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A Product Lifecycle Model for the Digitally Enabled Circular Economy

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Abstract: The circular economy (CE) is a promising model for sustainability, and digitalization is crucial for transitioning to this model, serving as an enabler for enhancing circular principles. Despite the impact of the CE on the lifecycle of products, a comprehensive understanding of the effects is lacking. This paper addresses this gap by developing a circular product life cycle model that especially focusses on digital technologies. Utilizing a systematic literature review and thematic content analysis, the model provides a comprehensive framework for the investigation of key processes in the CE.

Keywords: Design for Circularity, Product Lifecycle, Digital Circular Economy, Digitalization, Industry 4.0

1 Introduction

Motivated by climate change, the rise of greenhouse gases, and the loss of biodiversity, the sustainability megatrend is experiencing a continuous increase in relevance. Within the framework of the United Nations' political orientation, fundamental goals contributing to sustainable development were defined in the Agenda 2030. These goals, also known as Sustainable Development Goals (SDGs), serve as a guideline for sustainable development in politics, society, and industry (UN, 2015). These developments have led to heightened environmental awareness, subsequently resulting in additional regulations at the national and international levels promoting sustainable development, such as the European Green Deal (Fetting, 2020). Particularly, manufacturing companies face numerous challenges due to these restrictions, compelling them to make their existing business and resource consumption more sustainable (Acatech, 2021). In this context, the concept of the circular economy (CE) has emerged as a promising economic model (Ellen MacArthur Foundation, 2013). The circular economy fundamentally describes a regenerative economic system that expands the traditional concept of "End of Life" through the reduction, reuse, and recycling of materials and products. These principles, also referred as R-principles, provide insights into the general structure of returning the products. CE contributes to increasing the value of resources used along the entire value chain and simultaneously contributes to sustainable development (Kirchherr *et al.*, 2023; Ellen MacArthur Foundation, 2013).

Digitalization is considered a central enabler for the implementation of the circular economy (Antikainen *et al.*, 2018). Especially, digital technologies have a strong influence. In general, digital technologies are essentially understood as technologies that support the collection, linking, processing, storage, visualisation or transfer of data and information (Stähler, 2002; Cagno *et al.*, 2021). In this sense, digital technologies enable, among other things, an increase in the efficiency and flexibility of processes, while at the same time making product data and resource consumption more transparent (Cagno *et al.*, 2021; Pagoropoulos *et al.*, 2017). These capabilities of digital technologies result in numerous applications for the CE, such as increasing the efficiency of product refurbishment processes (Ghoreishi, 2023). Appropriate data analysis methods have the potential to check the quality status of components, allowing early identification of which components need to be replaced (Ranta *et al.*, 2021; Bressanelli *et al.*, 2018).

Despite the promising potential of the digitally-enabled circular economy, a significant paradigm shift from the existing linear economy is required (Ghisellini *et al.*, 2016; Pigosso and McAloone, 2021). Circular transformation necessitates a holistic and integrative consideration of the dimensions of product design, business model, value creation, and management of a company (Scholtysik *et al.*, 2023; Ellen MacArthur Foundation, 2015). Therefore, it is essential to examine the interactions between these dimensions along the whole product life cycle, which describes the defined sequence of phases that a product undergoes throughout its lifespan, from development to disposal. The phases of the product life cycle can be categorised into 'Begin of Life' (BoL), 'Mid of Life' (MoL) and 'End of Life' (EoL) (Kiritsis, 2011). BoL focuses on product development and production, while MoL addresses the use phase of a product. EoL covers the disposal of a product (Kiritsis, 2011). Despite the fundamental linear perspective of the product life cycle, companies must inevitably reassess and integrate new phases due to circular transformation (Ertz *et al.*, 2022; Nag *et al.*, 2022). Within these phases, specific processes take place, such as production, where a process is defined as an activity that requires a certain amount of input in order to obtain a defined output from the activity performed. Yet, companies lack experiential knowledge about the specific phases a product undergoes in the context of the circular economy and how these can be accompanied through digitization (Subramoniam *et al.*, 2021). Hence, a comprehensive model is needed to describe the product life cycle in the circular economy, incorporating digitization. Based on the challenges mentioned above three research questions arise:

How is the circular economy being implemented in industry (RQ1) and what processes are taking place (RQ2)?

What is the influence of digital technologies on these processes (RQ3)?

The aim of this paper is a comprehensive model for describing the product life cycle in the digitally enabled circular economy. To achieve this, a systematic literature review was conducted on existing digital enabled use cases in the circular economy. Identified use cases were coded using thematic content analysis, and suitable phases of the product life cycle were derived and modelled in a logical sequence. The structure of this paper is as follows: Section two provides an overview of existing approaches and models for describing the product life cycle. Section three explains the research methodology. The core results are described in section four, and finally, section five presents the discussion and summary of the results.

