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Generic Product Lifecycle Model: A Holistic and Adaptable Approach for Multi-Disciplinary Product–Service Systems

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Featured Application: The generic Product Lifecycle (gPLC) model supports stakeholders in bridging the intrinsic perspective of Product Creation with the sustainability-oriented drive of Circular Economy—creating value for manufacturers and consumers/users as well as for recyclers and society. Three industrial application cases of product–service systems based on multi-disciplinary material core products are presented: innovation for predictive maintenance and repair of aircraft parts, engineering decision support with regard to automotive parts, and material circularity at a large sugar fabrication company, targeting material and energy recovery.

Abstract: The linear economic model behind contemporary product lifecycle representations contradicts planetary boundaries and the idea of sustainability. At the same time, Circular Economy (CE) driven models lack consideration of profound technological insights. Based on observations in research and the application of projects of different industries, a quantitative and qualitative literature analysis is applied to identify both strengths and shortcomings of current lifecycle models. These findings are used to create lifecycle model portfolios and to derive a generic Product Lifecycle model (gPLC). The gPLC is validated by three industrial cases based on collaborative research projects. In practice, resource and energy consumption as well as waste production and emissions can be minimized with the help of established methods not only by economists, but also by engineers. Transparency of material and information circularity practically implies the opportunity to implement, for instance, Minimum Viable Products and DevOps approaches. The originality of the gPLC is characterized by three main aspects: first, material and information flows of multi-disciplinary product–service systems are recognized as the foundation for a modern CE; second, a differentiation between product classes and instances is elaborated to stimulate sustainable design of material core products and digital CE business models; and third, the stakeholder perspective is expanded from manufacturer and consumer/user to further perspectives, such as recycler and society.

Keywords: product lifecycle; system lifecycle; lifecycle management; circular economy; product-service system; multi-disciplinarity; product classes and instances; closing material and information loops

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1. Introduction

In reviewing prevailing strategies on future challenges and opportunities in Product Creation and innovation management, lifecycle aspects appear as a topic in many cases. Perspectives cover, for instance, digital business models based on fundamentals of data science, smart manufacturing and Integrated Product Development as well as Product and System Lifecycle Management (PLM/SysLM). Circular Economy (CE) was established as a term to represent the vision of treating circularity as a business opportunity, proposed in the early 1990s [1] and evolved throughout decades [2,3]. Nonetheless, all of these studies and publications are focused on specific aspects and perspectives. For instance, while CE integrates strategic planning and material flows, these established CE models do not consider established engineering methodologies. D'Amato et al. [4] review an extensive list of literature, focusing on links between green economy, bioeconomy and CE. Lifecycle aspects are only touched upon indirectly as a label for clustering, built by Latent Dirichlet Allocation. Guan et al. [5] focus on closed-loop Supply Chain Management (CLSCM). Search terms are limited to CLSCM, resulting in valuable but specific references to Supply Chain Management and logistics. Lopes and Farinha [6] contribute a special perspective on Industrial Symbiosis, identifying that this perspective on bridging industries in late lifecycle stages is essential but missing. Nunez-Cacho et al. [7] provide a valuable perspective on CE challenges and opportunities for family-owned enterprises. In all of these studies, the intrinsic perspective of Product Creation is not elaborated. This subsumes terms such as design, planning, engineering and Product Creation, which are not used as search terms and only partially considered in the analysis. Therefore, the benefits created over years of engineering design research and corresponding practical outcomes established in production companies are not utilized.

Vice versa, intrinsic product lifecycle models focus on value creation for enterprises, consumers and users, but neglect possible strategic benefits of late lifecycle phases. Approaches such as sustainable product development [8] adopt this perspective but are not sufficiently detailed to be practically implemented. Kozma et al. [9] are motivated by a similar deduction from the literature, focusing specifically on information technology. Frameworks such as ITIL and COBIT are core elements of their references. By adopting a perspective on product lifecycle, including Beginning of Life (BoL), Mid of Life (MoL) and End of Life (EoL), they consolidate findings of their literature review. In the building industry, Nunez-Chaco et al. [10] emphasize the importance of CE. Rahla et al. [11] provide conclusions for closing material and components loops. They emphasize the relevancy of data and Design-for-CE approaches regarding the long-lasting perspective in building lifecycles. Narrowing down the perspective on Product Creation, CE-related approaches are often focused on the circularity of resources in production. Researchers such as Bjørnbet et al. [12] as well as Lieder and Rashi [13] contribute extensive literature analysis results to frame CE in this context. Direct links to early phases of Product Creation are not considered, neither as search terms nor as the focus of their discussion. Rosa et al. [14] specifically focus on the relation of CE and Industry 4.0 in the literature. Like in other publications, planning and engineering are not considered core topics. As they search for literature related to certain technologies, such as Augmented Reality, there might be hidden links into these early phases of Product Creation. Eigner [15] puts forward a promising approach evolving Product Lifecycle Management (PLM) into Systems Lifecycle Management (SysLM) for mechatronic and cyber–physical systems.

Indications observed in overarching publications are supported by various research and application projects of different industries. Three projects shall be referenced as examples here. The European collaborative project RepAIR analyzed the potential of combining predictive maintenance tools and Additive Manufacturing as a technology to repair aircraft parts. Gaps in technology and information processing are still identified as barriers to step beyond for maintenance, repair and overhaul (MRO) optimization toward CE. As a second example, the German collaborative research project OptiAMix aimed at multi-criteria decision support for engineers designing parts and optimizing for the flexible process planning. Varying lot sizes are considered along the product lifecycle in the automotive industry. In a third bilateral research project with the company Nordic Sugar, the focus lies on fabrication of sugar products to be consumed. The fabrication process has been established for decades, but innovation is nevertheless realized across yearly campaigns. As an example, the company utilizes side products for in-house energy supply. Therefore, the focus on material flow is complemented by the perspective of energy consumption.

Motivated by these observations in literature and applications, the objective of the article at hand is to present a holistic and adaptable approach for multi-disciplinary product–service systems. Section 2 presents the research design, which is based on quantitative and qualitative literature research. Section 3 presents the results of the analysis focusing on specific, integrative and cross-cutting lifecycle perspectives. Two lifecycle model portfolios are derived from the stated findings of quantitative and qualitative literature analysis in order to compare and correlate results. Building up on these analysis results, the generic Product Lifecycle (gPLC) model is presented as a result of model synthesis. The project examples mentioned above are used for the validation of the gPLC in specific application cases. The results are reflected in the discussion of Section 4. Section 5 presents conclusions and future research directions.

2. Materials and Methods

The primary perspective is based on the intrinsic lifecycle view of the Product Creation process from product ideas resulting from strategic planning to going through engineering, realization into operation and decommissioning. Corresponding perspectives are applied to multiple disciplines that are required to create mechatronic and cyber-physical systems or even bundle them with services into innovative business models. Additionally, the perspective is focused on products and services within the scope of CE. Thus, they include a material core product with material flows. For instance, pure software/service bundles are only considered as a contribution to the larger perspective on product–service systems. The research question is the following: which elements are required in a generic Product Lifecycle model to bridge the intrinsic perspective of inter-disciplinary Product Creation with circularity according to CE? Figure 1 presents the research approach, which is designed as a systematic review based on Petticrew and Roberts [16]. The research landscape is first analyzed by means of a quantitative literature analysis used as a type of scoping review. For this purpose, search terms are derived from high-level publications of governments and the European Commission as well as observations from various research and application projects of different industries. Based on these results, the selection criteria are specified to ensure relevancy of the included studies [17]. Additionally, forward search through references in high-level publications is applied to identify the relevant literature. In this step, it was obvious that the initial focus on journal papers needs to be extended to monographies cited by authors from the subject areas involved. The findings are reflected, as recommended by [16,17], based on active technical committees in the German association of engineers (VDI). Due to the fact that the research question addresses content elements to be included in an integrative model, semantics are analyzed in terms of a narrative review reported in a structured way by portfolio visualization. Synthesis is realized by combining elements of the established lifecycle and CE models in a deductive way (cf., for instance, Kjaer et al. [18]).

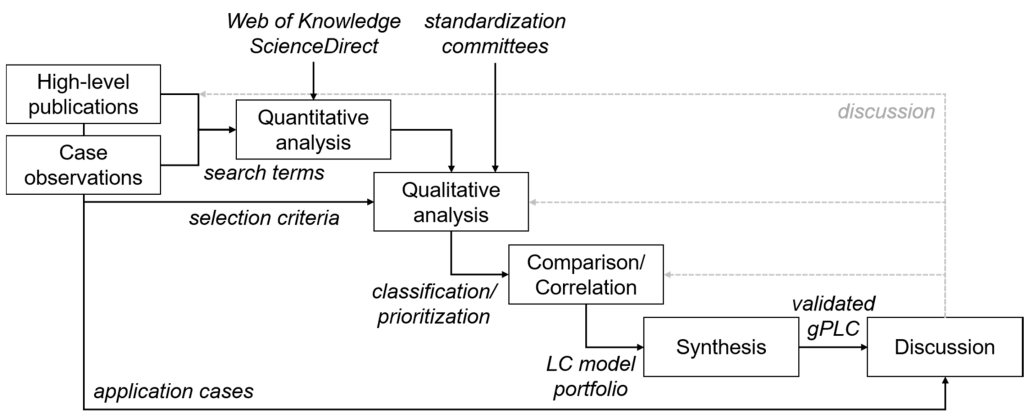


Figure 1. Literature-based research approach.

