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Enterprise Architecture for a Facilitated Transformation from a Linear to a Circular Economy

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Abstract: The circular economy is central to the agenda of responsible production and consumption with propositions for the conservation of natural resources and a broader understanding of the obligations of enterprises and product developers. The circular economy is challenging traditional operating models of enterprises due to the need to manage larger parts of the product life cycle and value chains. A linear economy will normally address a smaller part of the life cycle. The operating models of companies are supported with respect to information and technology with an enterprise architecture model. This article examines the necessary steps for analysing and designing the enterprise architecture model, aiming to facilitate the transformation of an enterprise from operating in a linear to operating in a circular economy model. The fundamentals and requirements of the circular economy enterprise are extracted to isolate the design requirements for the operating model, entailing cross-enterprise collaboration, traceability, and a broader value chain understanding. Furthermore, it conceptualizes enterprise architecture and its role and importance in connecting business strategies and operating technologies. This article develops an enterprise architecture framework, named the Circular Economy Enterprise Architecture Framework (CEEAF), which can form and support the effort of transitioning companies or be embedded into existing enterprise architecture frameworks. The CEEAF differs from traditional enterprise architecture frameworks by addressing the broader responsibility of the enterprise, the extended enterprise, the elimination of end-of-life perspectives and mind-sets, and the capabilities of the individual enterprise and its design activities.

Keywords: enterprise architecture; circular economy; enterprise capabilities; sustainable operations

1. Introduction

Large corporations, civil communities, and a range of governments are increasingly addressing the issue of the depletion of commodities, waste management, and consumption. The philosophy of the circular economy (CE) aims to think about resource consumption in terms of regenerative processes [1] preserving the objective value, or the capital, of the resource. Companies as well as governmental organizations must consider CE as a strategic effort rooted in top-level management.

The CE model captures and merges various environmentally sustainable concepts, therefore making it a much-appreciated model for a sustainable future [2]. As it has been strongly endorsed by China since 2008, with its CE Promotion Law [3], in addition to other endeavours in Europe [4] as well as by national governments, for example in the Netherlands [5], the U.S. [6], and France [7], it seems that a considerable portion, but certainly not all [8], of the world's most hefty economies are focusing on the CE as the future model for a sustainable economy.

For a thorough implementation of a CE, its underlying concept must reach every level of any organization willing to operate according to its principles [1]. Besides the theoretical definitions of CE business models [9–12], a CE must be connected as a strategic initiative to, and supported by, the relevant technological systems and processes of the enterprise. Although adopting CE practices in an organization has been tried by lean methodologies [13] or supply chain management [14], this complex problem is defined as the enterprise architecture (EA). It is, due to its capabilities, a very promising methodology to apply CE practices throughout an organization, but has not been studied to-date. This article aims to close this gap by defining a novel EA framework, specifically defined for CE, as, e.g., Yip and Bocken [15] thoroughly emphasise. In EA, the strategic objectives of the enterprise are enacted as initiatives, products, services, data, information, systems, applications, networks, and infrastructure. A fundamental hypothesis in this respect is that linkage of flow-of-goods with flow-of-information in classical industrial thinking must be reformulated into a CE-based industrial thinking. By designing an appropriate framework for the interrelatedness of CE and the information and technology architecture of the enterprise, open questions of making CE operational can be answered.

This article argues that appropriate adaption and relevant augmentation must be implemented within traditional EA frameworks to manage the requirements raised by a CE. The argument is underpinned by the traditional EA frameworks being both explanatory models for the current technological portfolio and transitional in terms of acting as a guiding mechanism to enact new technological solutions. An EA framework that is particularly designed for the successful implementation of CE business models does not exist to date. In this article, the development of such a framework, named the Circular Economy Enterprise Architecture Framework (CEEAF), is suggested to close this research gap. Scholars and practitioners can apply the framework for connecting and improving the interrelation between business strategy, technology, processes and consumption of resources [16].