2 State of the art

The following section presents an excerpt of existing frameworks for structuring the product life cycle. The ISO/IEC/IEEE 15288:2015 (International Organization for Standardization *et al.*, 2015) defines a comprehensive sequence of phases as part of the product lifecycle description. There are essentially six phases: concept stage, development stage, production stage, utilization stage, support stage and retirement stage. At its core, the concept stage involves the design and specification of a product, including the definition of requirements and underlying functionalities. The development stage then translates the previously defined requirements into specific physical dimension. The production stage implements all the manufacturing processes required to produce the product. The subsequent utilization stage is considered in parallel with the support stage and focuses on the usage phase of the product, complemented by the necessary services. Once the use phase has been completed, the retirement stage deals with the disposal of the product. The generic life cycle model illustrates the basic sequence of a product over its expected lifetime. However, this model does not specifically consider the influence of the circular economy and lacks a dedicated mechanism for the return of products, components, and materials (International Organization for Standardization *et al.*, 2015).

FORSBERG ET AL. (FORSBERG *ET AL.*, 2005) define the typical sequence of product phases for a high-tech commercial manufacturer. This sequence consists of three overarching periods: the study period, the implementation period, and the operation period. The study period is further subdivided into three phases. First, the product requirements are captured and defined. The technical functionality is described in the product definition phase, followed by the specification of the concept in the product development phase. Then, during the implementation period, a suitable prototype is developed and evaluated through an internal testing phase. Upon completion of the internal testing phase, an additional testing phase is conducted with external users. At the end of the implementation period, production processes are defined and implemented during the operations period, and the product is delivered to users. Disposal of the product marks the end of the operations period. This framework integrates not only the major phases of a product, but also the build and test phases. However, it does not include dedicated processes for product take-back or recycling (Forsberg *et al.*, 2005).

The Ellen MacArthur Foundation proposes a generic framework for describing how the circular economy works, known as the Butterfly Model (Ellen MacArthur Foundation, 2013). This model identifies four fundamental stakeholders - material manufacturers, product manufacturers, service providers and customers - as having a significant impact on the circular economy. The Butterfly Model focuses on visualising options for product take-back to extend or prolong the life of the product. The R-Principles are integrated into the model to illustrate which stakeholders are actively involved in the implementation of an R-Principle. For example, in the case of customer-initiated recycling, the material manufacturer is involved in creating a new recyclate from the available materials. In summary, the Butterfly Model focuses on the functioning of a circular economy but does not consider the necessary phases of a product throughout its life cycle. Furthermore, no interconnections are made to digital technologies (Ellen MacArthur Foundation, 2013).

VERTROVA and IVANOVA (VETROVA AND IVANOVA, 2021) present the Closed Product Life Cycle model, which integrates the principles of a circular economy while taking digitalisation into account. The authors divide the product life cycle into three phases: Production, Exploitation and End of Life. In the production phase, the authors define all the activities necessary to create a product, including product design, supplier selection and production processes. VERTROVA and IVANOVA provide examples of the use of big data, additive manufacturing, and digital twins, particularly in supporting the design process. The exploitation phase focuses on the use of the product, as well as repair and maintenance services. Digital technologies, such as sharing platforms, enable widespread access to products for a diverse customer base. In the end-of-life phase, the authors summarise the processes required for product recovery and refurbishment. Here the authors outline the potential of digital technologies, such as track and trace technologies, to determine the location of products. While the closed product life cycle addresses the characteristics of a circular economy, the phases are vaguely described, and the model does not provide a comprehensive understanding of the product life cycle in a circular economy (Vetrova and Ivanova, 2021).

CHOLEWA and HUYNH BA MINH (Cholewa and Minh, 2021) propose an alternative framework for the product life cycle. Essentially, the authors structure the product life cycle into the dimensions of BoL, MoL and EoL. Within these phases, the authors identify key stages to describe each dimension. In the BoL dimension, the authors further subdivide it into phases: Concept, Development, Prototyping, Launch and Production. Consequently, the core of BoL, according to the authors, addresses the conception and production of a product. Espacially, the launch phase is characterised by concrete measures such as product marketing. The MoL dimension is characterised by distribution, use, and optional services. Regarding the return of products or materials, the authors focus on recycling in the EoL. While the authors indicate a potential recycling option, other return options such as remanufacturing or refurbishment are not mentioned. CHOLEWA and HUYNH BA MINH provide a framework based on the dimensions of EoL, MoL and EoL, but only vaguely outline recycling and the extension of EoL. In addition, the authors do not address the potential applications of digital technologies (Cholewa and Minh, 2021).

