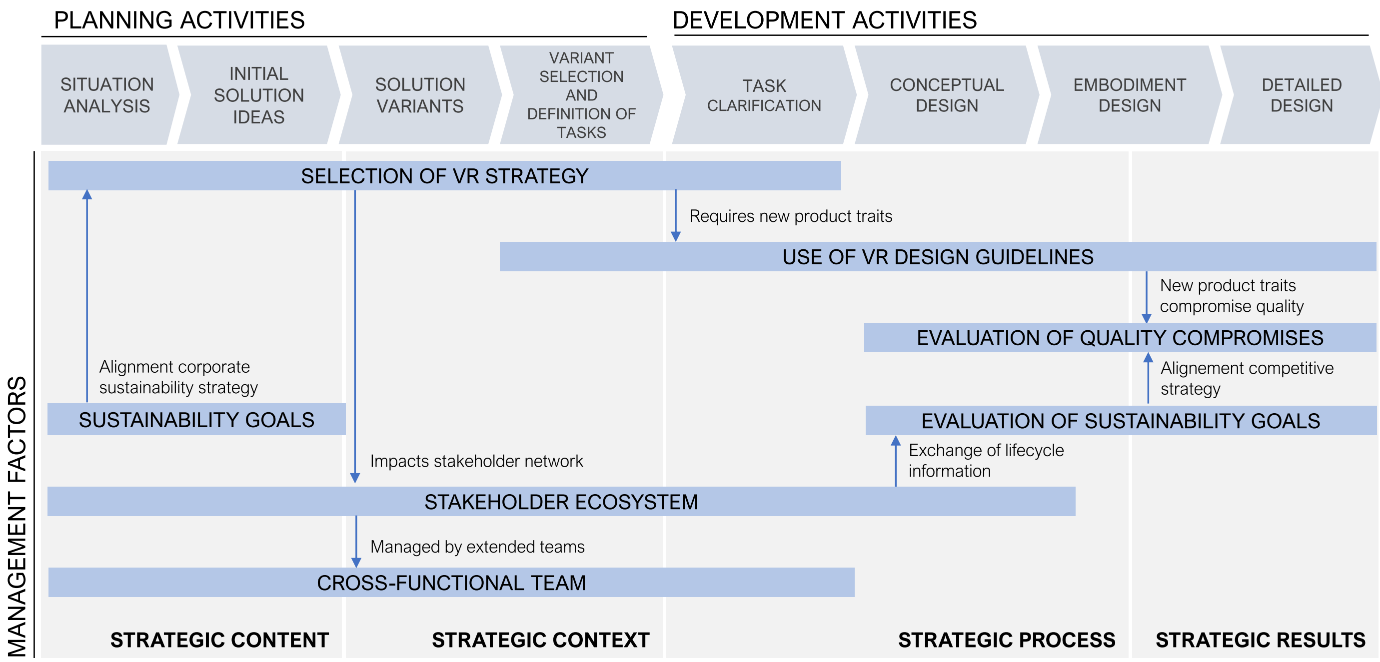

Fig. 4. Overview of management factors influencing circular product design emerging at different stages of product planning and development and main interactions among them.

4.1.1. *Selection of VR strategies*

In the process configurations analysed, VR strategies are identified as a subset of competitive strategies (both cost-leadership (OBS 10, OBS 12, OBS 9) and product differentiation (OBS 2, OBS 5). The selection of VR strategies often follows situation analysis activities (OBS 3, OBS 13) such as portfolio analysis (OBS 4, OBS 6), product benchmarking (OBS 20), and forecasting (OBS 18). In some instances, as VR strategies consisted of a subset of corporate sustainability strategies, outcomes were aligned with company sustainability goals. VR strategy frameworks provide a generic prescription of the product lifecycle stage in which they are to be implemented, the key actors involved, and the value and functionality recovery process (Reike et al., 2018). It is then the task of the companies to translate the VR strategies into new product concepts (as input for product idea-finding activities and identifying new product tasks) where the network of key actors is represented, and the internal business processes involved in managing the key actors are also identified. Accordingly, two conditions are required for the proper integration of VR strategies. On the one hand, they need to be addressed relatively early on; e.g., during product planning activities, so that potential synergies and goal conflicts are identified. On the other hand, a strong degree of integration needs to exist between product planning activities and product development so that designers can build on planner directions. These requirements are especially important for short-loop strategies, since these are more likely to be interconnected with strategic organizational elements.

4.1.2. *Applying design guidelines*

For product planning activities to be taken up by product developers it is important that a product proposal documenting product ideas is available, and which describes the main selection criteria and a preliminary list of design requirements. A VR strategy is integrated into the product by formulating VR-derived functional requirements. These then need to be taken up by developers and translated into design traits and working principles. Designers can thus use circular product design guidelines (DfX) and explicitly address issues such as design for environment, design for lifecycle, and design for recyclability, etc. However, in itself the recognition of a CE function is not the end of the designer's task. New functions have also to be integrated into a long list of requirements related to compliance (OBS 16) or customer preferences (OBS 10). In some instances, the direct involvement of product system stakeholders was described (OBS 19), e.g., in ensuring the fulfillment of the VR strategy or concerning the embeddedness of the new concept.

4.1.3. *Identify quality compromises*

Preservation of economic value is linked to the extent to which the product system is able to perform the functions for which it was conceived and the extent to which it is necessary for an organization to remain competitive in the market. Accordingly, the planning and development team must analyze how new design traits, working principles, and functionalities interact with product quality and decide whether circularity threatens product performance. One development routine suitable for assessing this in detail is the process of product evaluation. Product evaluations are more elaborate than the initial selection of concepts occurring in the planning phase in that they require decision-making support covering a wide range of objectives (task-specific, requirements, constraints) and encompass both the quantitative and qualitative properties of concept variants. The fulfillment of VR strategies can be checked during product evaluation routines by using various integrated circularity indicators (OBS 23). CE-related compromises relating to quality were identified in some configurations analysed, concerning, for example, modular architecture-aesthetics (OBS 6), recyclable materials-reliability (OBS 23), product-oriented PSS revenue model - serviceability (OBS 22), result-oriented PSS revenue model, and perceived quality (OBS 19).