Since strategic planning encompasses the triple bottom line of economic, social, and environmental positioning regarding sustainability alongside the matter of the growth of environmental awareness among all continents' inhabitants [17], this article focuses particularly on the enhancement of the environmental benefits due to it having been disregarded compared with the other two parts of the triple bottom line [18]. Nonetheless, CE and consequently the proposed CEEAF consider all three dimensions of sustainability. Environmental resilience is derived from CE's opportunities of conservation of resources [19,20], thus the proposed framework is addressing technological opportunities, representational systems and information assurance related to creating stronger and more resilient patterns of consumption.

This article is structured as follows: Firstly, theory necessary to understand the topic area, i.e., definitions and elaborations of EA and CE are given (Section 2). Secondly, the methodological approach is explained (Section 3), before we delineate empirical positions of CE practices in medium to large corporations (Section 4). Afterwards in Section 5, we define an EA framework for the CE, which is then discussed (Section 6) and concluded (Section 7).

2. Theoretical Background

2.1. Enterprise Architecture

EA is the 'analysis and documentation of an enterprise in its current and future states from an integrated strategy, business, and technology perspective' [21]. Its quintessence lies in building an organizing meta-context for the alignment of technology planning and business planning, with strategic planning as its primary driver [22,23]. Bernard [21] presents EA as a cubic representation consisting of the dimensions artefacts, segments, and levels as illustrated in Figure 1. Artefacts are large organizational entities of value creation. Segments are cross-cutting components of the enterprise, for example a human resource database. Levels are a hierarchical construct with the strategic initiatives of the enterprise at the top (level 1) and technology and infrastructure as the base layer (level 5).

Level 4 is systems and applications, level 3 data and information, and level 2 products and services. Fundamental to the EA philosophy is the transition from a documented present state to an intended future state. The level-based model serves as an illustration of and support for interrelations within the enterprise of the distinct technological levels. Each level plays an exclusive role in ensuring that the operating model of the enterprise, for example products and services, is a representation of the artefacts required for a business service and thereby a business model [24]. Business models are defined from the top level but rely on distinctive hierarchical dependencies [25]; business models might define the enterprise architecture, but the enterprise architecture can also be used in the creation of business models, for example in switching from delivering physical products to delivering services for these products.

Enterprise architecture is a complex discipline to master. Korhonen and Molnar [26] discuss EA as a (fundamental) business capability that is critical to the overall business creation. Ongoing discussions seek to capture the maturity of the enterprise in respect to EA and EA governance [27]. In the sense of EA representing the systems and applications of the enterprise, it is closely related to (strategic) software systems' portfolio management and thereby also decisive in the selection of the technological elements of the enterprise's operating model.

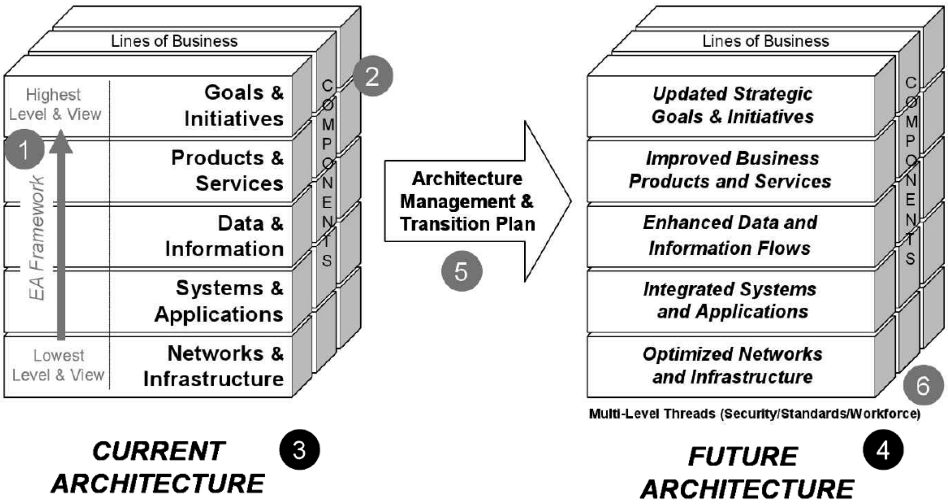

Figure 1. The basic elements of enterprise architecture (EA) analysis and design [16].