In summary, there are a variety of different approaches to structuring the product life cycle. However, these approaches do not fully capture the characteristics and opportunities of the circular economy. The integration of frameworks such as POTTING ET AL.'S (POTTING *ET AL.*, 2017) R-Principles is only vaguely implemented. The use of digital technologies is also only sporadically addressed. There is therefore a need for a holistic structuring framework that captures the product life cycle of a circular product, considering digital technologies.

3 Research methodology

In order to develop a model to describe the product life cycle in the digitally enabled circular economy, a systematic literature review was carried out. It was based on the methodological approaches of WEBSTER and WATSON (Webster and Watson, 2002) and XIAO and WATSON (XIAO AND WATSON, 2019), who propose a structured approach to collecting and analyzing the relevant literature. The process was carried out in four elaborated phases (Figure 1).

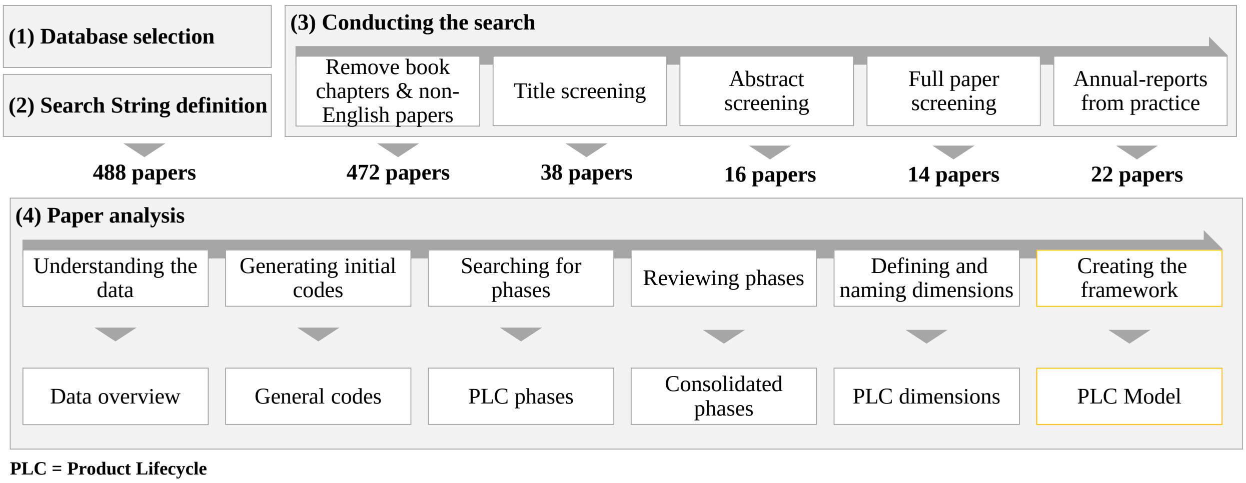

Figure 1: Overview of the conducted research methodology

Database selection: The aim was to establish a well-founded and comprehensive database for the research. Three databases were selected due to their comprehensive library of peer-reviewed articles in the field of circular economy research: Scopus, Science Direct and ProQuest. These databases are characterized by a broad coverage of scientific publications.

Search String definition: A three-part search term was created based on the research questions. The first research question is directly addressed by the first two parts of the search string. The primary concern here was to gain a comprehensive understanding of the generalized phases of the product lifecycle, especially from the perspective of practical application. The focus was therefore on studies and articles detailing already implemented use cases within the circular economy. The third research question, which focuses on the integration of digital technologies into the product lifecycle, was covered by the third part of the search string (see figure 2). A total of 488 potentially relevant articles were identified for the study.

„Circular Economy" AND ("Use Case" OR "Case stud*" OR "Application" OR "Implementation)	***How is the circular economy being implemented in industry and what processes are taking place?***
AND ("digital technologies" OR "industry 4.0" OR "digitalization" OR "digitization" OR "industry 5.0")	***What is influence of digital technologies on these processes?***

Figure 2: Definition of the search string

Conducting the search: A five-stage evaluation process was used to refine the results. First, book chapters and non-English language papers were excluded, so that a total of 472 papers were assessed as relevant. The papers identified are both conference papers and journal articles. Next, two researchers reviewed the remaining papers at title and abstract level. After these two steps, 16 papers remained, which were then analyzed at full-text level. Two further papers were rated as not relevant. In order to increase the practical relevance and topicality of the research, a search for gray literature was conducted. Studies and articles published between 2017 and 2023 that present best practices from the industry were specifically selected. Particular attention was paid to the manufacturing sector. In the next step, it was verified whether the companies highlighted in these studies and articles for their use cases have also published sustainability reports. These reports are crucial as they provide detailed insights into the implementation of circular economy business models and their environmental impact. These reports were included in the analysis as gray literature to ensure a holistic view of the circular economy approaches and their effectiveness. In this way, the data base provides a practical reference for the derivation of the product life cycle model. A total of 8 relevant sustainability reports were identified that provided important data and insights for the systematic literature review. In summary, a total of 22 papers and 8 annual reports were identified for content analysis.