For the scoping review, search terms are structured into search vectors, multiplied by cross product and applied to different search portals (ScienceDirect, Web of Knowledge). Vectors are presented in braces in first columns of Table 1 (upper part):

- Search term vector TS 1.1 (cross-product): {lifecycle, life cycle} × {circular} × {engineering, planning, design};
- Search term vector TS 1.2: {product, system, plant, asset, software};
- Search term vector TS 1.3: {*, literature}.

Table 1. Results of quantitative literature analysis (numbers finally updated on 2 May 2021, asterisk means wildcard).

Search Term			Web of Knowledge			ScienceDirect			
			1945–2021	Last 5 Years		Review Articles, Research Articles, Book Chapters		Review Articles	
TS1.1	**TS1.2**	**TS1.3**	**Total**	**Total**	**Highly Cited**	**1995–2021**	**Last 5 Years**	**1995–2021**	**Last 5 Years**
(lifecycle OR "life cycle") AND (circular) AND (engineering OR planning OR design)	product	*	371	324	8	14,662	8170	2204	1222
		literature	77	72	4	8751	5695	1516	1104
	system	*	321	276	8	18,273	9651	2604	1621
		literature	65	61	5	10,436	6476	1724	1215
	plant	*	61	52	1	9015	5128	1566	1054
		literature	6	6	1	5601	3566	1124	821
	asset	*	17	15	0	2121	1337	278	209
		literature	3	3	0	1530	1069	234	180
	software	*	25	21	0	7752	4630	689	499
		literature	6	6	0	4531	3125	556	419
TS2.1	**TS2.2**	**TS2.3**							
"lifecycle model" OR "life cycle model"	product	holistic	5	1	0	571	230	51	34
		generic	7	2	0	1140	77	305	31
	system	holistic	10	4	0	1284	85	341	33
		generic	15	7	0	638	58	255	36

TS1.1 sets the primary scope for the entire analysis. TS1.2 enables differentiation between subjects of the lifecycle perspective. TS1.3 checks for dedicated publications from the literature research, (secondary) literature analysis, etc., including the term "literature".

The analysis of publications indicated by the Web of Knowledge is focused on the last five years (since 2017). Highly cited publications are prioritized (ranked as "top 1% of their academic fields based on a highly cited threshold for the field and publication year"). Most appropriate results are Bakker et al. [19], Kjaer et al. [18], los Rios and Charnley [20], Merli et al. [21], Moraga et al. [22], Morseletto [23] and Urbinati et al. [24]. All papers provide a secondary analysis of relevant literature. In contrast to the paper at hand, they do not focus on consolidating different viewpoints into a generic Product Lifecycle approach.

ScienceDirect results can be narrowed down by including only review articles published since 2017 in the subject area "engineering", excluding publications on "building" (esp. building information modeling), i.e., the discipline of civil engineering. This simplification approach results in 46 papers that include the term "product" in TS1.2, 58 with the term "system" and further ones on "asset" (10), "plant" (29) and "software" (19). These papers are taken into detailed review. Due to the enormous number of heterogeneous results, a qualitative approach complements the study. This is initiated by specifically searching for lifecycle models aiming at an overarching level (see Table 1, bottom part):

- Search term vector TS 2.1: {lifecycle model, life cycle model}.
- Search term vector TS 2.2: {product, system}.
- Search term vector TS 2.3: {holistic, generic}.

Even with that specialization, the results are just embedding specific research into a wider context without dedicated methodical approaches. Usage of generic/holistic product lifecycle terms can be recognized mostly in motivation and introduction, but then the focus is shifted to specific aspects, such as sensors in Industry 4.0 networks or modelling aspects in Model Based Systems Engineering.

The results of this analysis are documented in the requirements cumulated from lifecycle models of all perspectives and in lifecycle model portfolios, covering the dimensions "means of Product Creation" (technical system, product-service system, further environment), "way of cross-linking lifecycle phases" (linear model, circle as a design element, circular model) and "degree of detail" (conceptual sequence, information flow, material flow). English results are validated by double-checking with corresponding German search terms. These foundations are reflected and generalized into an overarching perspective. The synthesis subsumes the following:

- Integrating core elements of complementary models.
- Contextualizing lifecycle phases regarding different perspectives.
- Visualizing both sequential dependencies and circularity (focusing on data/knowledge and products/material).
- Providing means for adaptation/tailoring.

The gPLC model is validated by retrospective application to the three cases carried out by the authors and introduced in Chapter 1: The RepAIR case [25], the OptiAMix case [26] and the SugarFab case [27]. Characteristics are documented in Table 2.

Table 2. Application case characteristics.

Application Case	Dimensions	Characteristics
RepAIR case	Domain	aeronautics
	Stakeholders	OEM [1], MRO [2] service provider, suppliers, machine manufacturers, IT service companies, QA [3] experts, predictive maintenance experts
	Product/Service	metal bracket of aircraft turbine: original part, repair process, spare part
	Material circularity	Repair
	Information circularity	RUL [4] estimation, predictive maintenance, decision support
OptiAMix case	Domain	Automotive
	Stakeholders	engineering services, third party manufacturer, IT service companies, decision support experts
	Product/Service	rear wing holder for luxury sports cars
	Material circularity	Anticipation of material flow
	Information circularity	Design guidelines based on aggregated digital twins, business model alternatives
SugarFab case	Domain	food
	Stakeholders	sugar fabrication company, farm cooperative
	Product/Service	sugar products for end consumers and for food industries
	Material circularity	Beets, energy from side-products in fabrication, package waste
	Information circularity	Supply chain from beet fields to warehousing and outbound logistics, intelligent process control

[1] OEM: Original Equipment Manufacturer; [2] MRO: Maintenance, Repair and Overhaul; [3] QA: Quality Assurance; [4] RUL: Remaining Useful Lifetime.

These cases are selected due to the complementary characteristics. First, they cover complementary domains. In aeronautics (RepAIR), products are engineered for a long period of product life with corresponding MRO demands. For the OptiAMix case, automotive was chosen out of several project case studies due to the relevancy as a B2C market with its outstanding dynamics. The SugarFab case is focused on continuous fabrication instead of discrete product instances. Second, different stakeholders and different types of product/service bundles were an essential requirement for case selection. As already mentioned, aeronautics and automotive have clear differences regarding customer characteristics. Consequently, cooperation is organized with different time horizons. With SugarFab, the involvement of a farm cooperative adds a very special aspect. Third, circularity is focused on material and information in all cases but with different balances in between. Issues and opportunities are reflected with regard to findings, portfolio analyses and bias of validation cases composed by these complementary characteristics.

3. Results

The results are sub-divided along the research approach presented in Section 2: results of the literature analysis (Section 3.1), interpretation of these results (Section 3.2) and synthesis, including application in three exemplary cases (Section 3.3).

3.1. Literature Analysis

Lifecycle models are differentiated with regard to their primary perspective. The literature can be categorized by three main categories with corresponding sub-categories. In the first category, specific perspectives are covered. These are focused on single disciplines or domains: systems (colloquial use is excluded from analysis), products, plants, material consumption/use, software, and services. Integrative perspectives already bring together at least two complementary perspectives. One example is the integration of product and plant lifecycles, and a second one is the integration of services with either material products or software. As a third category of perspective, there are cross-cutting topics, such as economics or ecology, which include CE, economics, information, technology and material. Results of the literature analysis are presented according to these three categories.

3.1.1. Specific Perspectives (Subjects)

Lifecycle perspectives are present in all disciplines that target technical solutions. In mechanical engineering, the main perspective lies in the Product Lifecycle: typical phases are product planning, development, realization, distribution, use and recycling [28,29]. Development covers both the development of the product and planning of the required production process to realize product instantiation. Beginning of Life (BoL) of an individual product instance is characterized by its production, Mid of Life (MoL) represents the use phase and End of Life (EoL) can be understood as a synonym for recycling [30]. Product Creation is starting with a clear product idea and development order [31,32]. The term is either used for the entire BoL [28] or covering the creation of the product definition exclusively, without execution of production [33]. These models are focused on product classes and production systems to instantiate them in terms of tangible manifestations. Product instances resulting from this production process are only implicitly assumed in the phase "manufacturing of parts" (see Figure 2a [31]). To enable production, plants have requirements according to their specific lifecycle perspective: design, building, ramp-up, operation and teardown [34]. Similar perspectives are stated for technical assets [35]. Instances are made from material, which are brought in as raw material or recycled from preceding products. Additionally, energy supply is an essential input (see Figure 2b [36]; cf. [37]). In software engineering, lifecycle phases range from specification, design, implementation, installation/deployment to use and removal [38,39]. Specific attention is paid to the continuous evolution of software products during their lives [40,41] (see Figure 2c). Another specific perspective is defined for services: service lifecycle phases cover service planning, design, implementation, delivery and decommission [42]. Focusing on learning aspects throughout service life, overarching phases of service design (before implementation) and service management can be differentiated [43] (based on [44]).