EA is discussed in initiatives on inter-organizational relationships [28,29] and technological interoperability [30]. As the EA is derived from the single organization's strategy, there are limitations to the ability to enact technological design in other enterprises, although most levels of the EA model rely on external relationships anyway, for example parts from suppliers, products for the market, and data sent to and from relevant parties. Drews and Schirmer [28] suggest that EA can be a positive driver for the creation of business eco-systems.

EA is generically supported by the dominant implementation and maintenance framework TOGAF (The Open Group Architecture Framework) [31]. TOGAF outlines a methodology for implementation starting with the setting of business objectives and describing the outcome [32] and structures an enterprise from the business, data, application, and technology architectures, whereby the reaching out to the business surroundings is addressed by the idea of an 'enterprise continuum' [33]. TOGAF strongly addresses enterprises' ability to adapt and adopt technology from maturity measurement, stating the readiness, organization, management buy-in, structuration level, and more, and implementation is considered as a continuous process known as the architecture development method (ADM) [34].

2.2. From Linear to Circular Economy

The contemporary socio-economic model is referred to in the literature as the linear economy model [35,36] (see Figure 2) in comparisons with other models, especially the CE model (see Figure 3). Its most obvious characteristic is the discarding of a product after its use, which implies illusionary assumptions of never-ending or even never-diminishing natural resources. Its practices are threefold, categorized by the extraction of resources ('take'), the use of them to manufacture a product ('make'), and their final disposal ('dispose') [37]. Practitioners often speak of a 'take, make, dispose' or 'cradle-to-grave' mentality [38].

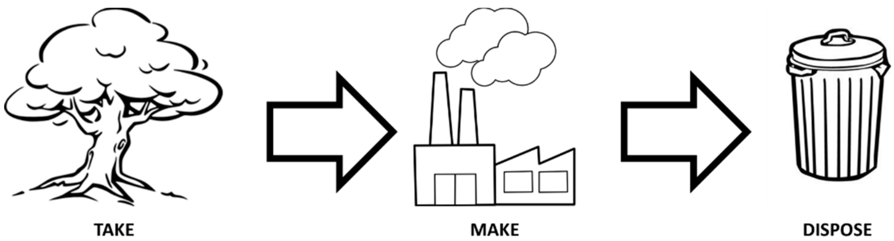

Figure 2. Linear economy model.

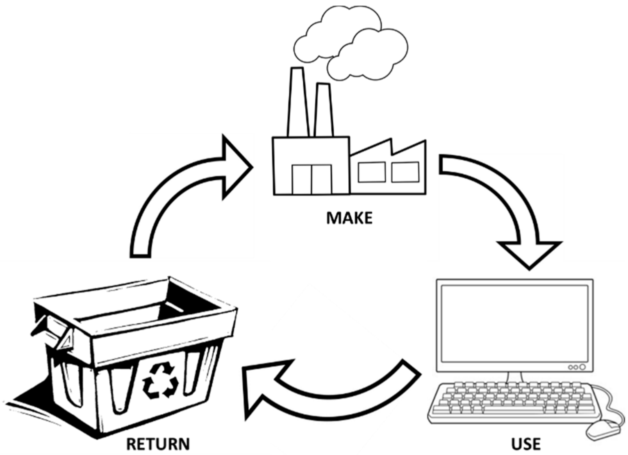

Figure 3. Circular economy model.

The CE model is entirely based on the fact that the prices for natural resources will rise and become more volatile in the near future [39,40]. It has emerged from various schools of thought and synergizes them; the first concrete features, with a focus on industrial economics, are developed by Stahel and Reday [41]. The most influential theories are cradle-to-cradle [42], the performance economy [43], biomimicry [44], industrial ecology [45], natural capitalism [46], the blue economy [47], and regenerative design [48]. Another crucial factor to realize CE business models is that organizations adopt to the concept of resilience [17,18]. It encompasses the issues of business security, preparedness for environmental changes, risk analysis, and survivability of the business [49]. Adopting to the concepts of resilience requests an enterprise to have a proactive, beyond a mere defensive, thriving attitude, inherent strength to withstand any crisis, and knowledge of its situation, its risks, vulnerabilities and current capabilities to make data-driven decisions [50].