Paper analysis: The thematic analysis followed a four-stage coding process based on Braun and Clarke (2006) (Braun and Clarke, 2006). The starting point for this detailed analysis was a detailed review of the raw data. This analysis consisted of reading each paper and identifying text passages that relate to the research questions. These text passages describing activities during the life of a product - from product creation to utilization and post-use phases – and have been adopted as direct citations for further processing. By highlighting and coding key words, phrases, and technical terms, it was possible to identify primary categories of codes, which formed the basis for further analysis. In the second step, these primary categories were analyzed in depth to discover correlations and patterns. This iterative process resulted in the formation of secondary categories that represent different aspects and processes of the product life cycle and were created by synthesizing the primary categories. In addition, the supporting digital technologies in each process were captured and coded separately to focus the themes further and exclude irrelevant subthemes and codes. The third analysis step focused on aggregating the identified processes into four overall phases of the product life cycle, representing a higher level of abstraction and coding. These aggregated phases, including the associated processes and digital technologies, were then discussed in detail, and checked for their relevance to the research questions. The result is a classification based on the primary categories and secondary processes that is both theoretically sound and practice oriented. A visual example of the resulting data structure, which illustrates the insights gained, is shown in figure 3. This structured representation illustrates the relationship between the identified categories, processes and the phases of the product life cycle and provides a comprehensive overview of the insights achieved.