4.1.4. *Product ecosystem stakeholder analysis*

The goal of this phase is to understand the external strategic context in which the product is embedded. Hence, stakeholder analysis was found to play a role in planning activities (OBS 11, OBS 3, OBS 4) – e.g., as part of the situation analysis (OBS 12) – and also in the conceptualisation of the product/service (OBS 19). Product ecosystems were acknowledged as important elements in facilitating value delivery in a CE (Konietzko et al., 2020). Ecosystems include stakeholders that directly interact with the product as well as those who do not. The main reason for targeting the first group is that the effectiveness of the VR strategy effectiveness is largely determined by the interventions of such actors. The effect that any new product functionalities have on their behavior thus needs to be carefully examined. Taking account of the impact on more indirect stakeholders derives from concerns relating to broader strategic design (Manzini and Vezzoli, 2003) and the potential for socio-technical transformations. Thus, companies determined to meet CE transformational aspirations and to achieve a certain degree of societal embeddedness, need to have a medium-long term vision of stakeholder management and to aim at influencing cultural actors, political actors, regulatory actors, and market actors (Baumgartner and Korhonen, 2010; Ceschin, 2013). As managing complex stakeholder ecosystems is beyond the scope and capabilities of most planning and development teams, the capabilities of different business units need to be integrated into development roadmaps whereby relevant tasks are allocated to the appropriate part of the team.

4.1.5. *Cross-functional system*

The goal of this activity is to manage those operational tasks unrelated to design within an extended cross-functional team. Product planning and development activities are interdisciplinary by nature, as they follow market, environment, or intra-organisational stimuli. Decisions involve the selection and detailing of new sustainable product ideas where the capabilities of designers and environmental experts are essential, and also determine whether a product's financial position or market performance is aligned with companies' competitive strategy. Thus, while the composition of an extended team depends on specific company structure, it commonly requires at least a) marketing capabilities to ensure a very good understanding of quality requirements (OBS 20), stakeholder management through communication activities (OBS 4), financial capabilities to assess product performance (OBS 20), and product management in order to perform risk analysis and feasibility studies. Hence, cross-functional information management systems such as product lifecycle management (PLM) were found to be effective in integrating information from different departments (OBS 9) with respect to the product data management platforms used in development. Not only a horizontal approach to information management is required, but also a vertical one, since the capabilities acquired through seniority are also relevant. The coordination of extended teams often requires the soft skills of a middle manager (OBS 23) to ensure management compliance in maintaining strategic alignment and to overcome any internal resistance among company board members.

4.1.6. *Environmental and social evaluation*

A sound environmental and social product performance is relevant for corporate sustainability strategies. In standardised product planning and development activities, two main decision steps guide the selection of product/service variants in which environmental and social criteria are integrated. These are generically termed product selection and product evaluation (Pahl et al., 2007). Product selection is typically conducted at an early development stage, where product systems embody relatively low levels of design, and thus where performance information is often difficult to quantify – the so-called design paradox (Ullman, 2002). In the context of environmental and social performance, several sustainability assessment methods have been found suitable for supporting evaluation in early process stages (Chebaeva et al., 2021). Quantitative environmental and social evaluation is possible at later stages of development even though the main methodological approaches have typically had a low degree of integration concerning design and development routines (OBS 1, OBS 7, OBS 9).

4.1.7. *Factor interdependencies*

Based on the observed interdependencies among the factors (Fig. 3), it is possible to derive some management priorities. Firstly, a strong interdependence among factors implies that all of them need to be present to some extent. This might require significant resources, which might, in many cases, negatively impact business profit margins. Accordingly, circular product design needs to be regarded as means for the company to achieve a competitive advantage, not only for products to fulfill new tasks. For this, VR strategies need to be planned before design activities take place (e.g., in product planning), where managerial actors can identify directions for further value creation. Secondly, product ecosystems need to consider a wider range of stakeholders involved as value creation and value-retention partners during the conceptualization of circular products. To ensure the planned VR strategies are pursued by design teams, a strong business process integration is needed. This should involve the integration of planning and development activities as well as teams responsible for managing information from a wider range of stakeholders. Finally, many interdependencies linked to the evaluation of environmental and social aspects emerge. This reinforces the need for stronger business process integration, allowing companies to connect teams internally, but also externally.

Table 3
Pairwise overview of interdependencies between strategic management factors.

	SELECTION OF VR STRATEGY	EMBODIMENT OF VR DESIGN GUIDELINES	EVALUATION OF QUALITY COMPROMISES	SET-UP OF A STAKEHOLDER SYSTEM	CROSS FUNCTIONAL TEAM
EMBODIMENT OF VR DESIGN GUIDELINES	VR strategy determines new product tasks				
EVALUATION OF QUALITY COMPROMISES	VR strategy needs to in alignment with competitive strategy	New design working principles compromises product quality			
SET-UP OF A STAKEHOLDER SYSTEM	VR strategy impacts different stakeholder groups	Integration of stakeholder perspectives during development	Direct determination of quality thresholds of product/service stakeholders		
CROSS FUNCTIONAL TEAM	VR strategies are translated into business processes	Integration of stakeholder perspectives during product development	Indirect determination of quality thresholds of product/service stakeholders	Cross- functional product/ service stakeholders information management	
EVALUATION OF ENVIRONMENTAL AND SOCIAL PERFORMANCE	Sustainability impacts of VR strategy in alignment with corporate sustainability strategy	Screening of social and environmental impacts	Product evaluation	Quantification of social and environmental impacts	System-specific impact datasets