From these models presented in very brief summaries, several findings are deduced that have to be considered when integrating disciplines and domains.

Finding 1. *All specific perspectives are focused on value creation as a key objective.*

Lifecycles are triggered by problems, needs or tasks. Material core products, services and software are engineered single-, inter- or multi-disciplinarily and realized to provide value in the operation phase. In CE, even the EoL phase is viewed from the perspective of value creation. Extending that perspective to sustainability, value is envisioned with respect to economics, ecology and society.

Finding 2. *Models are visualized either by cycle or chain metaphor.*

Cycles as such are highlighted in some of the models, chains are often used for the purpose of simplification. In many cases there is no clear indication whether the visualization is dedicated to logical, information/material flow or temporal dependencies.

Finding 3. *Focusing on different disciplines, a transparent differentiation of product classes and instances is essential. Especially when it comes to material, volumes are important in phases focused on product instances.*

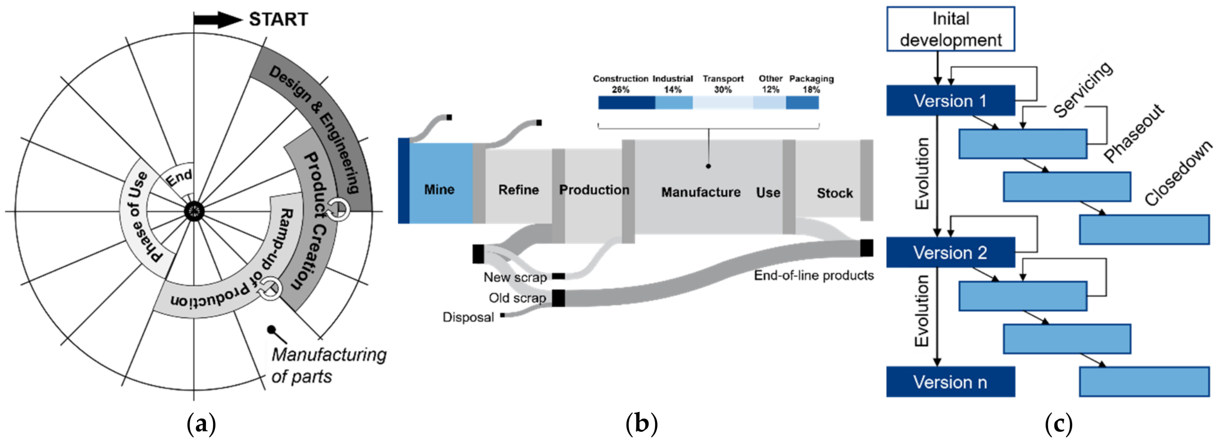


Figure 2. Specific perspectives of the product lifecycle: (**a**) intrinsic product lifecycle focusing on product development, production and use (based on [31]); (**b**) material lifecycle emphasizing volumes of material use in product lifecycle phases (see [36]); (**c**) software lifecycle illustration focusing on continuous evolution and resulting branches (based on [41]).

Analogous to product modeling, the specification of product classes is the required basis for instantiation in terms of individual product instances. This is a prerequisite to deal with the circularity of resources, i.e., material and information. In the case of material core products, instantiation takes place during production. Based on the product class specification and out of the delivered source material (raw and/or recycled), individual product instances are manufactured and assembled. In the case of software, instantiation happens with its installation, deployment or activation. When the user installs software (product class) on an IT device, a corresponding identifier can be assigned, representing the created individual product instance. Nowadays, the internet enables tracking such instances.

Finding 4. *While logical alignment is the primary objective, temporal alignment has to be treated as secondary but obligatory objective.*

While, for instance, software engineering can be conducted based on standard development environments, entire production systems and plants need to be built to realize material core products. Phase durations might range from a magnitude of months in development through years in (series) production and up to decades in product use. When trying to derive an abstraction of different disciplines, commonalities can be identified in strategic planning and early engineering phases, while differences occur in discipline-specific engineering, and especially in realization.

3.1.2. Integrative Perspectives

Focusing on material core products, integrative product–production perspectives [45] are established, bridging two academic communities as well as department boundaries in companies. The focus in the literature is set to production issues, such as land allocation, building, plant and production systems [34,46]; the product lifecycle crosses the production or plant lifecycle in the production phase [33,43,47]. This is supported by intense studies on standardization of smart manufacturing (see Figure 3a [48]; cf. [49]). This perspective is taken up with regard to the Digital Twin [50] (cf. [51]): as a digital representation of the current state of a physical product, it integrates data from development (digital master), production and use (digital shadow). It is also seen as an enabler for the integration of physical products and services. Even though services can be treated as products, a differentiation seems reasonable for the purpose of clarity. Hence, a product–service system consists of "tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs" [52] (cf. [53]). Both parts have to be considered with their specific lifecycles (see Figure 3b [54]). This approach can even be deepened when considering varying perspectives along the intrinsic product lifecycle: there are specific cycles in each phase (Figure 3c, highlights lifecycle data integration [55]).

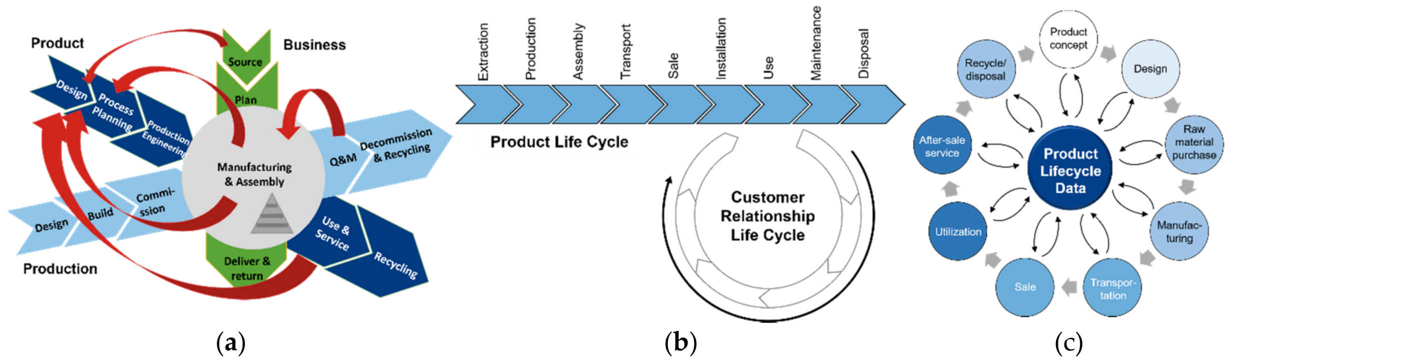


Figure 3. Integrative perspectives of the product lifecycle: (**a**) product, production and business perspectives represented by chain-like lifecycle visualizations (detailed in [48]); (**b**) product and service lifecycles integrated into product–service systems (adopted from [54]; (**c**) integrative view with macro-cycle and internal micro-cycles in each phase enabling Smart Manufacturing (based on [55]).

Again, several findings are deduced, which have to be considered with regard to the integration of perspectives.

Finding 5. *Lifecycle models need to be based on information circularity to utilize data science potentials and to enable knowledge management across cycles.*

Harmonization of terminologies is key to integrate data, models and processes. Integration is enabled by different methodologies in early phases (such as Integrated Product Development, Simultaneous and Concurrent Engineering). In these methodologies, lifecycle issues need to be incorporated. Consideration of different stakeholders is required, being responsible for or affected by different perspectives and phases.

Finding 6. *Realization is identified as the integrative phase, which (a) is to be prepared in engineering and (b) builds up the prerequisites for creating value.*

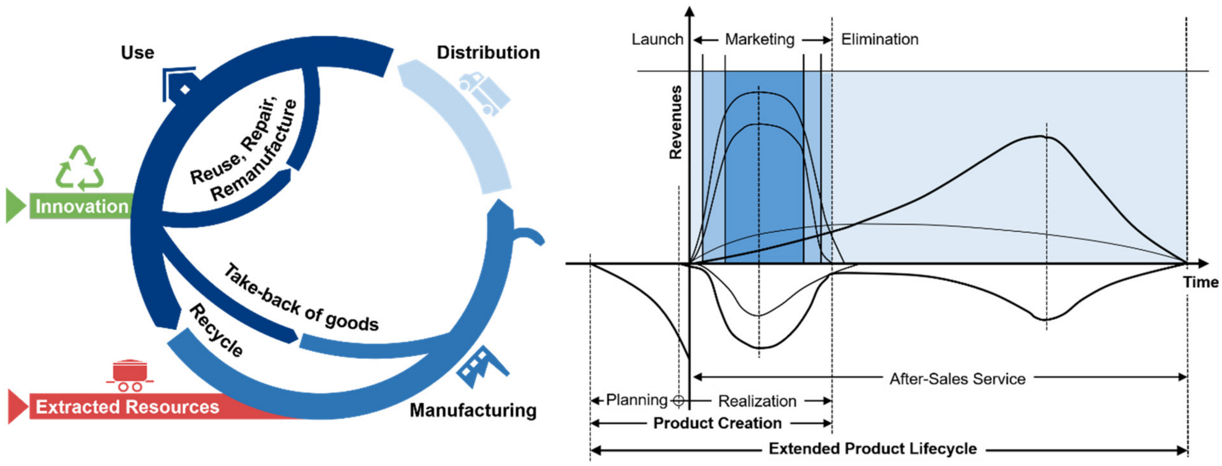
As soon as crossings are highlighted, models are often visualized using the chain metaphor instead of a circular representation. Integration is manifested in terms of product types, such as mechatronic products, cyber–physical systems and product–service systems. Thus, the view on integration as an intersection of perspectives is key for a comprehensive understanding of material and information flow when instantiating product instances from a product class. Therefore, the type of product characterizes the required lifecycle perspectives.