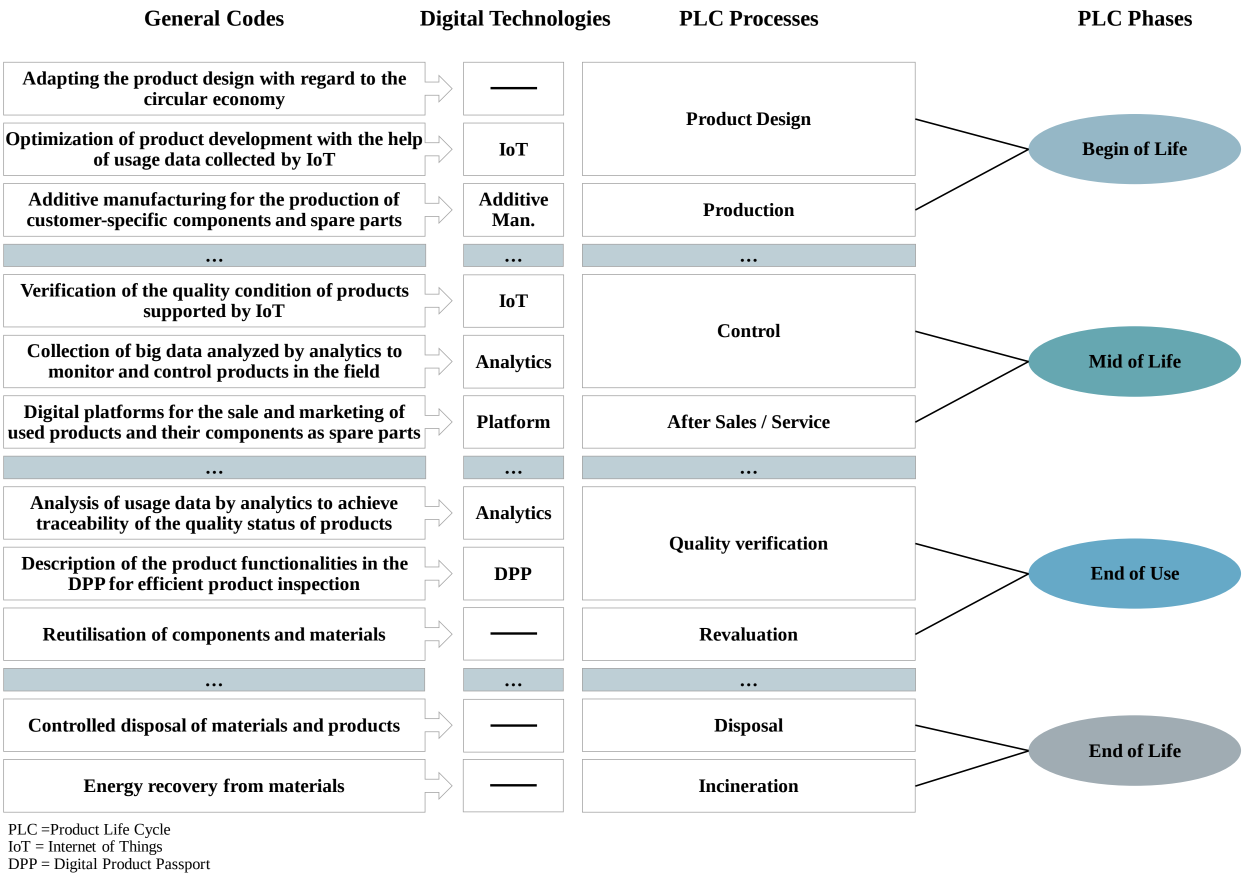

Figure 3: Excerpt from the data structure

4 Results

This section elucidates the outcomes of the aforementioned research methodology. Utilizing the existing codes, a comprehensive set of 16 generalized processes has been deduced to delineate the product life cycle across four central phases. Fundamentally, these identified phases adhere to the classical model of a product life cycle, categorized into Begin of Life (BoL), Mid of Life (MoL), and End of Life (EoL). Additionally, the coding data introduced an extra phase, namely End of Use (EoU). Figure 4 illustrates the alignment of the identified processes within their respective phases. Detailed explanations of the individual phases and their associated processes are provided in the subsequent sections.

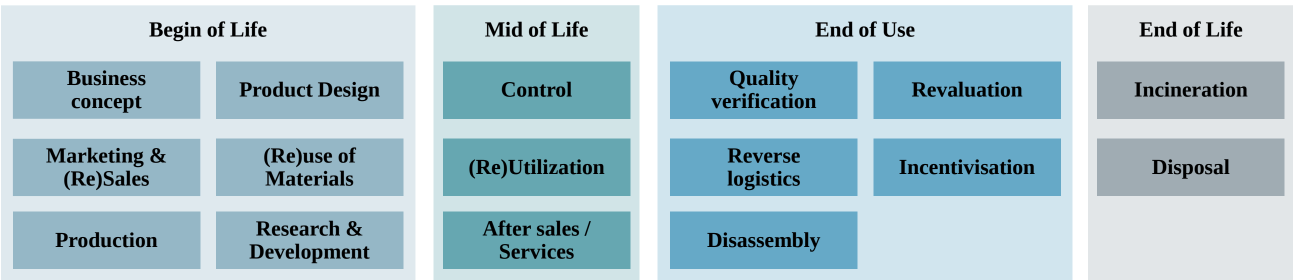

Figure 4: Overview of the derived processes and phases

4.1 Begin of Life (BoL)

The "Begin of Life" phase essentially encompasses all processes of creating and providing a product. Within the BoL, concrete design decisions, for instance, are made to enable the planned implementation of circularity. Furthermore, with the aid of digital technologies, activities in research and development can be supported, and production facilities can be made more efficient. Thus, all aspects of implementing a circular economy are addressed and initiated in the early stages of product development. This provides companies with the opportunity not only to adjust within an existing product but to rethink the entire product. The following outlines each phase of this dimension in detail.

Research & Development: The core of research and development involves formulating new solution principles and defining product design (Bressanelli *et al.*, 2018). In the context of the circular economy, companies can strategically integrate R-Principles such as Refuse and Rethink into the ongoing planning of the product life cycle (Stratmann *et al.*, 2023). Using digital technologies like blockchain or IoT, companies can leverage data from the operational phase to identify insights for new products or product features (Kouhizadeh *et al.*, 2020).

Business Concept: The business concept defines the fundamental business logic of the product under development (Stratmann *et al.*, 2023; Wu and Pi, 2023). This necessitates the development of multiple business models covering several product life cycles (Bressanelli *et al.*, 2018; Ingemarsdotter *et al.*, 2020). Companies can implement new and innovative business models, such as a sharing economy, with the help of digital platforms (Balder *et al.*, 2023).

Product Design: Product design involves the technical specification of the product. Based on specific design guidelines, such as *Design for Modularity* or *Design for Repairability*, the physical dimensions of the product must be structured in a way that operationalizes the predefined direction of circularity (Rossi *et al.*, 2020; Ingemarsdotter *et al.*, 2020).

(Re)use of Materials: The material to be used is defined as part of the product design. The raw material for production is then manufactured or recycled from used material in the "(re)use of materials" process. The choice and composition of materials determine the future implementation of recycling processes. (Neri *et al.*, 2023; Jensen *et al.*, 2023).