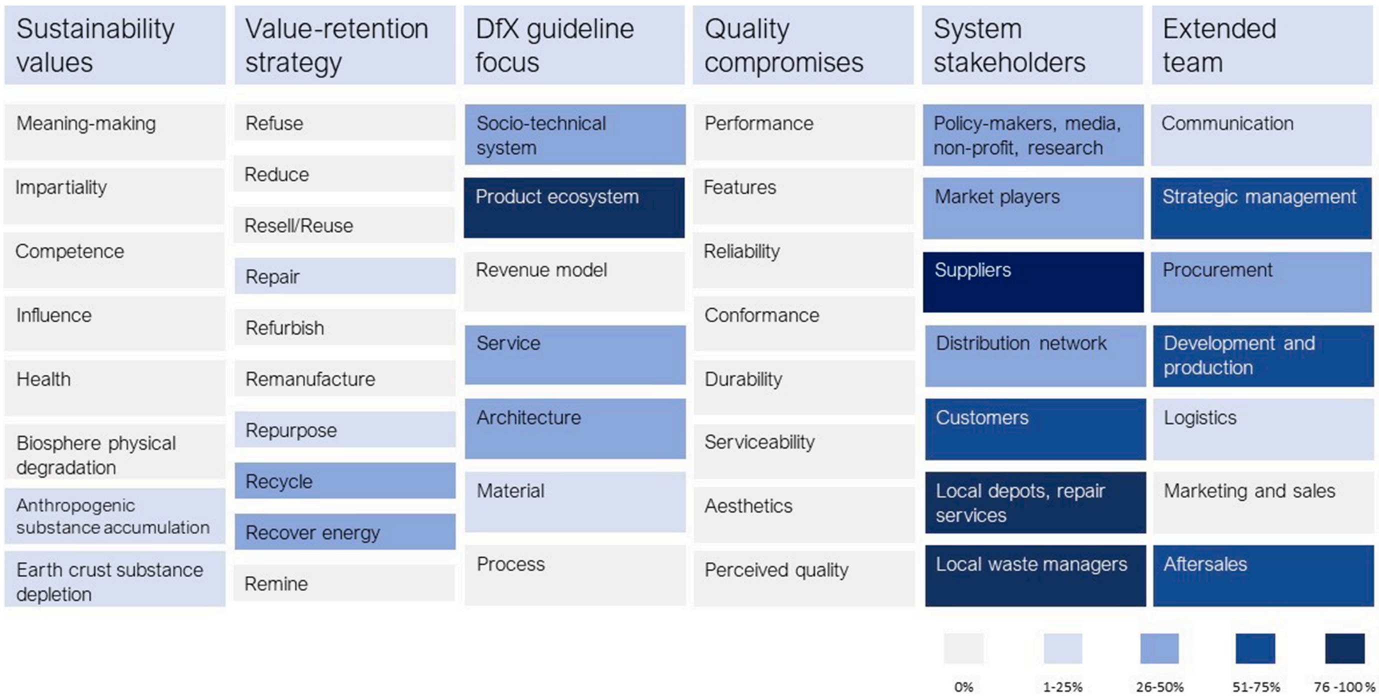

Fig. 5. Factor conditions of Cluster 1 and corresponding frequency of appearance.

4.2. Patterns of managerial factor configurations

This section uses the morphological field to analyze, from a corporate sustainability strategy perspective, the main management factor conditions observed in our sample. The factor conditions represented in the morphological fields have been assigned a scale of color reflecting the frequency of appearance within the cluster. This is expressed in terms of percentage of configurations in which the condition appeared out of the total of configurations within the cluster (Fig. 5, 6, 7, and 8).

4.2.1. Cluster 1 ($n = 6$): extroverted approach

This cluster is composed by instances of implementation OBS 11, 12, 17, 16, 24, 14 (Fig. 3). The configuration observed in the present cluster (Fig. 5) reveals that VR strategy sustainability performance has relatively low priority as it was scarcely mentioned. It is also possible to observe a long-loop approach towards value-retention (mostly seeking material or energy preservation). The design focus is predominantly oriented towards the intangible product dimensions (product ecosystem) and only slightly impacts tangible dimensions. However, on examining the instances of implementation in detail, it becomes possible

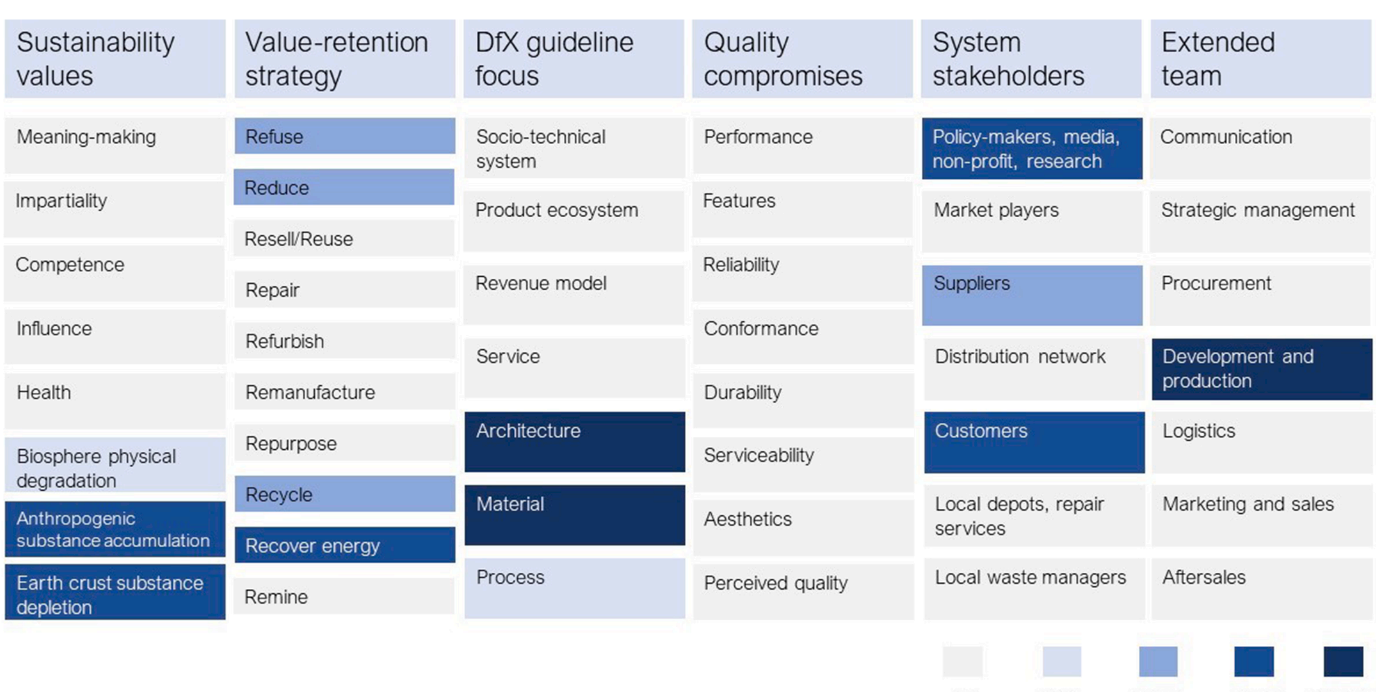

Fig. 6. Factor conditions of Cluster 2 and corresponding frequency of appearance.

