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Research article

Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management

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ABSTRACT

The concept of circular economy (CE) is of great interest for manufacturing companies since it provides a framework which allows them to align organisational objectives with the Sustainable Development Goals (SDGs). Corporate CE entails the adoption of several value-retention options (R-strategies) throughout companies' operations, which aim at creating, preserving and recovering the value of assets and products. The sustainable product development (SPD) process, in which around 80% of the total environmental impact of a product is determined, is employed to translate R-strategies into new product requirements. This study is aimed at investigating the implications of R-strategy adoption for decision-making in SPD. The research follows an empirical approach, combining a literature review and in-depth semi-structured interviews with product developers and sustainability experts working in companies operating in the technical material cycles of the CE. Thus, implications for product dimensions, inter- and intraorganisational actors, decision-making support types and lifecycle information flows so that SPD processes further accommodate CE principles into products are investigated. This study reveals new directions to adjust the contextual factors of SPD to further align existing processes with widely expanding CE organisational cultures.

1. Introduction

The population growth and economic boost experienced during the second half of the 20th century has posed severe environmental pressures on the planet and fallen short in consolidating more equitable societies. In 2015, the three pillars of sustainable development — economic, social and environmental — were reframed as part of a unified framework and adopted by all United Nations member states, and became known as Sustainable Development Goals (SDGs) (United Nations, 2020). Consequently, circular economy (CE) and related disciplines have become instrumental in helping businesses implement the principles of sustainable development (Ghisellini et al., 2016; Kirchherr et al., 2017). The CE has the ultimate goal of decoupling wealth and welfare creation from resource consumption (Stahel, 2019; pag 14). The underpinning CE conceptualisation for this study incorporates the following aspects: a) the implementation of value-retention options (R-strategies) (Reike et al., 2018); b) a multi-level perspective in application (Ghisellini et al., 2016); c) sustainability as the end goal (Geissdoerfer et al., 2017; Schroeder et al., 2018). Thus, the working definition adopted is stated as follows "A CE describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (prod-

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Abbreviations: AHP, Analytical Hierarchy Process; B2B, Business-to-business; B2C, Business-to-consumer; BIM, Building Information Modelling; BOL, Beginning of life; CAx, Computer Aided applications; CBM, Circular Business Model; CBMI, Circular Business Model Innovation; CD, Conceptual Design; CE, Circular Economy; EMF, Ellen MacArthur Foundation; EOL, End of life; DD, Detailed Design; DRM, Design Research Methodology; DS-I, Descriptive Study-I; ED, Embodiment Design; IMDS, International Material Data System; LCA, Life-Cycle Assessment; LCC, Life-Cycle Costing; MCDA, Multi-Criteria Decision Analysis; MOL, Middle of life; PSS, Product-service System; PLM, Product Lifecycle Management; QFD, Quality Function Deployment; R-strategy, Value-retention option; RC, Research Clarification; SDGs, Sustainable Development Goals; SPD, Sustainable Product Development; TC, Task Clarification.

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ucts, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017).

CE has become a strategic spearhead for many businesses and governments around the globe. The adherence to a CE has mainly been driven by not-for-profit organizations, championed by the Ellen MacArthur Foundation (EMF). Partnerships of these with public agencies and global consultancies have sparked the creation of supra-national policies such as the Circular Economy Action Plan adopted by the European Commission (European Commission, 2020), standardisation efforts, such as the BSI 8001 (British Standards Institution, 2017) or the ISO Technical Committee 323 (International Organization for Standardization, 2018), knowledge exchange platforms, such as the EU Stakeholder Platform for a CE (European Commission, 2017) or the World Circular Economy Forum (Sitra, 2017), and collaborative networks, such as the EMF's CE100 (Ellen MacArthur Foundation, 2013) or the PACE Platform for Accelerating the CE (World Economic Forum, 2017). Simultaneously, owing to the ubiquitous use of the term 'circular economy', the academic community has displayed a strong but slightly different kind of interest in the concept, a period which has been described as a process of 'validity challenge' (Blomsma and Brennan, 2017). Thus, CE academic efforts are focused on dissecting the various disciplines underpinning the concept (Murray et al., 2017; Sauvé et al., 2016; Winans et al., 2017), integrating discourses and definitions (Homrich et al., 2018; Friant et al., 2020), mapping tools for implementation (Genovese et al., 2017; Kalmykova et al., 2018; Lieder & Rashid, 2016) and developing assessment methods (Elia et al., 2017; Linder et al., 2017; Pauliuk, 2018; Saidani et al., 2017). Furthermore, the risks entailed in transitioning towards a CE are increasingly documented. For instance, authors question the thermodynamic performance of a CE and emphasize the need to account for the environmental impacts and resource consumption of implementing CE strategies to avoid overestimating their benefits, a task which is not frequently done in practice (Cooper et al., 2017; Korhonen et al., 2018). Additionally, Zink & Geyer (2017) have shown how decoupling may be undermined by rebound effects. For example, in cases where market forces prevent circular products from competing effectively with primary production, or where they result in price reductions, there may be a rise in overall rates of resource consumption. The social implications of CE implementation also need to be addressed. This is frequently an aspect of sustainability which is largely overlooked (Merli et al., 2018; Murray et al., 2017; Sauvé et al., 2016). Thus, in sum, the sustainability performance of a given CE intervention remains largely case-dependent.

Hence, due to the systemic nature of industrial activities and their context-dependent behaviour, it is often difficult to establish predefined conditions for CE practices that lead to greater or absolute decoupling compared to a linear one. CE frameworks propose that companies maintain the partial or total integrity of finished goods for extended periods of time by adopting a set of R-strategies. Different R-strategies then lead to varying degrees of structural preservation of products, entail a wide range of possible marginal benefits and involve different lifecycle stakeholders. As in the case of CE conceptualisation, transdisciplinary efforts are being made towards increasing the paradigmatic clarity of R-strategies (British Standards Institution, 2017; International Resource Panel, 2018). In order to investigate R-strategy implementation in companies, the present study has adopted the framework proposed by Reike et al. (2018), which synthesises a comprehensive interdisciplinary literature review of R-strategies into a single model encompassing 10 different typologies (Table 1).

For product developers, the adoption of an R-strategy ultimately means outlining product requirements and specifications for a given purpose and increasing the sustainability performance of a product throughout its (multiple) lifecycles. SPD literature, which has also focused on providing more sustainable products and services (Maxwell & Van der Vorst, 2003), has come up with numerous methods and tools for this purpose. However, despite the exponential growth of such methods, most have not been tested in practice (Baumann et al., 2002). Researchers have since identified a manifold gap between the methods developed and how users actually go about application. For example, SPD support is typically designed without taking the working culture of designers and their routines into consideration (Lindahl, 2006; Lofthouse, 2006). Insights from design disciplines were also found to be largely absent in the SPD literature (Brones & Carvalho, 2015; Dekoninck et al., 2016; Deutz et al., 2013), and the difficulty of choosing an appropriate method among all those available hinders their application in practice (Buchert et al., 2017). In general, SPD methods are excessively complex and time consuming and often require a high level of environmental knowledge beyond that of an organisation's capacity. It is also noticeable that the dynamics and competencies required by multidisciplinary design teams in decision-making and application of eco-design approaches for CE have barely been studied at all (Sumter et al., 2018). Thus, researchers are now being advised to move away from further tool development and to focus more on understanding how SPD may be integrated into process management and wider company goals (Prendeville et al., 2017).

The implications of an R-strategy for a finalized product are the result of a sequence of decision-making steps involving different actors, decision-making support, and information flows. Decisions made during the product development process are key, as it is generally stated that up to 80% of environmental impacts are determined during this phase (International Resource Panel, 2018, p. 9). Thus, this paper examines how the contextual factors involved in deciding upon CE products characteristics evolve throughout the different phases of product development. Based on this, the following research questions were formulated: *What product/service dimensions are addressed in an SPD process for a CE and what criteria are used to decide upon product/service design variants? Which key actors, decision-making support types and lifecycle information flows are involved in each phase of SPD for a CE?* Thus, the goal of the research is to better understand the context in which decisions around the development of products for a CE are made. The next sections are structured as follows: Section 2, describes the material and methods used for conducting the research. Section 3 presents the results: it discusses implications for products, actors, decision-making support types, and information management throughout the development process. These are aggregated into a conceptual framework that integrates these contextual factors and provides an overview of the product development for a CE. In Section 4, findings are discussed through the lens of SPD literature and practice. Finally, Section 5 provides an outline of relevant conclusions.