Production: The core of the production process is manufacturing all components and assembling the product. In the context of the circular economy, digital technologies like additive manufacturing have the potential to produce customer-specific components and needed spare parts (Bressanelli *et al.*, 2018; Uçar *et al.*, 2020). Additionally, resource consumption can be reduced by intelligently connecting and optimizing production facilities(Laskurain-Iturbe *et al.*, 2021).

Marketing & (Re)Sales: After production, the product must be sold to the customer. Appropriate marketing measures must be defined to communicate the added value of circular products to the customer (den Hollander *et al.*, 2017). Furthermore, the necessary sales and distribution processes need to be defined (Bressanelli *et al.*, 2021). Data analytics solutions can potentially optimize distribution process route planning, particularly to reduce CO_2 emissions during transportation (Balder *et al.*, 2023; Ranta *et al.*, 2021). The reuse of products requires their resale. It is therefore important to develop new sales strategies and describe the added value of used products (Bressanelli *et al.*, 2018).

4.2 Mid of Life (MoL)

After the delivery of a product, the focus in the Mid of Life phase lies on the usage phase of the product. Repair processes hold a significant position within this phase to prolong the usage as much as possible. In essence, during the usage, companies need to gain an overview of the product's condition to offer targeted and tailored repair services.

(Re)Utilization: The (Re)utilization process encompasses the concrete operational phase of the product at the customer's end (Bocken *et al.*, 2016). Integrated solutions such as *condition monitoring* can ensure secure product usage, preventing misuse. Generally, the (Re)utilization phase should be coupled with the Control phase (Bressanelli *et al.*, 2018).

Control: Parallely to the (Re)utilization process, specific control measures are necessary to assess the product, for example, in terms of its quality status (Ranta *et al.*, 2021) or location (Ingemarsdotter *et al.*, 2020). Companies can capture operational data during product usage through suitable data analysis methods and blockchain technologies and draw conclusions about the product's stress (Kouhizadeh *et al.*, 2020; Bressanelli *et al.*, 2018). This enables an estimation of which components may need refurbishment and which can be directly reused. Particularly in the context of a sharing economy, Track-and-Trace technologies are essential to locate the product and potentially transfer it to other customers (Balder *et al.*, 2023).

After Sales / Service: Based on the (Re)utilization process and appropriate control measures, companies can offer customer-specific services to extend the product lifespan or usage. These services may include repair services, innovative upgrades (Cagno *et al.*, 2021) for additional features (Ingemarsdotter *et al.*, 2020), or replacement parts. Automated repair offerings in the form of *predictive maintenance* not only provide additional value to the customer but also extend the product lifespan, thereby increasing the value of the resources employed (Bressanelli *et al.*, 2018). Furthermore, additive manufacturing contributes to the production of no longer available spare parts (Cagno *et al.*, 2021).

4.3 End of Use

Once the customer no longer needs the used product, the product enters the End of Use phase. In essence, the End of Use phase encompasses all product processes necessary to prepare a product for another lifecycle. This includes the return of products, quality checks, and the specific refurbishment of individual components and products.

Incentivization: In the context of incentivization, an exchange occurs between the customer and the company or another agreed-upon entity. The conditions for the return are either individually worked out or contractually established at the time of purchase (Jensen *et al.*, 2023). Incentivization can take a monetary form, such that the customer receives a discount from the company for returning the product. If ownership remains with the company, a defined contract duration, for example, dictates how long the customer can use the product (Bressanelli *et al.*, 2018).

Reverse Logistics: The product must also be returned from the customer to the company. There are possibilities for the customer to proactively initiate the return, engage an external service provider, or for the company to provide its own resources to collect the product from the customer (Stratmann *et al.*, 2023; Cagno *et al.*, 2021). Digital technologies such as Track & Trace or RFID technology have proven effective in tracking the location of a product, allowing companies or service providers to plan corresponding transport routes (Cagno *et al.*, 2021; Ingemarsdotter *et al.*, 2020).

Quality Verification: At the core of the quality verification process is determining product quality and functionality. This is a decision point for identifying which components can be exchanged or reused. By analyzing data during the usage, initial conclusions about the quality condition of individual components can be drawn. In the future, the functionality can be viewed in the digital product passport (Jensen *et al.*, 2023). However, data transparency and exchange are necessary, which can be realized through solutions such as Blockchain or IoT (Kouhizadeh *et al.*, 2020).

Disassembly: If only singular components are chosen to be reused, the product must be disassembled into its assemblies. Accessibility of the assemblies is a crucial requirement for this process. The disassembly process can be automated and standardized, for example, through robotic solutions (Cagno *et al.*, 2021).