Finding 7. *When integrating perspectives, logical and temporal integration is required.*

While cycles are often idealized in a way that a new cycle starts after the End of Life (EoL) of an entire product class, new cycles are typically initiated in parallel to a preceding cycle (cf. technology S-curves [56]). This view is often neglected by abstract lifecycle views.

3.1.3. Cross-Cutting Perspectives

Cross-cutting perspectives are motivated by generic system theory. Product lifecycles are based on cognition—leading to invention—utilized for innovation and brought into use by diffusion [57]. The concept of CE emphasizes the benefits that can be gathered from EoL: while value creation is typically focused on engineering, production and use/operation phases, business models shall even cover the recycling phase in future. Thus, sustainability is ensured not only by policy making, but with its intrinsic business value. For sustainability, circular material flow is essential. Different recycling options can be scheduled in early product development phases, but innovation is also possible in later phases (see Figure 4a [58]). For instance, new repair technologies can be applied for cars (product instances) in their use phase, which are not yet available in development times (when the product class is specified). For the EoL phase, several frameworks are conceptualized to cover options from the reuse of products to recovering material for energy generation [59–61]. The differentiation of product class and product instances is implicitly assumed in some economic models. Basic models are provided in strategic management [62,63]. They are focused on economic factors, such as turnover and profit, which are driven by the number of product instances. Assuming combined product and service offerings, the temporal differences are obvious: while at the end of production the delivery of new product instances to customers stops, services are still delivered with respect to product instances in operations (see Figure 4b [64]). This phase can be significantly longer than the BoL phase; product owners might change and instances might be subject to change [65]. Thus, the enabling of innovation in MoL and EoL phases is a challenge, as is opportunity in early phases (anticipation of "to-be" product life) and "as-is"/"as-was" information in later phases of system lifecycle management [66].



(**a**) (**b**)

Figure 4. Cross-cutting perspectives of the product lifecycle: (**a**) material flow in Circular Economy with innovation opportunities along all lifetime phases (based on [58]); (**b**) economic perspective of product–service systems, highlighting temporal effects of Product Creation (time of series production) and continuation of service in after-sales (based on [64]).

The following requirements add up to the items mentioned in Sections 3.1.1 and 3.1.2:

Finding 8. *Targeting Circular Economy, circularity needs to be understood as the macro-perspective of a product lifecycle, its information and its material.*

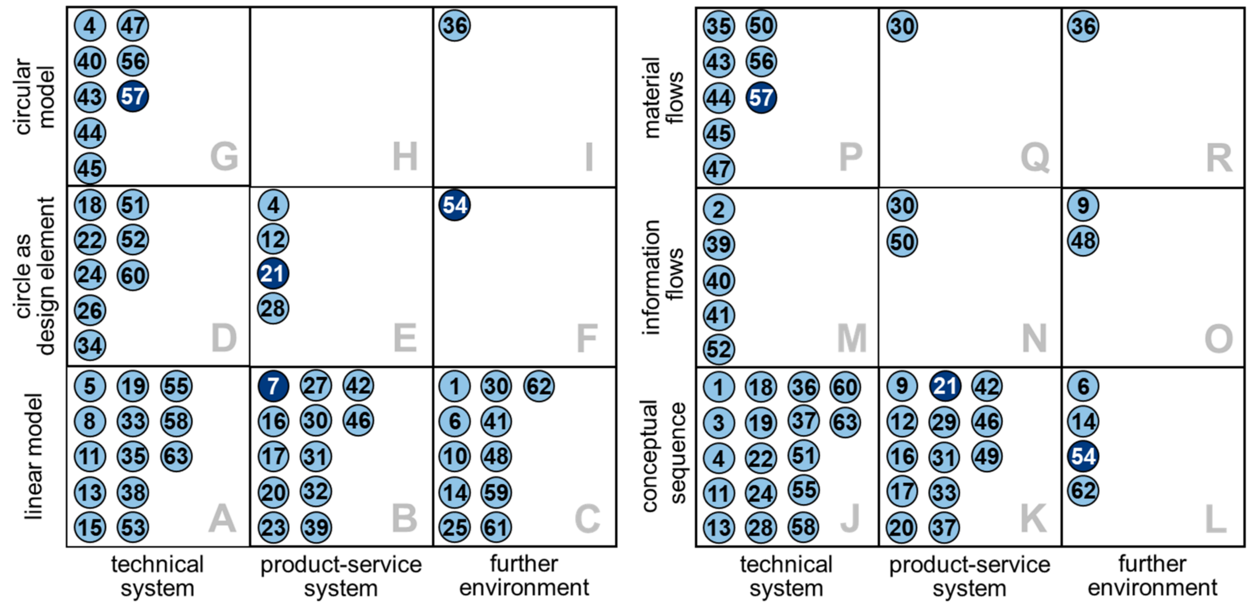
Sustainability as a relevant requirement needs to be implemented into all other perspectives aligning toward Circular Economy, incorporating "sustainable thinking" into business models targeting business opportunities, even in the EoL. Setting anchoring points or cross-cutting topics, such as innovation management, technology management, material development, enables contribution from enabling fields.

Finding 9. *The intrinsic perspective needs to be complemented by the economic perspective from business modeling to market saturation that correlates with the number of product instances.*

With respect to product classes, an intrinsic definition of phases from product ideas to recycling is reasonable (cf. Section 3.1.1). Investments are taken as long as a product class is developed, and realization is prepared. Return of investment starts with realization of product instances and delivery of services.

3.2. *Comparison and Correlation*

In the following section, two portfolios are derived from above-stated findings of the literature analysis in order to compare and correlate results (Table 3, Figure 5). In combination, they give a complete overview of relevant characteristics for the pursued objectives (Findings 3, 8, 9). Technical systems (Finding 6: need for engineering), product service systems and further environment are considered means of value creation (Finding 1) in both portfolios and, therefore, span the abscissa. As multi-disciplinarity is implicitly assumed but not concretized in many approaches, no further separation into single- and multi-disciplinary technical systems is taken. Product–service systems represent a combination of material core products with affiliated services during operations [52]. Although "further environment" is not relevant to the problem at hand in the narrow sense, it allows a view beyond the horizon. Thus, it forms a basis for the plausibility check. It extends value creation to the life cycles of, for instance, assets, factories, buildings or even food production. The compared lifecycle models are numbered uniformly in both portfolios in chronologic order and mapped to the references listed in Table 3.



(**a**) Portfolio 1 (**b**) Portfolio 2

Figure 5. Lifecycle portfolios focusing on technical systems, product–service systems and further environment with regard to product classes (light blue dots) and including instances (dark blue dots): (**a**) categorization differentiating linear and circular models; (**b**) categorization differentiating purely conceptual sequence models and models with specific focus on either information or material flow.

The ordinate of portfolio 1 (Figure 5a) is spanned by way of cross-linking life cycle phases among each other, and it represents the historical evolution from linear to circular modeling (Findings 2, 5). The representation of lifecycles in a linear form reflects the currently still prevailing principle of the linear economy or throwaway economy. Raw materials are used to manufacture products that are disposed of in landfills or incinerated after use. Only a small percentage is put to reuse. This linear economic model contradicts planetary boundaries and the idea of sustainability. However, the objective of modern CE is to minimize resource consumption, waste production, and emissions as well as energy waste. Energy and material cycles are slowed down, reduced and closed for this purpose. This can be achieved through design for durability, maintenance, repair, reuse, remanufacturing, refurbishing and recycling [67,68].

Figure 5a shows that linear lifecycle models are still prevailing. They are applied to technical systems (field A), product–service systems (field B) and further environment-emphasizing production systems (field C). Besides mechanical products, further single disciplines are taken into account. For example, Zarnekow et al. assign tasks of integrated development of IT services to lifecycle phases in a linear model [69] (13 in field A). "Circles as design element" (fields D, E, F) are a preliminary stage of circular lifecycle models, as they use the circular shape as a metaphor, but in terms of content they still adhere to a linear sequence of lifecycle phases. Circular lifecycle models primarily represent material flows (field G). Only Wellsandt et al. [30] (40 in field G) focus on information capture about product use and Hubka et al. [29] (4 in field G) represent information flows along the product life but neglect material flows. The approach of the Ellen MacArthur foundation [59] (36 in field I) comprises the consumer and user's viewpoints and thus, even includes food production. Whereas several product life cycle models for product–service systems already use circles as design elements (field E), there are no detailed circular approaches for technically demanding multidisciplinary systems available (fields G, H).