2. Material and methods

This study focuses on large companies operating in industrialised economies, transacting durable goods made of technical materials. Following Stahel's rationale, the ultimate common goal for these companies is to "maintain the quality and value of [...] stocks" (Stahel, 2019, p. 40). The Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009) has been adopted as a reference in order to approach the phenomenon central to this study. Product development is a complex activity, entailing multiple actors organized in different processes, and the application of various forms of knowledge, methods, and tools. DRM has often been adopted in design-related disciplines to provide a set of

Table 1
R-strategies identified by Reike et al. (2018)

R-Strategy	Definition
Refuse	To completely avoid the use of substances, materials, product components or entire products.
Reduce	To use less substances, materials, product components or entire products.
Resell/Reuse	To directly or indirectly enable a user-to-user transaction of sold, returned, or unsold products.
Repair	To have users, third party repair services or original manufacturers extend the lifetime of a product.
Refurbish	Maintaining the main structure of a multi-component product and effectuate partial repairs or replacements leading to a product upgrade.
Remanufacture	To completely disassemble, check, clean, repair or replace the complete structure of a multi-component product.
Repurpose	To reuse the discarded products or components adapted to another function in a distinct new lifecycle.
Recycle	To process mixed streams of post-consumption or post-production waste streams to capture nearly pure materials.
Recover (energy)	To extract the energy embodied in waste streams and capture it in combination with energy producing and storing technologies.
Re-mine	To perform a selective retrieval of valuable material fractions from multi-component products.

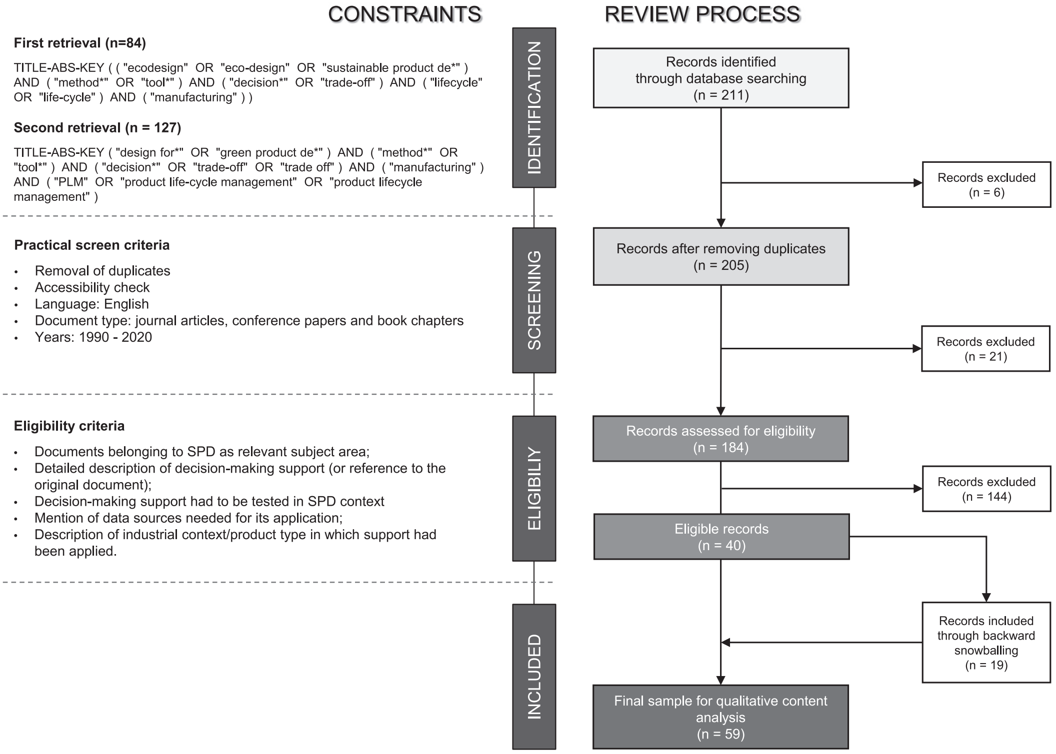

Fig. 1. Literature review process (Grant et al., 2009)

supporting guidelines that add methodological rigour to the understanding and support produced by researchers. The present paper incorporates the first two phases of the DRM research process, namely: a) Research Clarification (RC), in which contextual factors surrounding a phenomenon are examined theoretically, and b) Descriptive Study-I (DS-I), in which initial descriptions are expanded and often contrasted with empirical evidence (Blessing and Chakrabarti, 2009). The paper thus encompasses review-based RC and a comprehensive DS-I, in which the findings from the literature review are contrasted with data collected from interviews. The first step involved conducting a literature review (Grant et al., 2009) in order to explore the contextual factors of decision-making in SPD for a CE (Fig. 1).

The retrieval of documents was done using Scopus, one of the largest abstract and citation databases for peer-reviewed literature, covering scientific journals, books and conference proceedings (Nobre and Tavares, 2017). The retrieval process was limited to articles, conference papers and book chapters published since the early 1990s, as previous reviews indicated this was the starting point of the SPD literature (Baumann et al., 2002). An initial query string was built using keywords identified in the relevant literature and a second one was built using synonyms. After removing overlaps, a total of 184 documents underwent practical and content screening. Documents were selected for the final sample based on the following criteria: documents had to cover SPD as a relevant subject area; include a detailed description of decision-making support (or reference to the original document); decision support had to be empirically tested; data sources needed for decision support application had to be mentioned; documents had to contain an explanation of industrial context/product type in which the framework had been applied. The resulting sample (40 documents) was enriched through snowballing (19 documents). A final sample of 59 documents (Table A1) underwent qualitative content analysis using an aggregated codebook including 10 codes developed during the RC phase (Table A3).

The analysis was performed by coding segments of the text using the software MaxQDA and Excel. The codes provided the basis for pre-specifying the theoretical constructs present in the empirical data collection instrument, i.e. for the theory-based semi-structured interviews (Kumar, 2014). For purposes of selection, interviewees had to comply with the following criteria: 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 sustainabil-

Table 2
Profiles of recruited interviewees

Code	Role	Expertise	Sector	**Enterprise size** (number of employees)	Transaction	Country
INT 1	IT management	Information management	Automotive components	~ 300	B2B	Austria
INT 2	Design engineer	Design engineering	Aerospace components	~ 2.800	B2B	Austria
INT 3	Product sustainability manager	Sustainable product development	Building components	~ 180.000	B2B	France
INT 4	R&D Project manager	Production engineer expert	Measurement instruments	~ 3.400	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	B2C	Sweden
INT 11	Design engineer	Design engineering	Automotive components	~ 300.000	B2C	Austria
INT 12	Environmental officer	Sustainable product development	Automotive components	~ 170.000	B2C	Austria
INT 13	Lifecycle analyst	Sustainable product development	Telecommunications	~ 130.000	B2C	France
INT 14	Eco-design engineer	Sustainable product development	Electrical grid	~ 9.000	B2C	France
INT 15	Environmental risks and Eco-design engineer	Sustainable product development	Defense	~ 270.000	Business to public sector	France

ity expert executing SPD routines; c) have executed SPD routines within engineering teams or research and development departments. A list of interviewee profiles can be found in Table 2. The indicator used to identify large-sized companies was number of employees belonging to the organisation. In terms of OECD classifications (Organisation for Economic Co-operation and Development, 2020) this needs to be 250 or more. All interviewees were contacted via e-mail or LinkedIn and received a list of interview themes and an informed letter of consent so that the interviews could be recorded. Interviews were conducted between June and December 2019 by phone, computer voice call or in-person. Sample size was decided based on saturation point identification for theory-based content analysis (Francis et al., 2010). The first round of analysis was set for 10 interviews and theoretical constructs were populated with collected data. A preliminary analysis discarded possible spurious data saturation due to homogenous sampling. Construct saturation point was achieved through a second round of analysis, in which interviews were added until no new themes emerged for three further consecutive interviews. One researcher conducted the interview questions (Table A2), took notes on answers, transcribed the audios (12 out of 15 interviews were recorded), and coded and analysed the dataset using MaxQDA. Owing to the higher granularity of data contained in the interview dataset a deductive coding process was then followed and the codebook used in the literature review was disaggregated into 44 different sub-codes (Table A3). Inter-coder reliability (ICR) was assessed based on the independent analysis of a second coder (Seuring & Gold, 2012). Cohen's kappa (k) was used to measure ICR and it was calculated at the level of the ten main codes and based on the agreement per coded segment. Overall a Cohen's kappa of 0.71 was measured, which indicates a substantial level of ICR (Landis & Koch, 1977). Transcripts were anonymized and sent back for approval or correction to the interviewees. After the data collection and analysis phases were completed, a report with feedback and aggregated insights was provided to the participants.