to discern the existence of a common goal, namely, the transfer of product data information (OBS 12, OBS 16, OBS 17, OBS 24), a goal which is often facilitated by various architecture or material interventions. The transfer of information also explains the necessary involvement of entire lifecycle actors and the occasional involvement of wider socio-technical system actors. As the disclosure of product information might also entail disclosure of competitive advantage, managers need to assess how well this conforms with aspects of strategic management. The feedback of information from post-consumption lifecycle phases also involves aftersales departments. In sum, in this configuration there is a strong focus on external relationships and the potential for reaping the benefits of market transformations, but the sustainability-related incentives and motivations remain low. All in all, the factor conditions observed in this case seem to follow an extroverted strategic approach (Baumgartner and Ebner, 2010) towards circular product design.

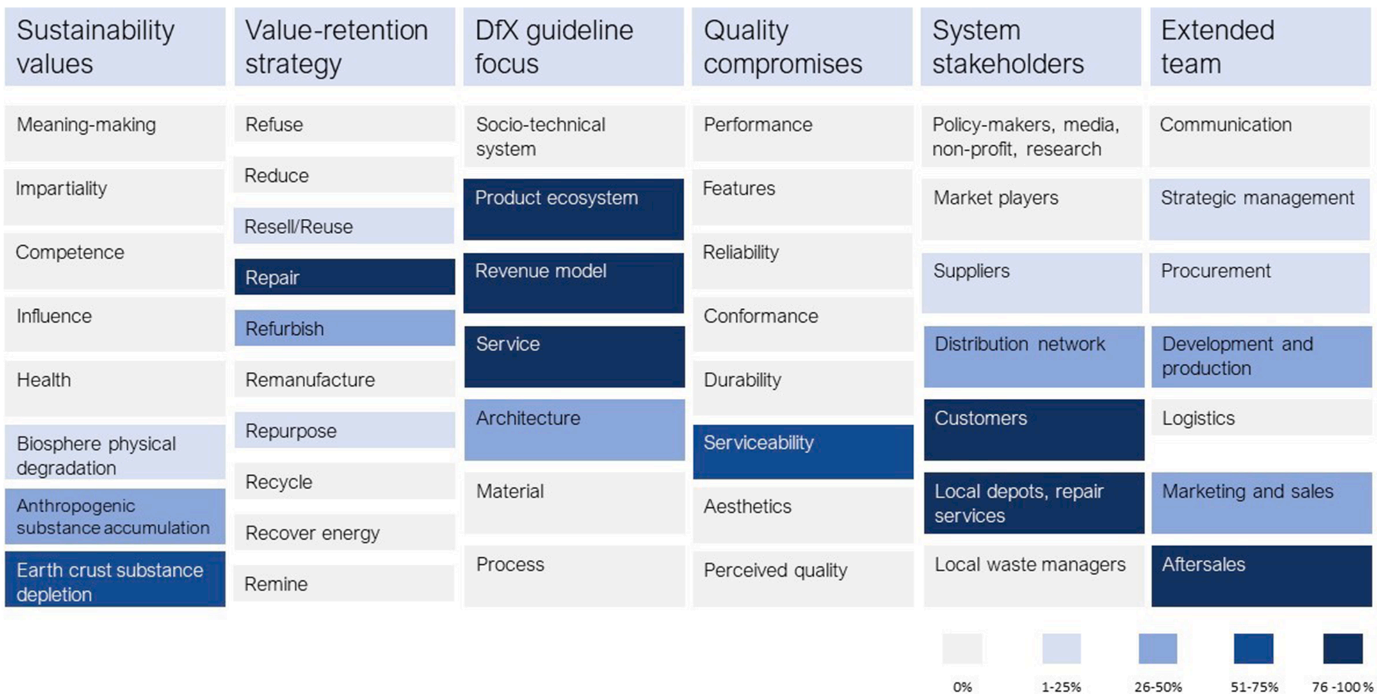

Fig. 7. Factor conditions of Cluster 3 and corresponding frequency of appearance.