Table 3. Chronological listing of lifecycle identified in literature.

No.	Authors	Ref	No.	Authors	Ref	No.	Authors	Ref
1	Grant 1991 (2002)	[70]	22	Schatten et al., 2010	[71]	43	Stahel 2016	[58]
2	VDI 2243:1993	[72]	23	Arnold et al., 2011	[73]	44	VDI 4800:2016	[74]
3	VDI 2221:1993	[75]	24	Balzert and Liggesmeier 2011	[38]	45	Bauer et al., 2017	[61]
4	Hubka et al., 1996	[29]	25	Diedrich et al., 2011	[76]	46	Dang 2017	[77]
5	Rajlich et al., 2000	[41]	26	Goll 2011	[39]	47	European Union 2017	[37]
6	Wirth et al., 2000	[78]	27	Meier et al., 2012	[79]	48	Lin et al., 2017	[51,80,81]
7	Schimmelpfeng 2002	[35]	28	Meier et al., 2012/2017	[82]	49	Meier et al., 2017	[82]
8	VDI 2243:2002	[83]	29	Freitag et al., 2012	[84]	50	Nußholz 2017	[85]
9	Meier 2004	[86]	30	Hepperle 2013	[43]	51	Bracht et al., 2018	[31]
10	Schenk and Wirth 2004	[34]	31	Laurischkat 2013	[87]	52	Tao et al., 2018	[55]
11	Abele et al., 2005	[88]	32	Thomas and Nüttgens 2013	[89]	53	VDI 4801:2018	[90]
12	Tan et al., 2006	[54]	33	Porter 2014	[91]	54	Wiktorsson et al., 2018	[46]
13	Zarnekow et al., 2005	[69]	34	Vajna 2014 (2020)	[92]	55	Hastenteufel et al., 2019	[40]
14	Westkämper 2008	[93]	35	Vielhaber and Stoffels 2014	[94]	56	Klenk et al., 2019	[68]
15	Hulvej 2008	[95]	36	E. MacArthur Fdt. 2015	[59]	57	Raabe et al., 2019	[36]
16	Becker et al., 2009	[96]	37	Helu and Hedberg 2015	[97]	58	Schleich et al., 2019	[98]
17	Eigner et al., 2009	[33]	38	Lehmhus et al., 2015	[99]	59	Tao et al., 2019	[100]
18	Robin et al., 2009	[66]	39	Lu et al., 2015	[101]	60	VDI 2221: 2019	[28]
19	Ropohl 2009	[57]	40	Wellsandt et al., 2015	[30]	61	Güntner et al., 2020	[102]
20	Aurich et al., 2010	[103]	41	Lu et al., 2016	[101]	62	Neuhäuser et al., 2020	[104]
21	Blinn et al., 2010	[64]	42	Mahut et al., 2016	[42]	63	Yousefnezhad et al., 2020	[105]

In addition to the lifecycle approaches illustrated in Figure 5, Ramaswamy presents the service lifecycle as a circle consisting of linear representations of service design and service management. However, he does not consider entire product–service systems and, therefore, is not included in the portfolios [43] (referring to [44]).

According to Finding 2 "Models are visualized either by cycle or chain metaphor", portfolio 2 classifies the lifecycle models' degree of detail (Figure 5b) from an overview illustration named "conceptual sequence" to a detailed model comprising information and/or material flows (Finding 8). The conceptual sequence includes both logical and temporal dependencies in the flow logic (Findings 4, 7).

Obviously, many conceptual sequences are found for all means of value creation: most apply to single-disciplinary or not further specified technical systems (field J), others apply to product–service systems (field K) and several to further environment (field L). Among these, only Eigner and Stelzer explicitly emphasize interdisciplinarity [15,33] (17 in field K). Their model comprises mechanics, electronics, software and even services. However, this approach serves as a visual model and, therefore, stays on a conceptual sequence level. Neither information nor material flows are concretized in detail. In sum, only few lifecycle models already address information or material flows (fields M, P, Q and R). Except for Hepperle 2013 [43] (30 in fields N and Q), no further lifecycle model addresses both linkages: information and material flows. Nevertheless, this approach represents a linear lifecycle model.

In addition to the structure of the portfolio, comparison and correlation of results is supplemented in both portfolios by color-coding lifecycle approaches. Thus, a consideration of the distinction between product classes and instances is made possible (Findings 3, 9): Those lifecycle approaches, which can be seen as preliminary stages of a product instantiation, are highlighted in dark blue. To conclude the results of comparison and correlation, the existing lifecycle models show the following deficits:

- Engineering-bound lifecycle models primarily comprise single-disciplinary products (exception: [15,33]) or make multi-disciplinarity not explicit.
- Business management-bound lifecycles for product–service systems do not address the specifics of technically demanding products, which is usually accompanied by multi-disciplinarity. As the model to be developed shall serve engineers as well as business economists, technical systems must not only be mentioned, but they need to be concretized in the way of their multidisciplinary interaction.
- No information- and material-flow-based view on Circular Economy of product–service systems incorporating multi-disciplinary material core products is concretized yet. However, this is needed to lay the foundation for a modern Circular Economy, minimizing resource consumption, waste production, emissions and energy waste. Further, the concretization of both information and material flows is a prerequisite for the development of new digital business models for CE.
- A full differentiation between product class and instance exists so far only in rudimentary form and has not yet been applied to the product life cycle of multi-disciplinary systems. This way, a sustainable design of material core products can be stimulated and a foundation for digital business models, Minimum Viable Products (MVPs) and DevOps for Circular Economy can be laid.
- Most existing approaches describe value creation from the manufacturer's point of view. Only a few lifecycle models take the consumer or user into account, such as [59]. The manufacturer's perspective is too narrow and needs to become expandable to further stakeholders, such as the user, consumer, recycler or society. This is due to the fact that different stakeholders have different views and interfaces to the same "thing" as outlined by Främling and Holmström against the backdrop of the Internet of Things [65].

The following research gap results from this comparison and correlation: a generic Product Lifecycle (gPLC) model is required, which details an information- and material-flow-based view on Circular Economy of product–service systems, incorporating multi-disciplinary material core products. Moreover, a differentiation between product classes and instances shall be torn, using techniques of product modeling. The model's perspective shall be open to different stakeholders. The stakeholders that must be regarded shall be decided in each specific application case.

3.3. Synthesis: The generic Product Lifecycle Model (gPLC)

Transferring the analytic perspective of the portfolios into a design oriented one, the results presented in Section 3.2 represent the basis of the gPLC. It is derived from the above-presented results (Figure 6). It serves as a model that has the following traits:

- intrinsic (based on the Product Creation process from classes to instances);
- circular (emphasizing material and information circularity);
- holistic (integrating single- and multi-disciplinary and cross-cutting perspectives);
- generic (applicable to a wide variety of specific industry branches);
- adaptable (providing handles to adapt inputs, phases and flows).

Product Creation is initiated by triggers, such as market pull, technology push or blue ocean strategies [106]. It is based on a company's knowledge base. In the initial step, a company brings in technology and competencies, which are available as as-is capabilities. In that process, technology management and competency management can be connected to the gPLC in order to conceptualize the development of to-be capabilities. Five phases can be identified in manifesting the product lifecycle for multi-disciplinary product–service systems: strategic planning (linking enterprise management and product planning), engineering (subsuming systems and disciplinary engineering), realization (including production and preparation of services), operation and service delivery (from basic services like maintenance to digital business models) and decommissioning.