3. Results

This section presents an overview of existing decision-making support types in SPD and contextual factors surrounding their use based on the findings obtained from the literature review and the interviews.

3.1. Summary of the reviewed literature

Although design requirements are the enabling mechanism to translate product functionalities aligned with a certain R-strategy into product physical properties, the present study deliberately focussed on the entire product development process. There were two main reasons behind this decision. First, recent studies highlight that "the design phase is too late in the development process to begin addressing the opportunity for VRPs [R-strategies]" and that "designers are not the primary decision-makers regarding what a product does or how it does it; rather, they focus on using creativity to meet such product requirements— specifications that are defined much earlier in the product development process" (International Resource Panel, 2018, p.155). Therefore, the reference model chosen here to map the different decision-making processes considers the entire process of product development (Pahl et al., 2007), as displayed in Fig. 2. The process starts with the Task Clarification phase (TC) phase in which the problem to be solved is defined and the properties fundamental to the tasks for which the product is intended are fixed. This is followed by the Conceptual Design phase (CD), which refers to the generation of numerous product alternatives that meet the given functional requirements. Following this, the process then continues with the introduction of several constraints that allow designers to converge around the best design variants. Once the potential design solutions have been identified, designers proceed to the Embodiment Design phase (ED), an iterative process of determining the likely shape, materials, and production process for the product. The whole process is then concluded by the Detailed De-

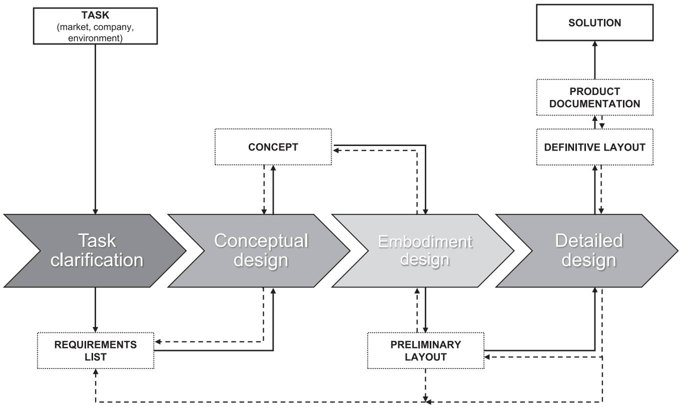

Fig. 2. Reference model for product development process (Pahl et al., 2007).

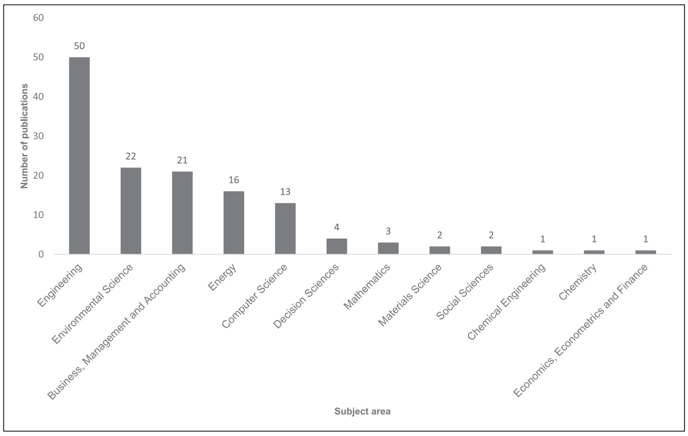

Fig. 3. Distribution of publications by subject area

sign phase (DD), in which the precise product specifications are determined.

Supporting decision-making tasks during product development is becoming more and more necessary as a growing number of digital tools now facilitate the generation of ever larger sets of design solutions. In this context, a general decision-making task involves comparing the performance of different variants against a set of predefined goals and selecting an optimal system based on the performance of each variant (Pahl et al., 2007). When it comes to SPD, evaluations are done with respect to sustainability goals, a task that includes the combination of design engineering techniques with environmental management methods and tools. This inherent multidisciplinarity is reflected in the broad range of subject areas under which the reviewed documents fall (Fig. 3). Main contents of use-case, core method, support modules and contextual information for each publication where synthesized in a tabular format (Table A1).

One initial observation derived from the literature analysis concerns the high prevalence of Life-Cycle Assessment (LCA) in supporting SPD decisions: 44% of publications explicitly mention its partial or complete deployment. LCA is a tool used to assess the environmental impact of a product throughout its life. It has undergone a strong methodological development since its inception and is now broadly applied in practice (Finnveden et al., 2009). Numerous publications have demonstrated its usefulness in solving sustainability dilemmas involving specific aspects of design such as material selection (Ribeiro et al., 2019), achieving optimal weight (Cicconi et al., 2018) or shape optimization (He et al., 2017). LCA may also help resolve multiple aspects of product design simultaneously (Buchert et al., 2019; Russo & Rizzi, 2014). One commonly observed practice has been to extend the environmental scope of an LCA to include economic performance by complementing the assessment with aLife-Cycle Costing (LCC) (Auer et al., 2017; Garcia-Muiña et al., 2019). Regardless of recent efforts at development and standardisation (Huarachi et al., 2020), no Social Life-Cycle Assessment applied in the context of SPD could be found in the set of publications reviewed. Publications using LCA in the context of SPD have frequently focused on the integration of digital infrastructure, i.e. how LCA databases may be connected with design engineering software in order to better integrate sustainability assessment into engineering tools (Stark & Pförtner, 2015; Tao et al., 2018). In the publications, it was common to find the use of Multi-Criteria Decision Analysis (MCDA) to identify optimal decisions in the presence of design trade-offs. MCDA emerged as a formal methodology for combining technical information and stakeholder values in order to support decision-making in a variety of fields (Huang et al., 2011). Two major types of MCDA-based decision-support were identified in the product development literature and practice: these are related to design problems and evaluation problems. In design problems, the number of alternatives is infinite or unknown and the solution is found through the use of a mathematical model (Sayin, 2000). In contrast, in evaluation problems, the number of alternatives is known, and the solution is found by weighting its performance against a set of goals (Mendoza et al., 2000). Both support in design problems (Miranda-Ackerman et al., 2017; Shimizu & Yamada, 2008) and support in of evaluation problems (Ben Slama et al., 2020; Feng & Mai, 2016; Manjunatheshwara & Vinodh, 2018) were found in the SPD literature. One additional class of decision-making support linked with multi-objective problems has been found to be decision trees (Buchert et al., 2015; Zarandi et al., 2011), in which tree-like flowcharts are depicted in order to guide decisions. The use of Quality Function Deployment (QFD) has also been found useful when pursuing environmental objectives (Romli et al., 2018; Younesi & Roghanian, 2015). QFD allows customer requirements to be translated into the appropriate technical requirements for each stage of product development and production (Sullivan, 1986). In such cases, the environmental requirements of products are translated into quantitative product parameters, together with additional quality requirements. Finally, the use of performance indicators has also been quite common when evaluating a number of environment-related aspects such as product recyclability (Dostatni, 2018) or product sustainability (Hallstedt, 2017; Lacasa et al., 2016). One common trait found among the publications reviewed was a generalized lack of contextual information. Insufficient details were provided on the location of support throughout the development process. For example, 51% of the reviewed publications did not make any specific reference to a product development phase. An additional 25% referred to “early design phases”,15% made specific references to the CD phase, 6% to the ED and 3% to DD phase. Despite the inherently multidisciplinary nature of the processes dealt with, there was very little detail on the actual users of the decision-making support: 57% of publications made no reference to the user nor to the final decision-maker. In all references made, the user had a purely technical role in the development task, with frequent descriptions referring to “designer”, “engineer” and “design engineer”. Thus, even though decision-making support is described in great detail, no concrete information regarding the context in which it is applied e.g. concerning users, product development stage, information sources, etc., is supplied.