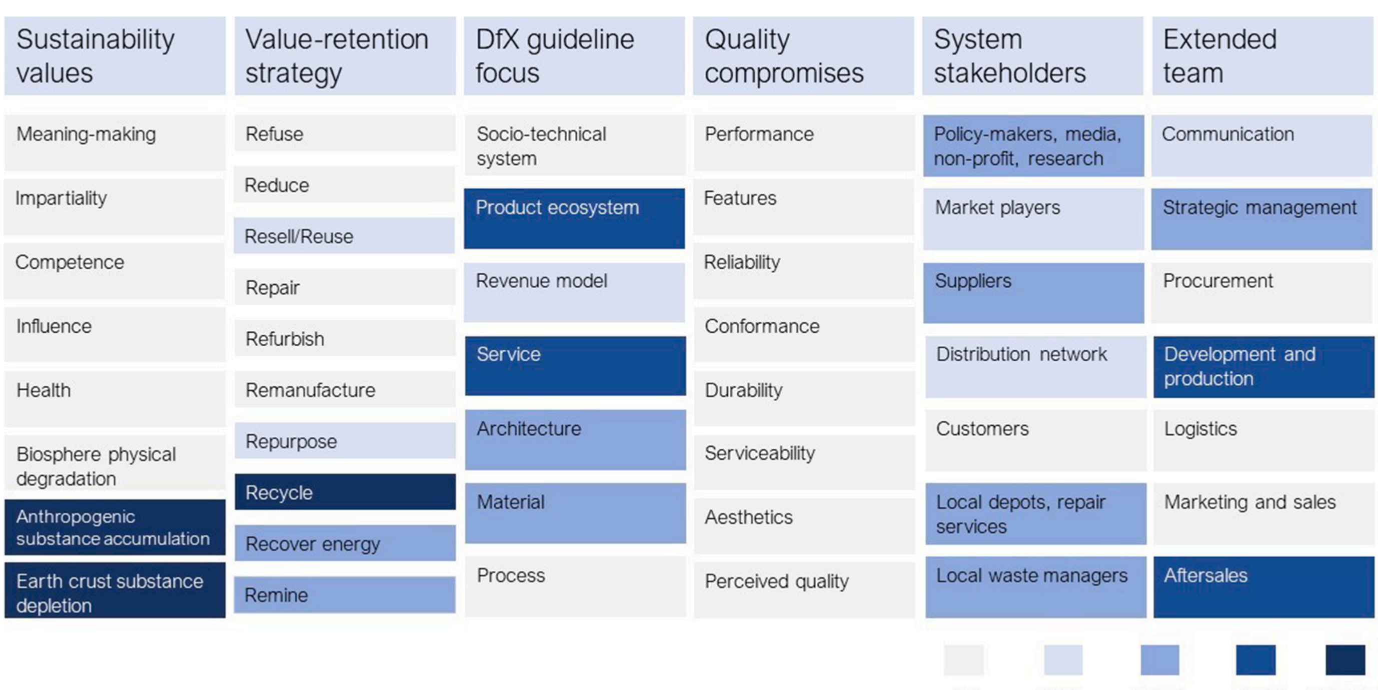

Fig. 8. Factor conditions of Cluster 4 and corresponding frequency of appearance.

4.2.2. Cluster 2 ($n = 4$): conservative approach

This cluster is composed by instances of implementation OBS 13, 1, 2, 18 (Fig. 3). Here (Fig. 6), organisations display a focus on resource-efficiency and emission reduction. This often means that environmental and social product evaluations after VR-strategy integration remain in alignment with the goals set by a corporate sustainability strategy. Nevertheless, a long loop approach towards value-retention can also be observed ('Refuse' and 'Reduce' here are observed as partial dematerialisation of products that do not imply a reflection on the tasks the product is fulfilling). The observed desire for incremental improvement is also consistent with the design foci, which are centered around material and architecture interventions, and, in a few cases, around production process improvements. As for the system stakeholders, there is a strong focus on customer-driven requirements and compliance-driven requirements that are mostly managed by the development team. There is a need to engage suppliers too, as they support the integration of component design modifications and the respective information flows. This approach towards circular product design follows a conservative strategic approach towards sustainability (Baumgartner and Ebner, 2010), a focus on improving environmental product/service performance through technological improvements, and a low level of attention with respect to the social dimension of sustainability.

4.2.3. Cluster 3 ($n = 5$): conventional visionary approach

This cluster is composed by instances of implementation OBS 5, 4, 6, 3, 21 (Fig. 3). In this cluster (Fig. 7), it is possible to observe environmental sustainability objectives being approached mostly through medium-loop VR strategies which seeking to extend the product lifespan or to enable the sequential use of the product in a new lifecycle for a different purpose. This mostly involves the redesign of intangible product dimensions such as the set-up of a product ecosystem, adapting the business model and the service accordingly, and making modifications in the relevant architecture so as to facilitate the recovery of functionality. Since the value retention activities are implemented as add-on services during the product use-phase, the risk of compromising serviceability was mentioned in cases where repair services were outsourced (OBS 5). The actors concerned are customers, local depots, repair services and internal aftersales departments. Architecture changes intended to facilitate value-retention involve development and procurement departments, and the modifications of the business model may also involve strategic management on some occasions. Considering all these aspects, we argue that this configuration cluster complies with a conventional form of visionary strategic intent (Baumgartner and Ebner, 2010) where the integration of sustainability issues is driven by market opportunities.

4.2.4. Cluster 4 ($n = 6$): systemic visionary approach

This cluster is composed by instances of implementation OBS 8, 19, 9, 22, 15, 20 (Fig. 3). Here, in contrast to Cluster 3, it is possible to observe a stronger focus on environmental sustainability performance being addressed through the redesign of intangible product traits (Fig. 8). This may be related to the ecosystem around the product or to the services it delivers, when seeking to fulfill long-loop value-retention. Here, in contrast to Cluster 2, a broader range of stakeholders is involved and thus, a broader distribution of tasks across different business units. We thus argue that this configuration pertains to a group of companies who are pursuing a visionary systemic strategy, as there is a clear focus on pursuing sustainable outcomes while addressing a broad range of market stakeholders. A visionary systemic strategy is also characterised by the existence of a market opportunity, and we believe this is reflected in the strong focus on recycling, and the reaping of benefits from secondary material markets.

5. Discussion

The present study contributes to broadening the perspectives on circular product design by examining the managerial factors that enable its implementation and the range of factor conditions that these factors might take. The main output of this research – the morphological field – helps both describe and prescribe CE implementation roadmaps. On the one hand, it can support practitioners and scholars in identifying the managerial conditions under which VR strategies are already integrated in circular product design in a structured manner. The range of factor conditions included in the morphological field can provide a reference for users attempting to evaluate the transformative potential of their product development processes. On the other hand, it can be used as a guideline for practitioners who wish to plan their own implementation roadmaps around product development. Finally, the structure provided by the morphological field can be used as categorization principle to create taxonomies of implementation in larger samples of organizations.

The above analysis of VR strategy implementation configurations ($n = 24$) obtained from expert interviews has served to identify specific elements pertaining to the four dimensions of implementation processes. These are: elements that relate to the strategic content – sustainability values, VR strategy formulation; elements that relate to the strategic context – product ecosystem and cross-functional implications; operational process elements – the configuration of extended teams; and implementation outcomes – the evaluation of product quality and sustainability. Systematic clustering of the configurations reveals the following: the way in which circular products are developed is not only dependent on the concept or product type at hand but is also influenced by the prevailing corporate sustainability strategy. The strong resemblance found between the clustered implementation configurations and the different corporate strategy maturity profiles observed by Baumgartner & Ebner (2010) suggests a strong influence of the corporate sustainability strategy on CE implementation roadmaps during product development. Recent publications exploring the interplay between circular product design and the competitive strategy agree that circular product design holds the potential to confer competitive advantages upon organizations (De Angelis, 2020; Burke et al., 2021). In return, the effects the competitive strategy has on CE design implementation have also been described. For example, it has been determined that the maturity degree of different competitive capabilities leads to different CE strategy implementation pathways (Katz-Gerro and López Sintas, 2019; Ünal and Shao, 2019). Similarly, Scarpellini et al. (2020) determined that dynamic capabilities influence CE-related activities, including design. As a result, we emphasize that future research on design approaches for a circular economy should take greater account of the existing dependencies within the corporate sustainability strategy context.