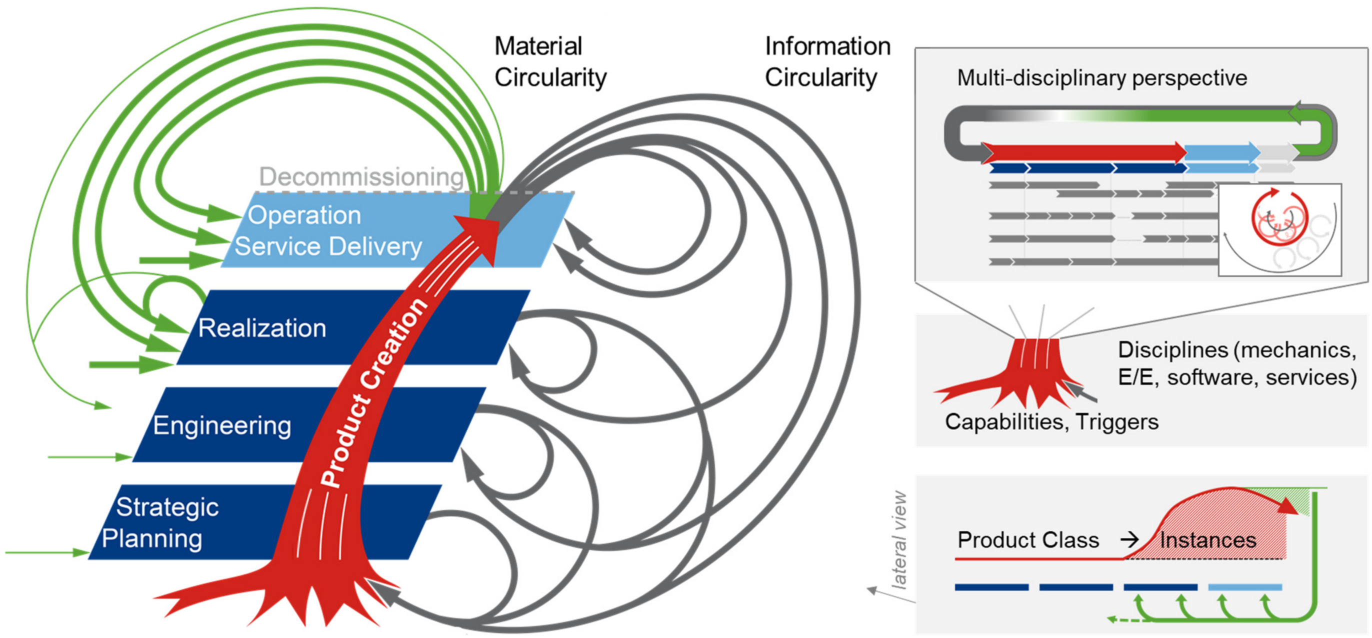


Figure 6. Visualization of the generic Product Lifecycle (gPLC): Circular Economy and Product Creation as drivers; material, ideas, technologies and capabilities as inputs and roots of the cycle; multi-disciplinary products bundled with services as types and instances along joint cycles and branches.

Circularity comprises material and information. In Figure 6, material cycles are presented on the left-hand side (green arrows). Options range from reuse of products in the operation phase, repair by servicing, refurbishment/remanufacturing in assembly processes, recycling of material for manufacturing [68] (thick green arrows) and recovery for other purposes, such as energy supply (slim green arrows). On the right-hand side of the gPLC, information flows are addressed. Here, the range spans from cycles within phases (for instance, process control based on real-time data analytics) and across phases (for instance, deriving engineering guidelines from operation feedback). Information enables full cycles by learning from products for parallel and succeeding system generations and for other products in a company's product portfolio. Thus, information can be treated as one of the roots of Product Creation.

Based on triggers, such as disruptive ideas, strategies, individual demands, market opportunities or technology push, the Product Creation process is initiated and begins with the strategic planning phase. Planning depends on enterprises and situations; while start-ups create their initial business models, established companies might evolve systems in terms of Product Generation Engineering [107]. Figure 7 details the multi-disciplinary perspective of the gPLC: planning can be seen as a commonality in all disciplines. For product–service systems, different viewpoints have to be merged. In engineering, processes, methods and tools vary between the disciplines. The end of this phase is marked by a design freeze. At least a Minimum Viable Product is specified, which is ready to be released to the market. Differences are obvious for the realization phase: for mechanic and electric/electronic (E/E) sub-systems, this means the step into production, including planning, ramp-up and production, depending significantly on lot sizes. Production subsumes manufacturing, assembly and quality assurance. For produced parts and products, supply chain management has to be constituted, including distribution to consumers or users. For software, design freeze means that all features of the software are specified. Realization means roll-out and deployment. For services, preparative actions are performed in realization, including, for instance, training of people. Service delivery might be started in the pre-sales phase already. An important point in time is the end of production, i.e., the completion of the whole product class. Production might be stopped even though product instances are operated for a long time beyond that. Service delivery is prolonged up to after-sales. Spare parts are produced and delivered by the OEM or service providers (cf. end of delivery obligation/EDO). For software products, maintenance has to be ensured, while updates can be rolled-out. The transfer phase into a succeeding cycle is often called decommissioning. It means to decommission physical assets, to finalize service provision and to remove software deployments.

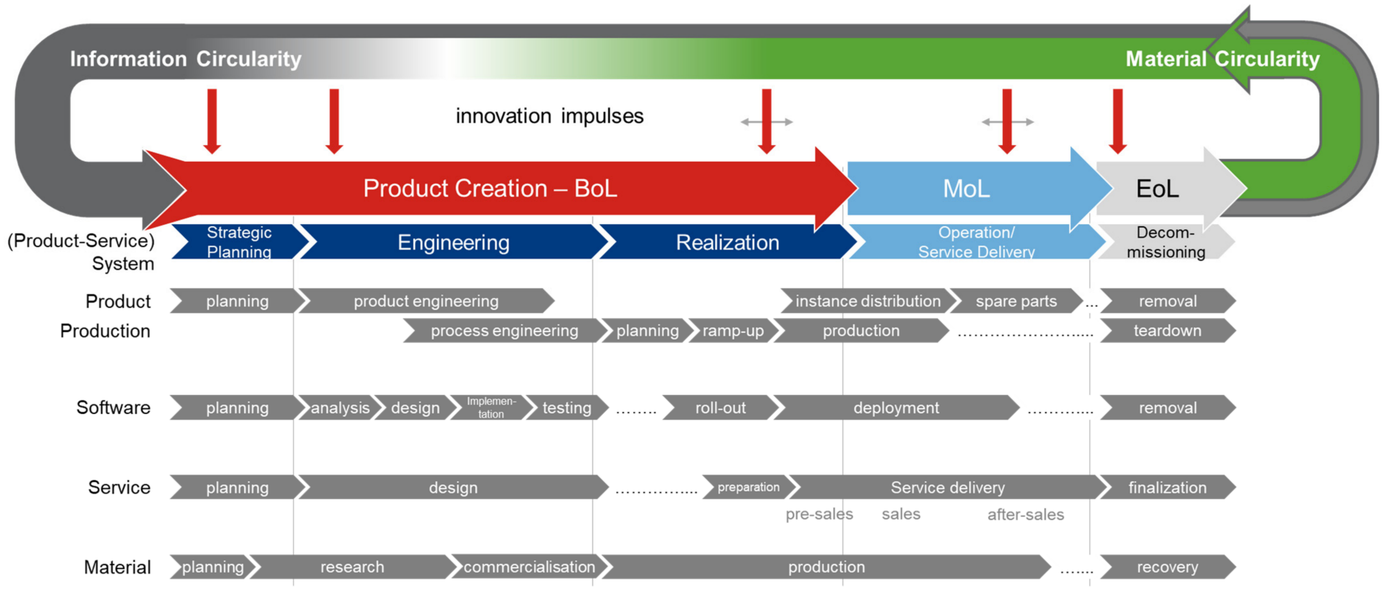


Figure 7. Alignment of technical disciplines and servicing under the hood of the Product Creation process, based on the intrinsic gPLC concept and extended by indications of material and information circularity (linear visualization for the purpose of clarity).

When aligning these processes, both risk factors and opportunities can be identified. Creating a new product–service system means to coordinate the involved disciplines and service management with logical and temporal relationships. The objective is to bridge discipline-specific methods with multi-disciplinary approaches. Chances shall be utilized. For instance, software engineering can be conducted in short cycles of a few hours with debugging leading to thousands of error messages to be handled. In contrast to that, engineers in mechanical engineering need to configure simulations or even manufacture prototypes for model analysis in the range of days and weeks. Additional engineering loops shall be avoided by explicit countermeasures, such as aligned terminology, methodology and model management. Differences between disciplines imply that within a product–service system's life, there might be more than one cycle of the material core product and a multitude of cycles of its software elements. These are considered inner multi-cycle relations in the gPLC (see Figure 8). Outer multi-cycle relations link the product-oriented perspectives with overarching perspectives, such as material and technology as well as, for instance, plant lifecycles, including land use and buildings.

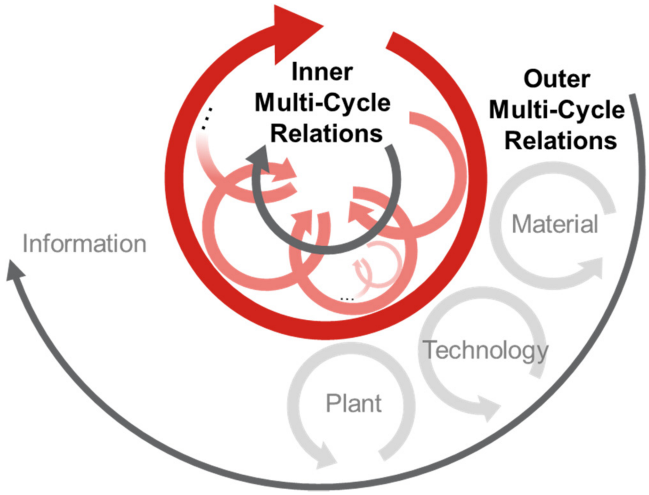


Figure 8. Inner and outer multi-cycle relations inter-linked by information flow.