3.2. Overview of recruited companies

Among the 15 respondents recruited, 3 discussed R-strategies as a consequence of adopting a CE strategy, 9 of them discussed

Table 3
List of R-strategies discussed in the interviews

Interviewee	Product	R-Strategy	Enabler	Degree of Implementation
INT 1	Measurement system	Repair	Design for repair	Implemented
INT 2	Aircrafts	Refurbish	Retrofit market	Implemented
INT 3	Building components	Repurpose	Modular design	Developing
INT 3	Building components	Repair	Predictive maintenance	Developing
INT 3	Building components	Repurpose	Material passport	Developing
INT 3	Building components	Recycling	Design for recycling	Explorative
INT 5	Not disclosed	Resell/Reuse	Product-service System	Implemented
INT 6	Automotive component	Remanufacture	Product-service System	Developing
INT 6	Internet box	Resell/Reuse	Reverse logistics	Implemented
INT 10	Passenger car	Reduce	Vehicle electrification	Developing
INT 11	Automotive component	Repurpose	Reverse logistics	Implemented
INT 11	Automotive component	Recycling	Material passport	Explorative
INT 12	Passenger car	Recycling	Design for recycling	Implemented
INT 12	Passenger car	Recover (energy)	Design for recycling	Implemented
INT 13	Internet box	Recycling	Design for disassembly	Implemented
INT 13	Not disclosed	Refuse	Material selection	Implemented
INT 13	Consumer electronics	Repair	Reverse logistics	Implemented
INT 13	Consumer electronics	Recycle	Reverse logistics	Implemented
INT 13	Consumer electronics	Remanufacture	Modular design	Explorative
INT 13	Internet box	Resell/Reuse	Product-service System	Implemented
INT 14	Energy grid components	Reduce	Resource efficiency metrics	Implemented
INT 14	Energy grid components	Recycle	Material passport	Explorative
INT 14	Energy grid components	Reduce	Biomimicry design	Explorative
INT 15	Defense system	Refuse	Obsolescence prevention	Implemented

R-strategies within the context of eco-design and SPD implementation, and 3 of them discussed R-strategies as long-existing markets within their sector. The R-strategies discussed can be found in Table 3. Respondents implementing R-strategies in consulting activities described large companies as being more static and slower in their implementation, and small companies as being more agile and disruptive. Factors mentioned as drivers for implementation were: a) both national and international regulations (such as the ELV directive 2000/53/EC or the REACH EC 1907/2006); b) the need to comply with various forms of certification; c) the impact of voluntary due diligence proposed by the main market players; d) increasing consumer demands; e) the proactive implementation of management policies; f) proactive implementation of intrapreneurial projects; g) the possibility of gaining an economic advantage. Once the choice of an R-strategy had been made, the process of embedding it into the design of products had to be addressed. This was described as being an iterative process, with multiple responsibility handover points and complex decision-making processes typically handled over the period of at least 10-15 days. Internally, it appears that the implementation of the R-strategy into product development was executed by teams ranging from 3-15 members (depending on the magnitude of the project and the complexity of product). These worked in a cross-functional fashion and were typically led by a project manager. Environmental and social implications coexisted simultaneously with a long list of requirements and design constraints deriving from the multiple functionalities that the products needed to fulfil. An adequate level of economic performance was generally described as being one pre-condition needed for the consolidation of an R-strategy. While the quest for profit maximization was not an absolute driver behind the choice of a specific product variant, it was also true that when faced with a trade-off, economic viability was never compromised.

3.3. Product dimensions and evaluation criteria for solution variants

This section examines how R-strategy adoption is translated into the modification of different design problems and common evaluation criteria used for new product/service variants selection.

As mentioned before, R-strategy adoption implies that new product functionalities are translated into the modification of a product's physical properties. Since transition to a CE entails more than mere technical modification, e.g., it invites the adoption of a more holistic approach including reconsideration of entire product systems, the present research has considered 2 tangible (material, architecture) and 3 intangible (service, business model, ecosystem) product dimensions to be affected by an R-strategy. The dimensions may be described as follows:

a) Product material: pertains to modification of one or more substances embedded in the physical product.
b) Product architecture: pertains to modification of one or more functional elements and physical components of products in terms of what they do and what their interfaces are with the rest of the device (Ulrich, 2003).
c) Product service: pertains to modification of the intangible services combined with the physical product so that they are jointly capable of fulfilling specific customer needs (Tukker, 2004).
d) Product business model: pertains to modification of any of the elements determinant in a successful commercial transaction involving the product, such as the sources of revenue, the intended customer base or further financing details.
e) Product ecosystem: pertains to modification in the set of actors – producers, suppliers, service providers, end users, regulators, civil society organizations – that contribute to a collective outcome and the joint creation of value, through collaboration, experimentation or platformisation (Konietzko et al., 2020).

In Table 4, these 5 dimensions have been linked to corresponding R-strategies. One notices at a glance that the dimension "product material" is the most frequently addressed. This category combines modifications such as reducing the mass of materials embedded in the exact same design or depleting hazardous substances from product components. This is often driven by the need to comply with legal regulations or the adoption of highly consolidated eco-design or Cradle-to-cradle® practices and the focus is often on material substitution. However, even though this category may potentially offer the means to the highest retention of value (Refuse, Reduce), it is not possible to derive quantitative conclusions in this case. Even more so, the reported lack of synergy between material modifications and the rest of intangible dimensions likely indicates

Table 4
Overview of product dimensions involved in R-strategy implementation

Code	R-Strategy	Product	Enabler	Product Dimension				
				Material	Architecture	Service	Business Model	Ecosystem
INT 13	Refuse	Not disclosed	Material selection	x				
INT 15		Defense system	Obsolescence prevention	x				
INT 10	Reduce	Passenger car	Vehicle electrification	x	x	x		
INT 14		Energy grid components	Resource efficiency metrics	x	x			
INT 14		Energy grid components	Biomimicry design	x	x			
INT 6	Resell/Reuse	Internet box	Reverse logistics			x	x	
INT 13		Internet box	Product-service system			x	x	
INT 1	Repair	Measurement system	Design for repair		x	x		
INT 3		Building components	Predictive maintenance			x		
INT 13		Consumer electronics	Reverse logistics					x
INT 2	Refurbish	Aircrafts	Retrofit market	x	x			x
INT 5		Not disclosed	Product-service system			x	x	
INT 6	Remanufacture	Automotive component	Product-service system		x	x	x	x
INT 13		Consumer electronics	Modular design		x			
INT 3	Repurpose	Building components	Modular design		x			
INT 3		Building components	Material passport					x
INT 11		Automotive component	Reverse logistics					x
INT 13	Recycle	Consumer electronics	Reverse logistics					x
INT 14		Energy grid components	Material passport	x				x
INT 11		Automotive component	Material passport	x				x
INT 13		Internet box	Design for disassembly	x	x			
INT 3		Building components	Design for recycling	x				
INT 12		Passenger car	Design for recycling	x	x			
INT 12	Recover (energy)	Passenger car	Design for recycling	x	x			

a rather marginal systemic impact. It is also possible to observe that material modifications are frequently addressed together with modification in product architecture in cases where products have been modified to better adjust to recycling systems – for instance, reducing the time needed to dismantle domestic routers so that the recycling process is more efficient (INT 13). Material modifications also entail synergies with "product ecosystem" (INT 14) due to the transfer of information on material content to downstream actors with material passports. Finally, material modifications appear with the lowest frequency in R-strategies requiring access to entire products or components (Resell/Reuse, Repair, Refurbish, Remanufacture, Repurpose). While the interview sample described here is not statistically significant for all manufacturing industries, it does seem to imply the presence of a design trade-off between recyclability and suitability for multiple product lifecycles.