The management factors identified in the present sample serve to augment those found in the existing literature. Firstly, the range of sustainability factor conditions based on the Framework for Strategic Sustainable Development (FSSD), which proposes sustainability principles for the biosphere and the society as a whole (Broman and Robèrt, 2017), helps couple strategic goal setting with product evaluation and provides operational definitions for measuring sustainability goals. These may then act as guiding principles in both product selection criteria during early phases of development and in product evaluation routines as sustainability indicators to be quantified once details of embodiment design have been settled. The FSSD range of factor conditions expands on the predominant sustainability goals existing in the development process, which currently mostly focus on environmental and user safety (Pahl et al., 2007). Second, VR strategies have come to play a two-fold role during product development: a strategic role, as a subset of a competitive strategy which might ultimately generate a competitive advantage for the company; and an operational role, leading to the development of new tasks and subtasks for the product or service being developed where designers need to make use of and ascribe new design working principles. DfX guidelines have been studied as the main tool for circular product design (den Hollander et al., 2017; Pinheiro et al., 2019). The range of external actors affected by circular product design has typically been limited to the supply chain of a product. If product ecosystems are discussed in earlier phases of development such as in product planning, this range can be expanded to a wider diversity of actors from the civil, industrial, and public spheres in fostering the sustainability potential of vale-retentions, and has been seen as a pre-condition for sustainability transitions and 'territorial' resilience (Delgadillo et al., 2021). While the mobilization of internal resources is frequently taken into account in business model innovation for a circular economy (Santa-Maria et al., 2021), a lack of tools oriented to circular product design implementation (such as strategy roadmaps) has been identified within the current literature. Hence, the present framework represents one of the first attempts to explicitly add a cross-functional perspective to the development process. The new framework also provides greater clarification concerning the different roles circularity and sustainability indicators play during the development process. The former aim at evaluating the degree of fulfillment of value-retention options (possibly interacting with quality objectives) after embodiment, and the latter serve to assess whether strategic sustainability objectives are ultimately met.

One of the main elements of criticism concerning CE initiatives is that its actual beneficial sustainability performance often lays on its premise (Corvellec et al., 2021). Our results are aligned with this view since we have identified several instances where CE is applied with very weak or non-existent sustainability intent —Cluster 1. Additionally, we have confirmed that sustainability-oriented VR strategies neglect the pillar of social sustainability values. This is not compatible with the widespread desire to overcome incremental sustainability by making use of CE in rethinking entire socio-technical systems. None of our VR strategy implementation configurations approaches sustainability from a holistic standpoint and only Cluster 2, following a visionary systemic corporate sustainability strategy, is driven by environmental improvements. A second point of interest is related to the VR strategies observed. These are mostly dominated by long-loop approaches where only marginal value retention is gained (through the recovery of material or energy). The extension of product lifespan is only observed in Cluster 3, albeit merely in the form of add-on repairing services following a market opportunity. It is also possible to observe that in most cases, system stakeholders most often affected by CE initiatives are those pertaining to the beginning of life and end of life of the product. The exchange with wider system actors, i.e., the policy-making sphere, was only driven by the need to comply with legal requirements. Only on relatively few occasions, were product users found to play an active role in the VR strategy definition. This has also been pointed out in the existing CE literature (Selvefors et al., 2019). With regards to cross-functional actors, most configurations involve the presence of strategic management and product development departments, areas that are key for strategic product planning (Pahl et al., 2007). A factor that has been emphasised in the literature (Ahearne et al., 2014), which has also been found to be relevant for VR strategy implementation as well in our sample, is the involvement of middle managers, as they act as organisational information flow connectors vertically and horizontally. All in all, the multiple interdependencies observed across managerial factors mean the integration of VR strategies involves a substantial investment of resources. Therefore, we argue managers need to be engaged in the conceptualisation of circular products to seize their strategic value and overcome financial barriers, which are regarded as the biggest challenge to circular economy implementation (Wang et al., 2022). Similarly, creating a competitive advantage through CE has also been discussed as a means to unlock a barrier towards CE implementation (Prieto-Sandoval et al., 2019). One of the competitive advantages is the stronger business integration required to manage a wider range of internal and external teams stakeholder, which has also been found relevant in the context of industrial economy implementation (Walmsley et al., 2019) and is aligned with the potential of digitalisation as an enabler of circularity (Antikainen et al., 2018).

Process progress control mechanisms have not been included as part of the managerial factors enabling circular product design. While control mechanisms vary case by case, some specific indicators for CE organisational transition are made available by circular economy organisations (Ellen MacArthur Foundation, 2021; World Business Council for Sustainable Development, 2021). Additionally, the present model does not touch upon interpersonal factors affecting VR strategy implementation, such as roles, attitudes, communication, and leadership styles, which are all known to play a major part in implementation effectiveness (Noble, 1999). The factor and factor conditions described above has been constructed using data from large-sized companies belonging to the technical cycles of the circular economy. Thus, it may not be automatically applicable to small-size companies or to those operating with biogenic materials. By enabling the classification of observations with respect to multiple variables, hierarchical clustering helps overcome one of the main limitations of empirical work in the CE literature, i.e. the over-reliance on "small-n" studies (Kirchherr and van Santen, 2019). One remaining limitation, however, is the method's reliance on researcher judgement in identifying an optimal number of clusters.

6. Conclusions

The present study contributes to the understanding of VR strategy integration during the circular product design. Thus, it examines circular product development processes from the perspective of strategic implementation. The analysis of 24 cases of VR strategy implementation identifies six key process factors in the development of products and services, while taking account of value-retention issues and principles of sustainability. The use of GMA enabled the compilation of a range of conditions under which each process factor takes place. This thus provides a framework which may be used as an implementation tool during strategic product planning and early phases of product development. In drawing on hierarchical clustering, the framework can also be employed as a taxonomic device in categorizing managerial practice. The resulting taxonomy reveals a strong connection between implementation configurations and various corporate sustainability strategy maturity profiles. This finding serves to underline the notion that design plays a strategic role within CE practices in private sector organizations. Further research is needed to elucidate upon CE implementation in companies. For example, the framework could be used to describe the prevalence of different implementation roadmaps with respect to the specific role an organization plays within the value chain, or with respect to different product types or different geographies. Furthermore, practitioners can use the framework presented here as a building block in their own VR strategy implementation processes.