In all phases, innovation impulses can be brought in. Strategic planning is dedicated to this objective, but in addition, innovation is possible along the entire lifecycle. Specifications of the product and process can be enhanced later during realization or during operation time or recycling. For instance, during realization, a company can switch production to an advanced manufacturing technology, which is not yet available on a robust level during the original engineering phase. In many cases of demanding technical systems, such as cars, aircrafts, industrial assets, the operation phase spans the longest time period of up to decades. Technology and material lifecycle models can be linked with the gPLC. These are typically structured into the research phase, commercialization, utilization and replacement. Additionally, CE means to put emphasis on the EoL phase right from the BoL. Nonetheless, there is a significant economic benefit in monitoring EoL opportunities throughout the whole product life.

In Figure 9, the differentiation between product class and instances is detailed. Economic lifecycle models, which highlight financial indicators, can be interpreted in terms of instance volumes. Instances are predominantly created in the realization phase. The number of instances increases according to production outputs, while at the same time, single instances are decommissioned step by step, leading to a reduction in active instances. These instances are typically treated as waste, turning into the product recycling. The cumulated sum of product instances represents the amount of input for recycling.

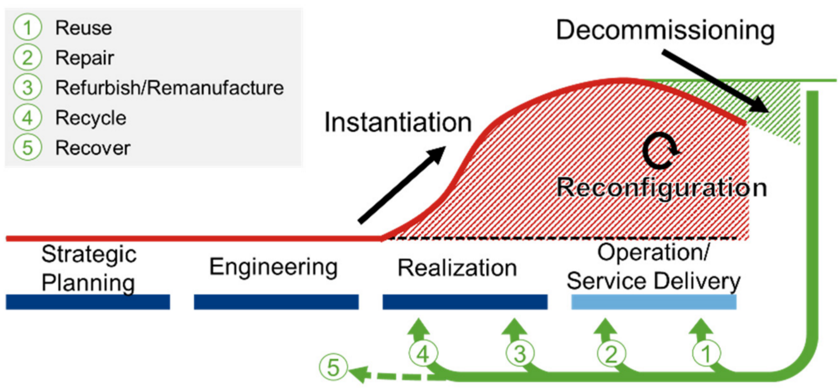


Figure 9. Lateral view of the gPLC: differentiation between product class and instances.

The synthesis of the gPLC is proven by application in three cases based on data acquired in collaborative research projects performed by the authors (see detailed comparison as a documentation of the selection of cases in Section 2). Figure 10 presents models visualizing case-based adoption with regard to product types, material flow and information flow. The line thickness describes the prioritization of material and information flow in each case. The RepAIR case combines various options of material and information flow regarding single metal part instances in operating aircrafts. The OptiAMix case is based on anticipation of material flow (dotted green lines) and information loops from aggregated product instances (thick grey arrows) into strategic planning and engineering phases. The SugarFab case is focused on resources in realization and information loops from the entire Product Creation process back to service and realization.

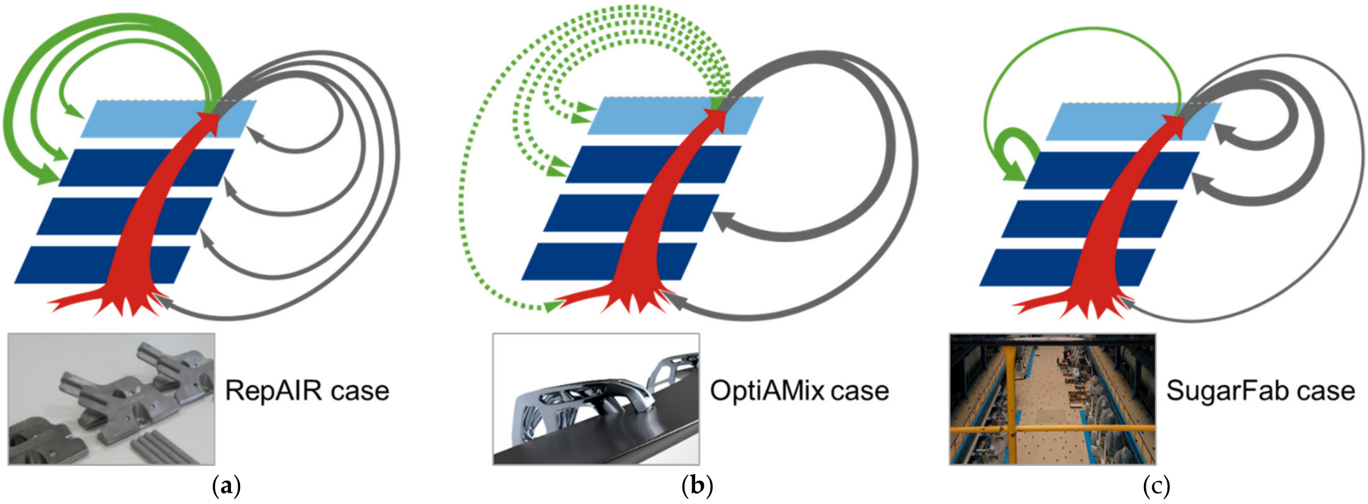


Figure 10. Application cases of the gPLC resulting from collaborative research projects: (**a**) European project RepAIR focusing on Additive Manufacturing of turbine blade brackets in aeronautics; (**b**) German project OptiAMix focusing on multi-criteria decision support in innovation and engineering management; (**c**) digitalization in sugar fabrication (here entitled SugarFab) targeting continuous evolution of production based on data analytics.

Subjects of the RepAIR case are structural parts of aircrafts manufactured from metals. As an example, turbine blade brackets are selected due to their manufacturability in both conventional processes and Selective Laser Melting. Parts are engineered and certified by an Original Equipment Manufacturer (OEM) of aircrafts and produced later on by suppliers both for series production and spare parts production. In future, Additive Manufacturing (AM) will be a relevant technology for the production of spare parts, especially in order to reduce CO_2 emissions in global supply chains. Spare parts are needed at MRO locations close to airports around the globe. By means of Remaining Useful Lifetime (RUL) estimation, predictive maintenance is enabled. RUL, in a basic version, is based on part life data derived from flight data, and in an extended version, from sensors detecting loads over time. Figure 10a presents the application of the gPLC to the RepAIR case. Product Creation is visualized by the red arrow, abstracting from different stakeholders (OEM, supplier). Service is provided either by MRO providers servicing the owner of an aircraft resp. of the turbine. Typically, parts are replaced by spare parts based on RUL at maintenance time. The disassembled part is checked and repaired/refurbished afterward either at the MRO service company or back in the production site. It can be brought back into the cycle either as single spare parts or assembled into products. Information circularity is based on life data (a) as a basis for the product and/or MRO process innovation at the OEM or the MRO provider [108], (b) as a starting point for product generation engineering at the OEM, (c) as data input for RUL calculations and (d) as a basis for decision support for stakeholders using the part in flight conditions (airline, MRO).

The OptiAMix case attaches importance to strategic planning and engineering. The OptiAMix case is focused on an automotive rear wing holder. The part is optimized for AM, but economic considerations imply that manufacturing highly depends on lot sizes. This means that different production technologies might be most suitable in the ramp-up phase, series production and spare parts production. For the latter, options vary between on-demand manufacturing by AM, which allows the decommissioning of assets and keeping the production line operating. The advantage of on-demand manufacturing is that production facilities, which are usually designed for high volumes, can be shut down. Figure 10b presents the application of the gPLC to this case. Assuming that a CE strategy is targeted, material flows need to be anticipated based on previous products and product generations. Volumes can be assessed based on, for instance, Enterprise Resource Planning (ERP) systems. Different types of recycling are considered, as material quality has to correlate with machine capabilities. While conventional manufacturing technologies are qualified for a variety of metals, allowing reuse of material, AM machines are (still) limited to specific material qualities. Thus, interrelations between manufacturing and recycling rates need to be taken into account when targeting CE strategies. The OptiAMix case involves an integrated multi-criteria decision support tool with simulation capabilities. To do so, information from manufacturing and operation are transferred to design guidelines which, subsequently, are implemented in digital support tools in terms of CAD and topology optimization. Due to aggregating information about the entire product life, information is provided for deciding on business models. For instance, regarding spare parts, logistics can be considered.

While RepAIR and OptiAMix cases are focused on products to be used, the SugarFab case concerns sugar as a product to be consumed (cf. differentiation in [59]). The focus of the lifecycle analysis is derived from the characteristics of production campaigns in which beets are harvested with immediate uptake into production. Campaigns typically last from September to January each year in Germany. While any type of recycling of the consumed product is out of scope for a sugar fabrication company, there are side products in production, which are used for biogas and energy generation. Using this concept, material circularity is ensured (see Figure 10c). With regard to information circularity, outbound supply chains are optimized. They connect realization and operation/service delivery phases. Optimization is conducted in a way to transport beets into plants efficiently to produce into stock and to deliver sugar products to end markets from there. Within campaigns, each stoppage of an asset means downtime for the entire fabrication line and, thus, risk of beet scrap. For the realization phase, information is acquired and used in two main use cases. In campaigns, process control is optimized by real-time data. In the second half of a year, information is used to prepare for the upcoming campaign. Production means are adapted, and new concepts are tested.