"Product architecture" is the second most frequently addressed dimension. As previously mentioned, it is very often coupled with material modifications (8 out of 11 cases) and is very often presented in connection with the synergies arising with systemic dimensions in Repair, Remanufacture and Repurpose strategies. Thus, architecture modifications appear to be compatible with both the dismantling and reconstruction of durable goods. Nevertheless, a frequent architecture-related enabler, modular design, was reported as being in conflict with an important product attribute in consumer electronics, i.e. aesthetics. "The problem with modularity is that it often implies more volume, and volume is the [design] enemy for us. It could work perhaps with desktop computers… or internet boxes, because [for the latter] consumers do not care about design" (INT 13). The dimension "product service" is mentioned slightly less frequently, and is closely linked to the aftersales support services companies provide in the use-phase of products, "which is a really good business, especially when users rely only on a single vendor" (INT 1). This explains the strong link between this dimension and "product business model" as it is often perceived as a source of income for manufacturing companies. This also explains why there is hardly any overlap between the dimensions "product service" and "product ecosystem". It seems that manufacturing companies have an economic incentive not to share information or repair know-how with third parties since in doing so they "risk that third parties reverse-engineer your product" (INT 11) or cannibalize on the aftersales offering. The "product business model" dimension is the least mentioned, and is found in two cases corresponding to Product-service System (PSS) implementation (INT 6, INT 13) and one explorative project with an automotive component. This is not surprising given that the sampled companies are large-sized and some respondents anticipated "big companies are less disruptive" (INT 7) or "you can do more with small companies because they are more flexible" (INT 6). Despite the increasing attention paid to circular business model innovation (CBMI), especially in the context of start-ups, it is a fact that, for both incumbents and large-sized companies, transitions to circular business models (CBMs) remain fraught with uncertainty (Hofmann & Jaeger-Erben, 2020). Finally, "product ecosystem" was identified in low value retention options (Recycle), and was very often linked to the transfer of information regarding product materials (INT 11, INT 14). This hardly interferes with manufacturers' ability to capture value as the market value of recycled materials is very often residual compared with the market value of a functional product: "The value is in the product itself, not its materials. The material content of an iPhone is only a couple of dollars" (INT 3). It is also possible to observe ecosystem synergies in repurposing strategies as long as the customer base of first and subsequent lifecycles do not overlap: "Some companies are working together with other companies to make use of second-life [car] batteries that are not commercially viable for vehicle use. In their second life, they would be sent to energy storage systems for powering, let's say, a supermarket" (INT 11). An additional well-consolidated repurpose loop present in the aeronautics sector was found to be the so-called retrofit market "Airplanes are also sold because of aesthetics, not only engines. The parts that make passengers say "wow!" are parts that can often be changed. There are companies that take internal fully functional structures of aircrafts that have been in the market for a while and refurbish the whole thing. This is a common practice, a competitive market." (INT 2). Finally, the creation of an ecosystem based on reverse logistics was also identified for consumer electronics (INT 13) "Old phones can be collected in the company's retail stores, which are sent to a non-profit organization that evaluates the status of the devices and decides for

Table 5
Criteria used to evaluate solution variants in SPD processes described

Evaluation Criteria	INT 1	INT 2	INT 3	INT 4	INT 5	INT 6	INT 7	INT 8	INT 9	INT 10	INT 11	INT 12	INT 13	INT 14	INT 15
Profitability	x	x		x	x			x	x	x	x	x	x	x	x
Regulatory compliance			x			x	x			x		x		x	
Environmental performance			x			x	x	x					x		x
Social performance						x								x	
Safety		x							x	x					
Aesthetics		x								x					
Aerodynamics		x													
Weight		x										x			
Quality											x			x	x
Customer specifications		x				x					x				

the best strategy. If a device cannot be used second hand, they will send it to recyclers" (INT 13).

Interviewees were asked about the evaluation procedure and criteria for solution variants. In product development processes, evaluations involve an assessment of the technical and non-technical elements of a solution, and whether these can be applied across several phases of product development (Pahl et al., 2007). Evaluation of technical, environmental, and economic performance is often applied at the end of the main process phases in order to determine the value of the solution being developed. Despite the variation in specific evaluation points across companies, it was possible to observe some commonalities among respondents in terms of the various formats and evaluation criteria they reported. Several interviewees described the use of comparison matrixes to compare concept variants: "You can use KPIs in a matrix… sometimes it does not go really deep but it allows you to really understand how different solutions compare" (INT 6). "We had the decision matrix method. There are some 20 attribute leaders can give their comment and their rating in the same way and in the same weighting for different alternatives to be decided. And at the end a sum is made of all the ratings of all attribute leaders and best solution from most common consensus is chosen. So, it is just a decision matrix that works very well and works fairly, in my opinion" (INT 12). "There is a whole matrix that is used. I do not know the formal name but when I saw it, I was a bit shocked because I thought there would be something a lot more sophisticated. This is a table with a priority for each criterion, already weighted by the chief financial officer. For other decisions, I do not have much to do, even though I wish I could, because very often we have to deal with poor choices" (INT 11). All in all, decision-making processes for product development appear to be relatively formalized even though they also accommodate the specific influences that different company actors have to face within their own organization. In order to understand the priorities for decision-making, interviewees were also asked to mention the criteria that were considered in their evaluation of SPD processes (Table 5). Clearly, economic performance (profitability) is the most frequently mentioned criterion. It is also possible to observe that criteria relating to product attributes play an important role in technical evaluations, even though they vary by product type (aerodynamics, aesthetics, weight…). As is only to be expected, criteria such as safety and regulatory compliance are also important. Finally, criteria related to sustainability were also mentioned, with evaluation of environmental performance clearly dominating over the social dimension of sustainability. While it was possible to identify a certain level of awareness among interviewees concerning the social aspects of developments, such aspects were pushed into the background by considerations of information management or the availability of the necessary tools. This is reflected in statements such as: "Information management needs to adapt to social issues" (INT 1); "Our [eco-design] software products do not offer any social approach" (INT 8); "there is a lack of tools, a lack of methodology during the design phase… we had a lack of tools when it comes to answering questions regarding social attributes or social indicators" (INT 12). In addition, even though developments in the evaluation of environmental impacts have advanced rapidly in recent years, a few interviewees still reported the need for them to be simplified in order to meet organizational resource constraints: "We use a checklist format because some quantitative tools are too time-intensive and need too much workload to get good answers to the questions in time. If you have to react in a very short time you need other tools and those tools are more or less qualitative or quasi-quantitative. Other companies do it this way as well" (INT 12) or "We do not have the luxury to make it quantitative, of really putting numbers to it. But we are more aiming to achieve sustainability by seizing the big picture with all the stakeholders" (INT 6). Last, but not least, among evaluation criteria are those relating to satisfaction of customer needs. The nature of customer input varies depending on the type of development project at hand. For market-driven development projects, involving wide design spaces, the results of market analyses are considered and embedded in the designs in the initial development phases, as discussed in Section 3.4. Nevertheless, customer-driven and partial innovation projects also exist, and these are highly influenced by the customers: "Some clients are really strict: if the client says *I want that material*, we make the product with *that material*" (INT 2). In such cases, it is also common to evaluate prototypes together with the client and improve samples of the final product iteratively. This process is described as being extremely expensive, owing to the lack of production scale, and also as being a very unsustainable process due to the large amount of materials needed (INT 2, INT 11).

3.4. Progression of contextual factors for decision-making along the product development process

This section addresses the evolution of the decision-making context during the development process. An overview of disaggregated insights can be found in Table 6. This presents the SPD phases with keywords collected through the interviews.