CRediT authorship contribution statement

Anna Diaz: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Tatiana Reyes:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Rupert J. Baumgartner:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

Anna Diaz, Tatiana Reyes and Rupert J. Baumgartner received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 765198. The financial support given to Rupert J. Baumgartner by the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology and Development, and the Christian Doppler Research Association, is gratefully acknowledged. The authors acknowledge the financial support provided by the University of Graz. The research support provided by the Swedish Morphological Society is gratefully acknowledged. Previous versions of this work were presented at the 23rd International Conference on Engineering Design and the 20th European Roundtable on Sustainable Consumption and Production.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106344.

Appendix

Table A1, Table A2, Table A3, Table A4, Table A5

Equation A1. Calculation of Cohen's Kappa

$$\kappa = \frac{Pr(a) - Pr(e)}{1 - \Pr\ (e)}$$

where

$$\Pr(a) = \frac{a + d}{a + d + c + d}$$

$$\Pr(e) = \frac{\left(\frac{cm_1 * rm_1}{n}\right) + \left(\frac{cm_2 * rm_2}{n}\right)}{n}$$

being:

	RATER 1			
		Yes	No	Row marginals
RATER 2	Yes	a	b	$rm_1 = a + b$
	No	c	d	$rm_2 = c + d$
	Column marginals	$cm_1 = a + c$	$cm_2 = b + d$	n = number of rated variables

Table A1

Interviewee details and selection criteria. Interviewees had to: a) to be working for a large enterprise belonging to high-quality value chains operating in industrialised economies; b) have at least three years' experience in the role of product developer or sustainability expert executing SPD routines; c) have executed SPD routines within engineering teams or research and development departments. Adapted from Diaz et al. (2021).

CODE	ROLE	EXPERTISE	SECTOR	COMPANY SIZE	TRANSACTION	COUNTRY
INT 1	IT management	Information management	Automotive components	> 300 employers	B2B	Austria
INT 2	Design engineer	Design engineering	Aerospace components	> 2.800 employers	B2B	Austria
INT 3	Product sustainability manager	Sustainable product development	Building components	> 180.000 employers	B2B	France
INT 4	R&D Project manager	Production engineer expert	Measurement instruments	> 3.400 employers	B2B	Austria
INT 5	Senior researcher product development	Sustainable product development	Academia	All enterprise sizes	Transdisciplinary research	Sweden
INT 6	Mechanical engineer	Mechanical engineering	Design consultancy	All enterprise sizes	B2B	The Netherlands
INT 7	Chief executive officer	Sustainable product development	Eco-design services	All enterprise sizes	B2B	France
INT 8	Chief technology officer	Information management	Eco-design services	All enterprise sizes	B2B	France
INT 9	R&D Project manager	Sustainable product development	Materials engineering	All enterprise sizes	B2B	United Kingdom
INT 10	Director engineering unit	Mechanical engineering	Automotive	> 100.000 employers	B2C	Sweden
INT 11	Design engineer	Design engineering	Automotive components	> 300.000 employers	B2C	Austria
INT 12	Environmental officer	Sustainable product development	Automotive components	> 170.000 employers	B2C	Austria
INT 13	Lifecycle analyst	Sustainable product development	Telecommunications	> 130.000 employers	B2C	France
INT 14	Eco-design engineer	Sustainable product development	Electrical grid	> 9.000 employers	B2C	France
INT 15	Environmental risks and Eco-design engineer	Sustainable product development	Defense	> 271.268 employers	Business to public sector	France

Table A2
Themes addressed during the interviews. Adapted from Diaz et al. (2021).

INTERVIEW THEMES	INTERVIEW SUBTHEMES
External factors influencing the SPD processes	Influencing international, national, regional SPD policies Influencing sectoral industrial standards Influencing market dynamics (consumer demand vs. niche initiatives)
Internal factors influencing the SPD processes	Company size (micro-, small-, medium-, large-, large multi-national enterprise) SPD processes maturity (embedded in strategic, tactical and operational level) SPD governance (outsourced, internal department, embedded in engineering teams)
Operational level of SPD activity	Description of the phases of design process in the company SPD methods integrated at each phase of design process Tools used to integrate the methods (specific software or protocols of data exchange, among others) Time, budget and workforce involved
Characterization of actors and IT platforms	Characterization of SPD design team members and characterization of team expertise – team structure, background, skills, and tasks Identification of internal actors located in different departments/locations acting as sustainability data sources – identification of IT platforms used to transfer information Identification of external upstream and downstream (i.e., pre-manufacturing, post-manufacturing) actors acting as sustainability data sources Identification of IT platforms used to transfer information
Characterization of the decision-making process during SPD	Design criteria considered Priority of criteria (economic, social, environmental) Identification and handling of cross-functional conflicts Future data integration models (open-source vs. PLM)

Table A3
Correspondence between design guidelines and corresponding circular product traits included in the morphological field.

DFX GUIDELINE TYPE	FOCUS OF DESIGN						
	Production process	Material	Architecture	Service	Revenue model	Product ecosystem	Socio-technical system
Df Sustainability			x	x		x	x
Df Circular product ecosystem			x	x	x	x	
Df Circular Business model			x	x	x	x	
Df PSS				x	x	x	
Df Multiple lifecycles			x	x	x	x	
Df Sustainable use				x	x	x	
Df Product life extension		x	x	x	x		
Df Remanufacturing	x	x	x				
Df Disassembly		x	x	x			
Df Recycling		x	x				
Df Energy recovery	x	x					

Table A4
References of design guidelines reviewed and corresponding circular product traits identified.