4. Discussion

The gPLC model consolidates the wide variety of lifecycle models, which are created from single-disciplinary, integrative or cross-cutting perspectives. While generalization always implies an abstraction of specificities, the gPLC covers all highlighted aspects. It is focused on value creation (Finding 1) but with a scope on both intrinsic Product Creation (value for consumers/users) and CE (expanded value for the enterprise). The cycle metaphor is used to emphasize circularity of material and information, while the Product Creation process is highlighted with its problem-solving, goal-oriented characteristics (Finding 2). Product classes are used as the primary viewpoint, but the instantiation of single product instances is introduced as an essential secondary viewpoint (Finding 3). In the gPLC visualization, it is presented as a lateral view of the Product Creation process. Hence, treatment of instances by users and material flow can be analyzed within the overall context of the gPLC. Besides logical dependencies, temporal alignment across phases and disciplines/domains is reflected (finding 4). Information circularity is hardly recognized in other Product Lifecycle models. In the gPLC, however, it is elaborated on the same level of detail as material circularity (Finding 5). Information refers to product class, single instances or aggregated instances. Based on this differentiation, cycles are possible between all gPLC phases. Both differences in realization and integrative aspects are incorporated (Finding 6). Regarding differences in realization, this covers the preparation of servicing and the production of material core products. Integrative aspects are concerned with utilizing assets and material to produce product instances, deploying software on core product platforms, etc. When doing so, the temporal synthesis recognizes flexibility in between phases and across disciplines (Finding 7). For instance, software sub-systems might follow more cycles in terms of versions than a service that is related to it. While preparation of a service as part of a product–service system is more or less finalized after realization, realization and operation of material products overlap until production is discontinued. Circularity is understood as the main driver of economy in the future, highlighting both information and material (Finding 8). CE is applied to both categories: besides material circularity, CE is also combined with data economy. Based on the differentiation of product class and instances, it is now possible to include the economic view on lifecycle phases into the gPLC (Finding 9). This strengthens the support for CE ambitions.

The gPLC model is a key to frame planning, design and engineering of circular business models. It is coherent with the perspective of [20], valuing early Product Creation phases as a key to achieve closed loops. While they focus on design skills necessary to create products for closed loops, the gPLC guides the perspective of skilled engineers. It is compatible with established engineering methodologies in different disciplines. It serves as a generic model to evaluate and extend Design-for-X (DfX) purposes, fostering Circular Economy adoption acknowledged by [24] and specifically detailed by [109]. Relevant DfX purposes are mainly design evaluation, design decision support and design knowledge management. The intention is to support even design as a driver of CE transition. Therefore, the gPLC extends the focus on the Product Lifecycle phase of VDI 2221 [28] regarding inter-disciplinarity, product types from material products to product–service systems and the CE perspective. The alignment of Product Creation phases is meant as a framework to adopt procedural models, such as the V-model for mechatronic and cyber–physical systems [110]. Engineering-specific types of products, such as pure service/software bundles, can be supported by reduction in the gPLC. The concept of System-of-Systems Lifecycle Management confirms this assumption [9], recognizing information sharing as an essential criterion. The notion of “products” is taken there from an information technology perspective to prepare for interdisciplinary linkage. It is an essential feature to focus on links between disciplines and service engineering, but at the same time, to allow flexibility in shifting temporal and logical constraints. For instance, the concept of Minimum Viable Products (MVP) is driven mainly by software-based products. The gPLC pinpoints links between disciplines. The MVP of software, pre-sales activities for service and ramp-up of material production shall be viewed from an integrative perspective. The combination is enabled based on an appropriate and, again, integrative selection of manufacturing technologies, material and distribution networks. Therefore, the gPLC can be understood as a supportive approach for handling the complexity in product, tools/assets and organization. Innovation triggers are considered throughout the entire lifecycle, proposed in terms of touchpoints of consumer intervention in [111]. Complexity is not neglected, but comprehensiveness is supported. With that ambition, challenges can be solved, especially for family businesses with their specific stakeholder relationships [7]. Use cases might range from very systematic to pragmatic based on a comprehensive understanding of gPLC details. The gPLC seems compatible with the two-step framework proposed by Kjaer et al. [18]. The two steps are interdependent strategies to advance to a Circular Economy strategy by designing product–service systems and even beyond to absolute resource decoupling. These steps obviously focus on resources but are based on information circularity as an enabler.

This includes the clear focus on digital transformation of enterprises and products. Information, which means data with semantics, is incorporated as an enabler of Product Creation and CE. This is coherent with the idea of product stewardships, where product stewards are highly dependent on information systems [112]. Digital twins [50] hold as an example for information circularity. Single digital twins of product instances are based on the digital master of a product class, enriched by digital shadows from realization and operation. Firstly, benefits are derived from single instances for which a close cycle could mean the provision of data to MRO services. The question arises as to whether product life extension and/or product recycling should be preferred from a sustainability perspective through design but backed up by data from an individual product instance [19]. Secondly, benefits are gathered from aggregated digital twins, allowing conclusions for an entire product class. Again, value can be created within one product lifecycle applying versioning of a product, or in between product lifecycles learning from one to another product generation. For instance, in the RepAIR case qualification of AM technology for spare parts production was a side effect enabled by circular information management. Like CE does for material, business models should envision business value in information circularity considering partnership for all gPLC phases. Besides the product perspective, it is essential to include a perspective on information lifecycles in future work on holistic lifecycle modeling.

Finally, sustainability is an ultimate objective with social and societal impact. That covers labor practices and decent work, human rights, society and product responsibility [113]. While the first three aspects are out of scope of the analysis at hand, product responsibility is often correlated with taxes, normative restrictions and regulations. Instead of challenging value creation by sustainable Product Lifecycle Management, just costs are determined and compared in Lifecycle Assessments based on, for instance, CO_2 taxes. Therefore, an extension of typical CE approaches (cf. [21]) toward engineers as stakeholders in industrial symbiosis through specific projects is required. In the gPLC, the focus is clearly shifted to CE. The material flow needs to be anticipated in strategic planning, covering all types of recycling over time. Extendibility with regard to more advanced targets in CE [23] is reflected in the gPLC by generalization of material flow design options. Again, this means including an anticipation of product instances which will be produced, but also product instances decommissioned over time to close cycles. Specific focus on product obsolescence supports this view [114], covering even building industries where a shift from construction site-oriented building toward products manufacturing is envisioned [11,115]. This means stepping beyond Product-as-a-Service business models, creating value in EoL. For this purpose, it is essential to integrate material lifecycles into the gPLC.

5. Conclusions

The generic Product Lifecycle (gPLC) fills the research gap identified by portfolio analysis regarding the differentiation of product class and instances, multi-disciplinarity up to the heterogeneous constituents of product–service systems and the integration of CE and intrinsic Product Creation. As summarized before, the gPLC model is compliant with all findings resulting from a comprehensive literature analysis. Material and information flows of multi-disciplinary product–service systems are recognized as the foundation for a modern CE. The gPLC provides an opportunity to exploit synergies from both the intrinsic perspective on Product Creation, mid and end of product life as well as the Circular Economy perspective extended from material to information circularity. Value creation is integrated as an overarching objective, including the late lifecycle phase, considering business value even in different types of recycling. Anchors for utilizing potentials of information technology are attached along all lifecycle phases, supporting digital business models. Thus, the gPLC enables taking advantage of data science, technological evolution and economic innovation by bridging multiple disciplines. A differentiation between product classes and instances is elaborated to stimulate sustainable design of material core products during product marketing and in after-sales phases.

The gPLC model, as such, is available to support both systems engineers and subject matter experts, but in particular, it is meant to provide a basis for decision makers in holistic System Lifecycle Management. It is compatible with planning, engineering and servicing methodologies. Instead of restrictive policies, the gPLC viewpoint supports sustainability by design. In practice, resource and energy consumption and waste production as well as emissions can be minimized with the help of established methods not only by economists, but also by engineers. Transparency of material and information circularity practically implies the opportunity to implement, for instance, Minimum Viable Products and DevOps approaches in agile product development and lifecycle management.

The study is limited to the inner multi-cycle relations identified in the literature and validated by application to three cases. Additionally, specificities within disciplines are only touched upon. For instance, the differentiation between elements of a product–service system is a topic in itself, which is not handled in the publication at hand. The study is focused on a technical perspective of product lifecycles without deepening the economic viewpoint on revenue streams. These are topics that are highly relevant for future research. For instance, information circularity is a special perspective into knowledge management. At the same time, information cycles could be part of revenue channels instead of or in combination with monetary ones. Special focus of the authors in future research lies on combining data from product lifecycle with anticipation of upcoming cycles by means of, for instance, agile Scenario–Technique. The different elements of the gPLC are used to transform collected data along gPLC phases and across different cycles into quantifiable estimates of the future, dependent on influence analysis, projections and consistency analysis.

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