3.4.1. Product dimensions and criteria considered by product development phase

In the TC phase, the product dimensions addressed tend to focus on intangible ones such as "business model", "lifecycle actors", "services" (INT 6). The criteria used to decide on these di-

Table 6
Overview of contextual factors evolving throughout the product development process

Contextual factors	Task Clarification	Conceptual Design	Embodiment Design	Detailed Design
Product dimensions addressed	• Business model • Lifecycle actors • Services attached • Distribution channels	• Overall form and function • Materials • Suppliers • Services	• Overall form and function • Physical parts	• Physical parts • Detailed engineering • Manufacturing processes
Criteria considered	• Company goals • Market surveys • Interest/Influence of lifecycle actors • Lifecycle sustainability hotspots	• Compliance (product-oriented: hazardous substances, recycling quotas...) • Economic performance • Resource efficiency • Functionality (aesthetics, ergonomics...)	• Technical feasibility • Economic performance • Functionality (aesthetics, ergonomics...)	• Compliance checks (manufacturing process-oriented: energy efficiency, health and safety...) • Technical feasibility
Actors involved	• Strategic (i.e. CEO), tactical (i.e. product manager) and operational (i.e. mechanical engineer) • Lifecycle stakeholders • Outsourced service providers • External consultants/Facilitators • Cross-functional actors (Marketing and communications, Business analysts, Finances)	• Tactical and operational • Design engineers • Cross-functional engineering teams	• Tactical and operational • Design engineers • Cross-functional engineering teams	• Operational design engineers • Customers
Decision support	• Baseline studies • In-person discussions • Visual systems mapping • Participatory workshops • Consultation	• LCA indicators • Checklists and guidelines (DfX) • Functionality and value analysis • Internal carbon pricing • Cost-benefit analysis • Weighted matrices/Dashboards • Product KPIs	• LCA indicators • Checklists and guidelines (DfX) • Weighted matrices/Dashboards • Product KPIs • Sustainable product portfolio	• Improvement iterations
Information flows	• Predominantly qualitative • Quantitative information tends to be from generic sources • Unstructured	• Qualitative and quantitative • Quantitative information tends to be from generic sources • Structured and unstructured	• Qualitative and quantitative	• Predominantly quantitative
Design tools	• Sketching/drawing • Mapping	• 1:1 mock-ups/print outs • CAD/CAE software • PLM/PDM software	• CAD/CAE software • PLM/PDM software • Prototypes	• Prototype testing

mensions appeared to be often based on qualitative and subjective data. They can, for instance, involve the extent to which sustainability hotspots are addressed, the impacts on current and potential lifecycle stakeholders (environmental and social impact baseline studies) and the impact on companies' market segments. Baseline studies are a very common data collection mechanism. These include things such as policy analysis, market analysis, consumer surveys and, in the case of infrastructure and the built environment, environmental and social impact assessments (INT 14). It was quite noticeable that relatively few interviewees, especially mid-level profiles very specialised on solving technical tasks, had taken an active role in this phase. Only a few reported their participation from a managerial position, e.g., as a consultant or product manager. The answers relating to the stages conceptual design and embodiment design indicated a progressive narrowing of the scope for decision-making throughout SPD, increasingly focusing on tangible dimensions such as product architecture or materials. From ED onwards, decisions appear to be essentially technical. Decisions might involve new or different suppliers (such as a result of material selection) (INT 12). The criteria driving these decisions include the extent to which concrete legal and market requirements are met. At this point, the sustainability dimension with the greatest influence appears to be economic performance (profitability), even while ensuring that social or environmental constraints are not breached. Criteria relating to environmental and social performance play a relatively minor role, and the focus here is placed on meeting labelling or certification requirements. During the detailed design stage (DD) a product's physical characteristics and functionalities are further refined, and trade-offs among product attributes are resolved. Decisions made during this phase often focus on the product architecture or material dimensions. Quality and technical criteria are used for evaluation. Production engineering is detailed, and the environmental impacts of production processes are also considered. The remaining aspects requiring attention during DD offer little potential in terms of allowing for improvements in product sustainability.

3.4.2. Key actors and commonly used decision-making support

Interviews revealed that the initial level of diversity existing among actors, decreases as one progresses along the design process. The presence of "external consultants", "management", "lifecycle stakeholders external to the company" and "intermediate managers" was found to be common in the TC phase (INT 6). The types of decision-making support mentioned included "participatory workshops", "systems mapping exercises" and "in-person discussions" (INT 6, INT 14). Assessments of the environmental and social impacts related to the implementation of an R-strategy appear to be largely qualitative and leave quite some room for subjectivity, together with occasional quantitative input. Accordingly, the sourcing of information appears to be mostly unstructured and incorporates tacit knowledge: "Sometimes, a choice is made because somebody knows that it worked for a certain company" (INT 6). Nevertheless, technical profiles such as design engineers or industrial designers are usually present to provide a feasibility base-

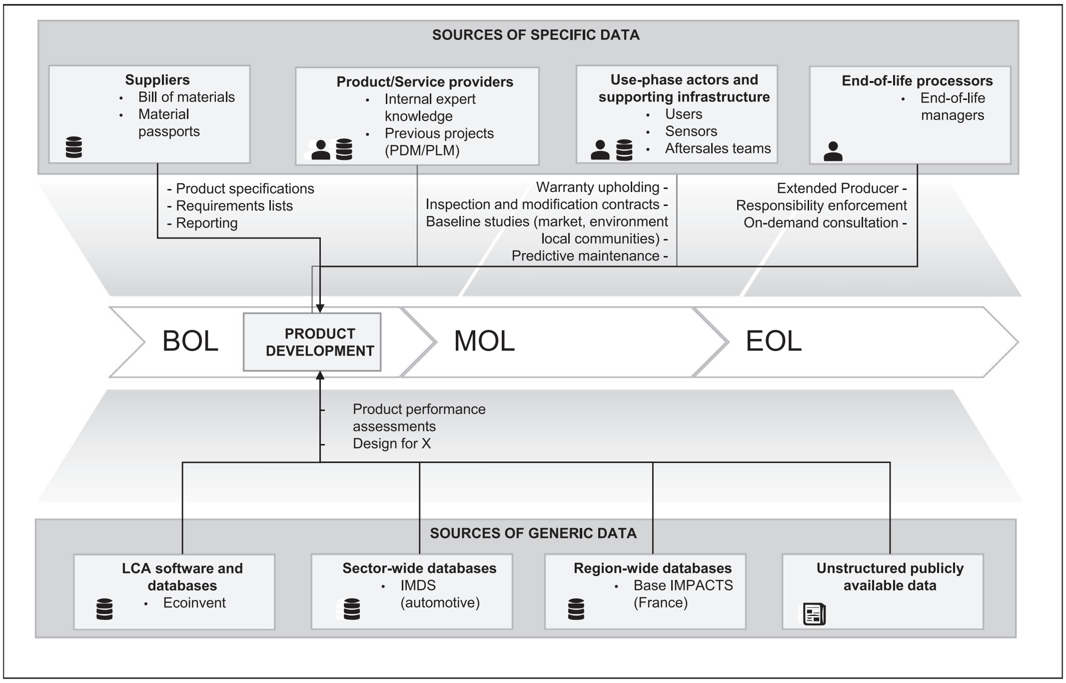

Fig. 4. Mapping of sources of information and retrieval processes along the lifecycle, based on interviewee responses

line. R-strategies are chosen based on the input from all participants, often weighted by the relative influence of the decision-makers. Prospective trade-offs and synergies are resolved through in-person discussions and thus, the figure of a facilitator from within or beyond the company is very common (INT 6, INT 9). In the subsequent CD phase, decision-making support mostly seems to address the technical aspects of design, with the information being sourced in a more structured manner and processed individually prior to the discussion. This means that relevant analyses and reports are conducted prior to the building of consensus. Decision-making support was found to be backed by “cost-benefit analysis” (INT 15), “internal carbon pricing” (INT 14), “functionality analysis” (INT 8), “eco-design guidelines (INT 12) and centred on the product or service in question. The process of achieving final consensus is usually supported by means of weighted indicator matrixes and written refutation statements (INT 11, INT 12). Actors from different departments join the discussions. Issues arising are cross-functional and thus, the need for a cross-departmental discussion facilitation is often fulfilled by a managerial role. In the ED phase, the discussion focuses on the product level and thus, the profile of actors is similar to that found in the CD phase, but with a greater proportion of operational employees. Formal decision support also relies on the use of index metrics and weighted matrixes, and here greater amounts of quantitative information are used as input. Finally, decision-making processes in the DD phase, which focus on detailed engineering and production processes are highly fact-based, using primarily performance data collected through, for instance, prototype testing. Those participating in this phase are largely operational employees and cross-departmental. The latter point is important since product completion involves embedding product parts that have been developed in different departments (electronics, materials, etc…). It is also common practice to involve the product customer in order to acquire validation for the final decisions on product prototypes (INT 2, INT 11).