Revaluation: The conclusion of the End of Use phase is the revaluation process. At the core of this phase is reconditioning reusable components or products. The components or products are processed according to the company's quality requirements (Andersen and Halse, 2023; Neri *et al.*, 2023). Depending on the defined direction, the processed components or products are re-entering different phases of the BoL and MoL.

4.4 End of Life

In cases where the functionality or quality of the product is not suitable for reuse, the product enters the End of Life phase. This phase is primarily characterized by the **product's incineration and/or disposal**. Depending on the product's design, components may be incinerated, for example, to generate thermal energy for the company's production. The disposal process is the final stage of the product's life cycle. When reuse or incineration is not possible or appropriate, the disposal process becomes critical (Wu and Pi, 2023). It involves the responsible disposal of the remaining parts of the product in an environmentally sound manner. This could include measures to minimize any potential environmental harm, such as proper waste treatment methods or compliance with electronic waste disposal regulations in the case of electronic products. The aim is to reduce environmental impact and contribute to sustainable waste management practices (Andersen and Halse, 2023).

4.5 Product Lifecycle Model for a digitally enabled circular economy

Building on the extracted phases and processes of the product life cycle for the digitally enabled circular economy, the following section translates the identified phases and processes into a comprehensive product life cycle model. The individual processes are organized in a logical sequence, and various possibilities for implementing specific R-principles are highlighted. The following Figure 5 visualizes the resulting model.