DfX GUIDELINE TYPE	REFERENCE	Production process	Material	Architecture	Service	Revenue model	Product ecosystem	Socio-technical system
Df Sustainability	Ceschin F. (2014) Towards a New Way of Designing and Managing the Societal Embedding of Sustainable Product-Service System. In: Sustainable Product-Service Systems. SpringerBriefs in Applied Sciences and Technology. Springer, Cham.			x	x		x	x
	Vezzoli C., Ceschin F., Diehl J.C. (2021) Product-Service Systems Development for Sustainability. A New Understanding. In: Vezzoli C., Garcia Parra B., Kohtala C. (eds) Designing Sustainability for All. Lecture Notes in Mechanical Engineering. Springer, Cham.			x	x		x	x
	Vezzoli, C., Kohtala, C., Srinivasan, A., Xin, L., Fusakul, M., Sateesh, D., & Diehl, J. C. (2017). Product-service system design for sustainability. Routledge.		x		x		x	x
Df Circular product ecosystem	Desai, A., Lindahl, M., & Widgren, M. (2017). Actors and system maps: a methodology for developing product/service systems. In Sustainability Through Innovation in Product Life Cycle Design (pp. 217–232). Springer, Singapore.			x	x	x	x	
	Konietzko, J., Bocken, N., & Hultink, E. J. (2020). Circular ecosystem innovation: An initial set of principles. Journal of Cleaner Production, 253, 119,942.			x	x	x	x	

(continued on next page)

Table A4 (*continued*)

DfX GUIDELINE TYPE	REFERENCE	Production process	Material	Architecture	Service	Revenue model	Product ecosystem	Socio-technical system
Df Circular Business model	Lewandowski, M. (2016). Designing the business models for circular economy—Towards the conceptual framework. Sustainability, 8(1), 43.			x	x	x		
	Lüdeke-Freund, F., Gold, S., & Bocken, N. M. (2019). A review and typology of circular economy business model patterns. Journal of Industrial Ecology, 23(1), 36–61.		x	x	x	x	x	
	Pieroni, M. P., McAloone, T. C., & Pigosso, D. C. (2019). Business model innovation for circular economy and sustainability: A review of approaches. Journal of cleaner production, 215, 198–216.			x	x	x	x	
Df PSS	Kimita, K., & Shimomura, Y. (2014). Development of the design guideline for product-service systems. Procedia CIRP, 16, 344–349.				x	x	x	
	Foglieni, F., Villari, B., & Maffei, S. (2017). Designing better services: a strategic approach from design to evaluation. Springer.				x	x	x	
Df Multiple lifecycles	Asif, F. M., Roci, M., Lieder, M., Rashid, A., Mihelič, A., & Kotnik, S. (2021). A methodological approach to design products for multiple lifecycles in the context of circular manufacturing systems. Journal of Cleaner Production, 296, 126,534.		x	x		x		
	Akturk, M. S., Abbey, J. D., & Geismar, H. N. (2017). Strategic design of multiple lifecycle products for remanufacturing operations. IISE Transactions, 49 (10), 967–979.			x		x		
	Badurdeen, F., Aydin, R., & Brown, A. (2018). A multiple lifecycle-based approach to sustainable product configuration design. Journal of cleaner production, 200, 756–769.		x	x	x	x	x	
Df Sustainable use	Wever, R., Van Kuijk, J., & Boks, C. (2008). User-centered design for sustainable behavior. International journal of sustainable engineering, 1 (1), 9–20.				x		x	
	Selvefors, A., Pedersen, K. B., & Rahe, U. (2011, June). Design for sustainable consumption behavior: systematising the use of behavioural intervention strategies. In Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces (pp. 1–8).				x	x	x	
	Wastling, T., Charnley, F., & Moreno, M. (2018). Design for circular behavior: Considering users in a circular economy. Sustainability, 10(6), 1743.				x	x	x	
Df Product life extension	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 304–305). London: Springer.		x	x	x			
	Khan, M. A., Mittal, S., West, S., & Wuest, T. (2018). Review on upgradability–A product lifetime extension strategy in the context of product service systems. Journal of cleaner production, 204, 1154–1168.		x	x		x		
	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 302–303). London: Springer.			x	x	x		
Df Remanufacturing	Guidat, T., Barquet, A. P., Widera, H., Rozenfeld, H., & Seliger, G. (2014). Guidelines for the definition of innovative industrial product-service systems (PSS) business models for remanufacturing. Procedia CIRP, 16, 193–198.		x	x				
	Ijomah, W. L., McMahon, C. A., Hammond, G. P., & Newman, S. T. (2007). Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. International Journal of Production Research, 45(18–19), 4513–4536.	x	x	x				
	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 305–307). London: Springer	x	x	x				
Df Disassembly	Favi, C., Germani, M., Mandolini, M., & Marconi, M. (2016, August). Disassembly knowledge classification and potential application: a preliminary analysis on a washing machine. In International Design Engineering Technical Conferences and Computers and Information in Engineering		x	x	x			

(*continued on next page*)

Table A4 (*continued*)

DfX GUIDELINE TYPE	REFERENCE	Production process	Material	Architecture	Service	Revenue model	Product ecosystem	Socio-technical system
	Conference (Vol. 50,145, p. V004T05A011). American Society of Mechanical Engineers.							
	Soh, S. L., Ong, S. K., & Nee, A. Y. C. (2015). Application of design for disassembly from remanufacturing perspective. Procedia CIRP, 26, 577–582.		x	x				
	Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. -. (2007). Engineering design: A systematic approach. Engineering design: A systematic approach (pg. 388–396) doi:10.1007/978–1–84,628–319–2	x	x	x				
Df Recycling	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 299–300). London: Springer	x	x	x	x			
	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 304–305). London: Springer		x	x				
	Vezzoli, C. (2018). Design for environmental sustainability: Life cycle design of products (pg. 300–301). London: Springer.		x	x				
Df Energy recovery	Bonvoisin, J., Mathieux, F., Domingo, L., & Brissaud, D. (2010, May). Design for energy efficiency: proposition of a guidelines-based tool. In International Design Conference-DESIGN 2010.	x	x	x				

Table A5
Cohen's Kappa values obtained for Interrater reliability test sample of the dataset ($n = 8$).

FRAGMENT ANALYSED	COHEN'S KAPPA VALUES
OBS 1	84.02
OBS 2	84.01
OBS 3	92.52
OBS 4	88.89
OBS 5	81.82
OBS 6	81.88
OBS 7	75.51
OBS 8	79.75

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