3.4.3. Inter- and intra-organizational information flows

An overview of all lifecycle information flows in the product development process is displayed in Fig. 4. Keeping track of information flows is essential as this provides input for decision-making support throughout the entire lifecycle of the product.

The data sources are thus classified according to their relative position along the lifecycle. The Beginning of life (BOL) phase, encompasses the pre-production phases; the Middle of life (MOL) phase, includes the use-phase of the product; and the End-of-life phase (EOL), covers product disposal. The emphasis of the decision-making tools on sustainability performance meant that the focus here was placed on BOL, with data collection in the MOL and EOL phases being much less frequent. Product-specific data from suppliers was collected through processes linked to verification activities such as “reporting” or “requirements verification” (INT 15) and was related to queries made by the original equipment manufacturers or service providers, or, in the case of public organisations, to calls for tenders. Due to the evolutionary nature of the product development process, a lot of information is collected from product data management and Product Lifecycle Management (PLM) platforms, which contains products physical characteristics and lifecycle performance information from already existing products. Information appeared to be collected from the MOL phase as well. The retrieval of information was conducted in response to binding commitments relating to things such as inspections, warranties, and maintenance contracts. Thus, many departments or outsourced companies managing MOL services are likely to own impact data which may be used to inform SPD and related R-strategies. A detailed mapping of the data sources mentioned can be found in Fig. 5. Interviewees’ answers reflected on the degree of representativity of data coming from LCA datasets (such as Ecoinvent), for example, when looking at the impact of their own company processes. This idea may be seen in the following comment: “In general, companies have two types of production processes: processes that are generic and in common with many other companies, and some others that are specific to their differentiation value. An idea is to reduce the workload of impact data collection by combining specific and generic data sources according to the degree of “specificity” of the process at hand” (INT 7). Observations were collected with respect to data sources: “I think primary data is necessary, but with proxy data you can

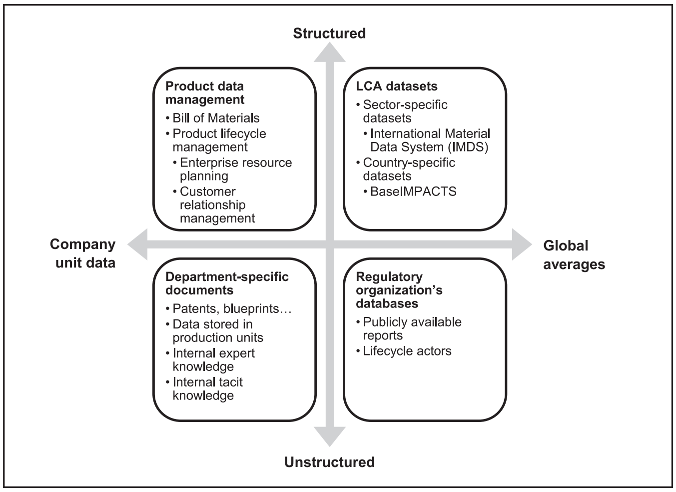

Fig. 5. Data sources mentioned in the interviews sorted by degree of structure and representativity of companies' activities

also get a really good feel for how circular a product is. It is not good measure with the micrometer if you are going to mark with a chalk, but it is important to understand the level of uncertainty in your dataset" (INT 9). The possibility of capturing the environmental impacts of product design variants in real time, using design software platforms such as Computer Aided applications (CAx) and Building Information Modelling (BIM), was also stated. One specific cross-company data source mentioned was the International Material Data System (IMDS), a database for materials used in the automotive industry. Region-specific databases were also mentioned, such as BaseIMPACTS from France. Nevertheless, responses also pointed to the use of unstructured external data sources, such as scattered reports from different consultancies or international agencies. These were used, for instance, as input for design benchmarking processes. Cross-functional communication between departments and greater digitalisation of documents could also serve to foster the exchange of data: "Digitalising these exchanges has been a great advancement in terms of productivity, but it has also caused some disadvantages. Some [SPD] projects are enriched and [have] been kept alive by in-person interactions and, when these are done remotely, projects die" (INT 12). Finally, a resounding lack of communication with EOL stakeholders was apparent across all respondents, who themselves also emphasized the need to improve this point: "Maybe 99% of companies have no idea of what actually happens to their products at the end of life. We can see it because in the assessment software they can choose if they want to simulate the end-of-life automatically or whether they have some data to put inside the software. And every time they choose the automatic simulation" (INT 8). Two different reasons were identified in order to explain this: "lack of trust among lifecycle stakeholders" (INT 11) but also "lack of processes and culture to carry out the collection of impact data from EOL phase actors" (INT 14). In this respect, the following remarks made by two interviewees proved somewhat exceptional. Consultation with EOL managers would occasionally take place on-demand (INT 14) or EOL stakeholders would be invited in TC phase discussions (INT 6).

4. Discussion

According to interviewees' responses, the implementation of R-strategies has been observed in companies that have neither devised a CE roadmap nor set explicit goals with respect to improving sustainability. R-strategies appear to have been implemented as means to support corporate competitive strategy, e.g. to gain access to specific markets within an industrial sector. Given that the term 'circular economy' serves as an umbrella concept and captures an amalgam of disparate activities (Blomsma and Brennan, 2017), it should come as no surprise that such well-established practices are included. While this provides CE academics and practitioners with an excellent opportunity to tap into multiple, well-founded bodies of knowledge, it also has its drawbacks. The most prevalent CE models comprise R-strategies ranked by the principles of waste hierarchies and thus, some of them might entail a marginal contribution to the Inertia principle (Stahel, 2019), the ruling principle of the CE (Mendoza et al., 2018). There is the possibility then, that inclusion of long-existing practices may serve to undermine the transformative potential of the CE towards more sustainable production systems by reducing it to a series of relatively small, incremental improvements. Instead of settling on the mere re-labelling of long-existing practices, perhaps CE experts could make a more valuable contribution by understanding circularity as a socio-technical challenge and addressing it through interdisciplinary solutions, thus helping to overcome the (often inherent) tendency towards already existing technological approaches. For this purpose, emerging disciplines such as design for sustainability transitions (Ceschin & Gaziulusoy, 2016) can provide a baseline for determining where, how, and to what extent, the implementation of an R-strategy may add value to existing SPD practices.

High-value R-strategies interfere with the corporate competitive strategy since their structural consequences are "important, in terms of the actions taken, the resources committed, and the precedents set" (Mintzberg et al.,1976). Their translation into new product designs fits very well into the concept of strategic design for sustainability put forward by Manzini & Vezzoli (2003) who stated that this requires "the creation of new stakeholder configurations, the development of integrated systems of products, services and communication that are coherent with the medium-long term perspective of sustainability while being economically feasible and socially appreciable". This requires a reflection on existing organisational cultures, as this obviously has a direct impact on the interactions occurring across various processes, languages, and activities at different levels of management. This is exemplified by the decision-making process used in evaluating potential solutions described by some interviewees. On the surface, it appears that actors simply follow a standardised and mature methodological process involving comparison matrixes. What needs to be remembered, however, is that underlying all this is, there is a specific set of decision-making criteria which have already been weighted to reflect the priorities of the most influential corporate actors. In addition to that, the development of CE products is no different from previous practices when it comes to the influence of customers: their constraints largely determine the functionalities of manufactured products, especially in customer-driven projects. Therefore, a corporate CE culture would not only take their customer requirements in consideration, but also initiate joint discussions with customers on R-strategy co-creation. Secondly, there is also the need to explicitly adapt existing processes to these cultural changes. As seen, existing development and evaluation processes frequently lead to isolated material substitutions, to profit-driven PSS, to circular ecosystems as long as partners do not capitalise on each other's markets and within which there is hardly any business model innovation. Yet interviewees stated a proactive attitude from management to contribute to sustainable development, current SPD processes further deliver on the CE €1.8 trillion gain opportunity forecasted by 2030 (EMF, 2015) rather than on the SDGs. All in all, interviews confirmed that an absence of alignment between corporate culture and management processes makes sustainability strategies likely to fail (Baumgartner, 2009).