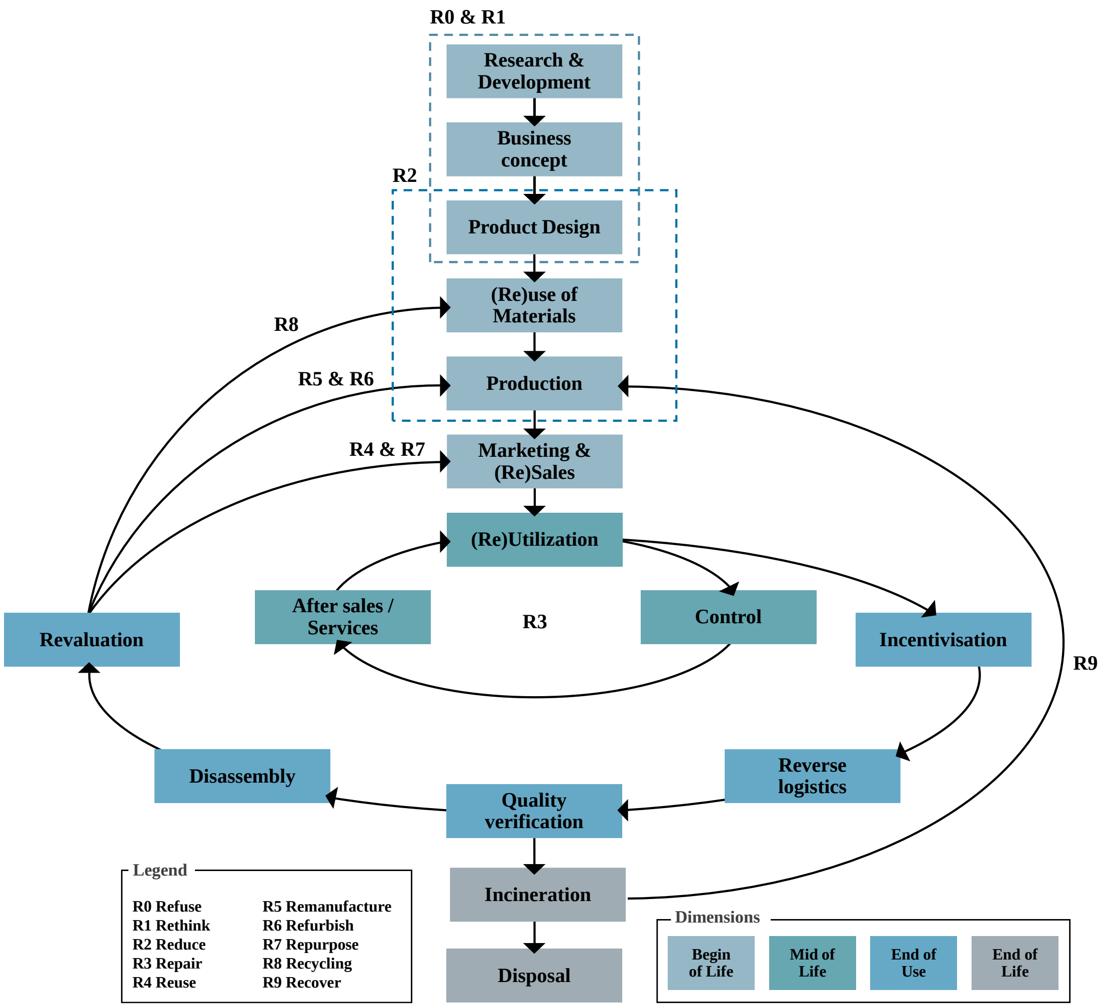

Figure 5: Product life cycle model for a digitally enabled circular economy

The processes outlined in Begin of Life are sequentially traversed, illustrating the conventional approach to product development. The R-principles Refuse and Rethink can be assigned to the research & development, business concept, and product design processes. These more strategically oriented R-principles significantly impact the implementation of each process. In the research & development process, new and innovative product ideas, for example, through the combination of different product functions (Refuse), can be developed and concretized through the development of the business concept and product design. The R-principle Reduce essentially interacts with the processes of product design, (re)use of materials, and production. Within these processes, companies have influence over reducing, for example, the materials used. With the sale and distribution of the product, there is a phase shift from BoL to MoL. The processes (Re)utilization, control, and after sales/services are carried out almost simultaneously in a cyclical manner. The operating condition is monitored during the product's use, and relevant services are offered if necessary. This iteration between processes continues until the decision is made to no longer use the product in the (Re)utilization process. The subsequent End of Use phase is a transitional process to operationalize the return and reuse of products or components. After the retrieval processes (Incentivisation and reverse logistics), the quality verification process acts as a decision point. If the product can be reused, the disassembly follows; otherwise, the product is transitioned to EoL. Following the disassembly, the revaluation of individual components or products occurs. Depending on the specific implementation of an R-principle, the return of components or products occurs in different processes of BoL. If a product is entirely reused (Reuse and Repurpose), it is transitioned to the marketing & (Re)sales process. When components are exchanged or reused, they are returned to production. In the case of material reuse, the used material, such as recycled material, is returned to the (Re)use of materials process.

5 Discussion and Conclusion

This paper presents a comprehensive model of the product life cycle for the digitally enabled circular economy. A total of 16 processes in four phases (BoL, MoL, EoU, and EoL) were extracted from relevant literature and amalgamated to depict the fundamental processes of the product life cycle. Additionally, the influence of digital technologies on these processes was examined in response to the third research question. Compared to the state of the art, the product life cycle model presented here offers a comprehensive view of the phases and processes relevant for the operationalisation of a circular economy. By adding the End of Use phase, the transition from the MoL phase is concretised by the necessary remanufacturing processes. The product lifecycle model thus clarifies which processes are necessary for the reuse of products and components, without assigning them to the EoL of a product. In addition, the visualized streams highlight different options for implementing specific R-principles. The influence and possible applications of digital technologies within the described processes are also illustrated. The use cases identified and analysed are used as examples to show which digital technologies are already being used in the circular economy. Further findings from the data analysis and the limitations of the paper are explained below.

Benefits and Limitations

From a research perspective, the product life cycle model provides a comprehensive understanding of the stages and processes involved in a circular product. Particularly noteworthy is the holistic yet specific approach to product lifecycle processes. In contrast to the state of the art, this model serves as a basic framework for more in-depth analyses of individual processes within the model, providing researchers with a basis for deriving further insights into the practical implementation of the circular economy. Existing models often focus on specific stages or implementation options, such as recycling. By linking individual processes to the R principles, a generalised approach has been derived. In addition, the inclusion of digital technologies highlights areas where optimization opportunities exist within specific processes, contributing to a more nuanced understanding of the interplay between circularity and digitalization.

For industry stakeholders, the model serves as a valuable tool to structure and understand the intricacies of the circular economy. The detailed breakdown of each phase and illustrative examples of how digital technologies can be applied provide companies with actionable insights. This enables companies to draw inspiration for future circular economy initiatives and promotes a strategic approach to integrating circular principles and digital innovation into their operations.

However, the paper presented here has some limitations. It should be noted that the defined search string focused on already implemented practical applications for a circular economy. This means that the theoretical influence of digital technologies on the individual processes is not fully addressed. In addition, the product lifecycle model was derived from the literature. Although the focus was on realised use cases, an industry-related validation of the whole model is necessary and will be considered in future research. Furthermore, the paper focuses on the integrative view of the circular economy and digitalisation. It would therefore be useful to examine whether the model can also be applied to products without the use of digital technologies. The limitations described above give rise to three research questions that should be addressed in future work:

What digital technologies fundamentally impact the implementation of the circular economy?

Can digital technologies create added value throughout the product life cycle, or are they only beneficial in specific processes?

Can the outlined product life cycle model be applied to all products (including non-digital ones)?

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