A well-accepted definition of the fairly recently emerged research field of CE is formulated as 'an industrial economy that is restorative or regenerative by intention and design' [1]. Similarly, a CE is defined by other scholars as the 'realization of [a] closed loop material flow in the whole economic system' [51], as an economy that is 'restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times' [51], or as 'design and business model strategies [that are] slowing, closing, and narrowing resource loops' [11]. In the authors' opinion, the most comprehensive definition is proposed by Geissdoerfer et al. [35], who describe CE 'as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.'

The overall field has received increasing academic interest with a variety of recently published reviews [52–54], in addition to more specific research in closed-loop value and supply chains [55], circular business models [11], and circular product design [56].

2.3. Identifying Enterprise Architecture Requirements for a Circular Economy

By definition, EA is 'the analysis and documentation of an enterprise in its current and future states' [21], of which the documentation can be divided into the aforementioned five basic levels of analysis and design to propose ways to make them more tangible and steerable [57]. The process begins with the choice of an appropriate EA framework, that is, defining clear boundaries for the architecture, since the integration of suppliers into the EA could be beneficial depending on the situation [58]. An EA framework for a business operating in a CE must encompass the extended business network to the fullest extent of relevance, while each distinctive line of business must investigate the building of its segment with its specific business partners, which are subsequently implemented in the overall EA [21]. In cases of organizations belonging to the manufacturing industry, the extended manufacturing (supplier) network [59] must tentatively be represented in the EA. Additionally, investigations must be made on the other side of the value chain, that is, gathering data concerning the usage and quality of the product, because of the CE's aspiration 'to keep products, components and materials at their highest utility and value, at all times' [51]. As the rationale for successful implementation of the CE model, changeable EA components, such as goals, processes, standards, and resources, need to comprehend the CE's first core principle of customers renting, leasing, or sharing instead of owning products. The second core principle of merely using cradle-to-cradle materials again aims 'to keep products, components, and materials at their highest utility and value at all times' [51]. Business models for the CE [11] need to be designed and implemented at that stage. Subsequently, the current state of the existing architecture must be recorded on each level of the framework; that is, every line of business with its corresponding supplier, and ideally customer, needs to be represented in conjunction with its components. Accordingly, a baseline is established that must be acted on contextually towards the CE's aforementioned two core principles, ultimately concluding in the fourth element of analysing and designing an EA, namely the formulization of a future architecture. Ambitiously, no concessions regarding the utilization and quality loss of products, components, and materials are allowed, which results in a formulization that seems to anticipate, at that point of time, a utopian ideal final result [60].

How a smooth and efficient ongoing transition from the current to the future state is realizable is described in a living management plan that clearly states the present capabilities, their performance gaps, and the future capabilities with resource requirements, planned solutions, a sequencing plan, a time frame, and a summary of the current and future architecture [21]. If the aforesaid ideal final result were understood as *what* needs to be attained, the management plan would outline *how* those conditions can be attained [22]. The identified performance gaps need to be minimized by solutions of which the development and implementation require resources that are predefined and documented in a sequencing plan that is part of an overall transformation project time frame. Lastly, the threads of the EA concerning IT-related security, standards, and skill considerations are described. Due to the increasing complexity and uncertainty of the globally connected world, particularly careful elaboration must be exercised on the IT-related security. The type of data stored in such an EA would for many third-party stakeholders be of the greatest interest, since it contains information about the entire business line of suppliers, organizations, and customers in one single entity. Furthermore, using international, national, or industry standards at all levels enhances the integration of EA components and their individual controlling abilities. Another often-observed thread is the concern that employees are not able to unfold their full skills because of their impression of being tied into too strict guidelines or other factors that influence productivity, efficiency, or creativity negatively.