Regarding the contextual factors of the product development process, it could be argued that the TC phase is the most appropriate for addressing product dimensions impacting on socio-technical systems (and thus, requiring high-value R-strategies), as this is the phase when baseline studies (i.e. market analyses, environmental and social impact assessments) help outline the value proposition (Table 6). It is also the phase that could accommodate inter- (circular ecosystem) and intra-organizational (top management) actors who are likely to have some influence on the scale at which a given R-strategy is intended to impact. Accordingly, recent academic efforts have started exploring the interconnections between company levels in the context of CE adoption. For example, Prendeville & Bocken (2017) outline how service design tools may be adopted during business model innovation; Mendoza et al. (2018) propose the integration of backcasting – a business strategic planning approach – within the product innovation cycle; Pieroni et al., (2018) explore the synergistic relationship between business models and product design in the context of a CE, and Konietzko et al. (2020) mention the need for a cross-organisational perspective when designers wish to ensure that their products contribute to the creation of CE ecosystems. While these integrative approaches developed so far provide an important steppingstone for decision-making on product implications of R-strategy adoption, some interviewee's (INT 1, INT 2, INT 4 and INT 10) highlighted that SPD was done in an evolutionary manner, i.e. previous product versions were used as the starting point for new models. This indicates that current product development routines reduce the potential opportunity for re-thinking current value-propositions and discussing their systemic implications because initial stages of development are not revisited as frequently as the final ones. Therefore, greater emphasis on strategic product planning and task clarification activities are an imperative to SPD for a CE.

Decision-making support types should serve different purposes throughout product development phases. At initial stages (TC, CD), decision-making support should help a joint evaluation of product variants by streamlining cross-functional discussions on the design problems emerging from the new CE requirements. According to interviews, cross-functional evaluation is often done through matrixes that compare variant's technical and economic values at the end of each product development phase, including environmental values in the case of SPD. In literature, there are several examples of CE product evaluation using performance matrixes based on MCDA (Bertoni, 2019; Kamp Albæk et al., 2020) including circularity indicators. Notably, the use of CE indicators was reported by one interviewee (INT 9) and the reference was made to the material circularity indicator (MCI) developed by the Ellen MacArthur Foundation. Indicator sets present some advantages: these are modular, can be used to accommodate various dimensions of sustainability and be leveraged for reporting to different audience types. Nevertheless, it is worth to mention that given the ongoing standardisation developments, they are still prone to internal or external political bias, which is especially relevant in the CE domain as concepts such as sustainability and circularity are open to interpretation (Lindgreen et al., 2020). During the final stages of SPD (ED, DD), decision-making support should help optimise the combination of design parameters to meet product functionalities and devise manufacturing processes. For this purpose, multi-objective design optimisation has found to be useful when dealing with aspects of environmental compliance (e.g., meeting recyclability rates). In the literature, several examples have been found (Miranda-Ackerman et al., 2017; Shimizu & Yamada, 2008). However, the task usually becomes essentially technical, leading to its resolution within detached teams, and thus displacing cross-departmental discussion. A similar use-case applies to the inclusion of sustainability aspects in QFD, where algorithms can be used to identify threshold values for technical requirements (Younesi and Roghanian, 2015). Therefore, it is important to combine cross-functional discussion tools with computational decision-making support.

In the literature, most of the tools supporting decision-making relating to the sustainability implications of product configurations were based on LCA. Notably, some methodological questions are open concerning the use of LCA in the context of CE evaluation, especially in regard to consistent modelling of open recycling loops or when attempting to account for changes in stock (Peña et al., 2020). In interviews, no respondents mentioned LCA as directly impacting the development process. One respondent stated that LCAs can only be performed at least 3 months after the product is launched in the market due to the inherent data uncertainties involved (INT 3). Here, by way of explanation, one may draw on the so-called Design paradox (Lindahl and Sundin, 2013). This paradox refers to the fact that the greater freedom of action present in early product development phases occurs in parallel with greater lack of product information. While the respondents were generally aware of the existence of LCA databases and the possibility of aggregating impact data in order to observe how variations in design may impact upon sustainability, none of them mentioned its use in work routines. Moreover, some respondents were aware of the data uncertainty issues surrounding such tools, both with respect to their own products, and with respect to supply chain and production processes. The incorporation of modules enabling the evaluation of the social dimension of product design would provide a common avenue in aligning decision-making support more closely with moves towards further sustainability. Disciplines such as human-centred design or user-experience design could help provide insights into how product-related norms, uses and behaviours might be adjusted to engage product users as active facilitators of value retention options. Additionally, usability requirements should also be taken into consideration in order to establish greater compatibility of decision-making support tools with CE product developers, an issue which was already pointed out in previous studies for eco-design tools (Lindahl, 2006; Lofthouse, 2006). In this regard, some suggestions from interviewees were: a) to be adaptable to different company contexts (terminology); b) to be intuitive, accessible to non-experts, educational; c) to require in-person interactions and exchanges; d) to be simple, easy to use; e) to provide granular results, and disaggregated information.

Interviewees' answers have confirmed that access to lifecycle information data is still a major barrier for SPD (Schöggl et al., 2017), which also affects decision-making processes. In practice, it has been observed that decision-making support incorporating environmental criteria was based on the use of secondary impact data coming from cross-company impact databases such as Ecoinvent (INT 3, INT 7, INT 10, INT 12). The processes for collecting primary data from the entire lifecycle reveal uneven levels of maturity among lifecycle phases: upstream, interviewees stated that processes of data exchanges with suppliers were common, streamlined and time-consuming (INT 1). Product developers did not appear to be using data collected during the use-phase of a product during design routines, even though they highlighted that data is obtained by other departments in charge of aftersales service or maintenance contracts (INT 11). This is particularly relevant for PSS: since the product still represents an asset for the manufacturer during the MOL, manufacturing companies have a greater incentive for learning about the products (Sakao & Sundin, 2019). Finally, regarding the collection of primary data at the end of products' life, it was found that companies are generally not aware of the fate of their products at the end of their first lives nor of the impact of their different R-strategies (INT 2, INT 4, INT 8, INT 11, INT 15). The observed lack of information gathered by development teams on product performance after their first life-cycle is aligned with results reported by recent academic work. For instance, Lindkvist Haziri, L. (2020) remarks an absence of information feedback loop from remanufacturing actors back to product designers due to a lack of demand for it by designers. Thus, in order to monitor the extent to which their R-strategies are fulfilled and theoretical sustainable performances are actually met, organisations need to fill the existing gaps in data and information flows.

5. Conclusions

Given the exponential growth in the production of knowledge concerning the implementation and assessment of CE R-strategies, the objective of the present paper was to investigate the implications of these for SPD activities. For this, a literature review together with 15 theory-based in-depth interviews with product development experts working in durable goods manufacturing companies were conducted. In order to advance the already mature inclusion of economic and environmental values in existing SPD methodologies, it is recommended that SPD processes approach circularity as a socio-technical challenge. This involves first and foremost to revise the alignment between organisational cultures and product development processes. As SPD has been found to be very often applied in an evolutionary way, i.e. new product designs often start from existing ones, it is suggested that greater emphasis should be placed on addressing CE during strategic product planning and task clarification activities. Moreover, these development phases offer a greater potential for the involvement of actors that can influence the product dimension an R-strategy intends to impact (product ecosystem, revenue model, lifecycle actors…). Additionally, considering circularity as a socio-technical challenge would allow for further synergies with different design disciplines, such as user-centred design. Thus, decision-making support at these stages should facilitate cross-functional discussions and involve various business functions and departments. Further inclusion of circularity principles is recommended in existing decision-making support, for instance, by adding circularity indicators in product evaluation comparison tables. At later development phases, cross-functional discussions can be supported by optimisation of design parameters in order to identify actual sustainability performances. In this regard, the so-called Design paradox has been made evident concerning the information available throughout product development, and this has explained the scarce implementation of LCA during product development. This means that information regarding the sustainability of product design variants is still hard to screen ex-ante. Additional limitations that decision-making support of SPD for a CE should aim at overcoming are also related to information management systems. More specifically, to the lack of consideration of social impacts and the lack of actual information concerning products' EOL, which, at present, remain in a black box. In sum, this research has reflected on the different implications the CE paradigm poses in SPD decision-making systems at all company levels.

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The authors declare that they have no financial interests or personal relationships that might influence the work reported in this paper.

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Supplementary materials

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