3. Methodology

The chosen methodology for the intended creation of a new EA framework that is customized for the implementation of CE business models and product designs falls into the scheme of design science research [61]. Characterizing this methodology are three inherent research cycles that connect the three indicating fields of any design science research project: Firstly, the contextual environment, that is, an application domain; secondly, the knowledge base of scientific foundations, experience, and expertise that informs the research project; and, thirdly, the actual design science research activities of building artefacts and evaluating them. Those three fields obviously intervene in each other when it comes to the creation of a new artefact. Hevner [62] entitles these intervention cycles, both a relevance cycle and a rigor cycle that bridge the contextual environment, respectively, the scientific knowledge base for the actual design science research activities. Within this field, a design cycle iterates between the artefacts' building activities and their subsequent evaluation [61]. By focusing on the defined research problem while adhering to the methodology of design science research, an EA framework development methodology is employed, as described by Bernard [21] or TOGAF [63]. Accordingly, a systematic literature review [64] was conducted to identify, evaluate, and interpret all available research relevant to find existing EA frameworks in addition to CE business models. As little research exists regarding EA correlated with the CE, the search expanded into EA in relation to general sustainability, green technology, inter-organizational relationships, and value/supply chain management. The existing EA frameworks were then succinctly assessed in relation to their feasibility regarding CE business models together with recommendations for modifications. Ultimately, the process concluded with the creation of a new EA framework for organizations operating in a CE model, which we call the Circular Economy Enterprise Architecture Framework (CEEAF).

4. Empirical Positions of CE Business Models

For the purpose of providing readers with empirical positions of CE business models to see the requirement of a specific EA framework, we selected three case studies from disparate industries. Criteria for this particular selection of empirical positions were the diversity of industries, the size of the enterprise or extended enterprise, and the feasibility in geographically collocated businesses a novel EA framework must be applicable to. These studies do not only motivate the construction of an EA framework particularly designed for CE business models, they also show how various industries benefit from such a framework. In the previously described systematic literature review, numerous case studies were found (e.g., References [65–67]), but due to the aforementioned arguments of multi-industrial applicability the three subsequent studies are elaborated more in detail.

4.1. Printed Circuit Boards

Wen and Meng [68] evaluate quantitatively the CE performance of printed circuit boards (PCB) in an eco-industrial park in China's Suzhou New District where all enterprises which are required to realize CE business models are collocated. The strength of the implementation of CE business models in such an industrial symbiosis is examined by a substance flow analysis and a resource productivity indicator for the core materials of any PCB (copper, water, energy). The authors define five categories of enterprises necessary to realize a circular substance flow, i.e., CE business models, which are displayed in the subsequent Table 1.

Since any for-profit organization measures its uttermost performance in monetary profit, the resource productivity is given in thousand yuan per ton. Disparate scenarios with and without waste utilization are examined. Although geographical proximity of involved enterprises is in this case given, each of the three core materials still have a lower, i.e., more profitable, resource productivity without waste utilization than with waste utilization. Precisely, 21.38 compared to 23.15 thousand yuan per ton for enterprises of category 1, 64.15 compared to 71.32 thousand yuan per ton for enterprises of category 2, and 176.47 compared to 211.21 thousand yuan per ton for enterprises of category 3. The two residual categories process PCBs and are hence not taken into account in these calculations.

Table 1. Categories of enterprises in an industrial symbiosis necessary for circular economy (CE) business models.

Category	PCB-Specific Role	Generic Role
1	Production of electrolytic copper foil	Provide raw materials
2	Usage of electrolytic copper foil to produce copper clad	Refine raw materials to manufacturing materials
3	Usage of copper clad to produce PCB	Use manufacturing materials to produce component
4	Usage of PCB to assemble and produce electronic products	Assemble components in products
5	Collection of waste etching solutions, recover copper sulphate from the waste, make a regenerated etching solution, collect and regenerate copper waste	Collection and regeneration of waste and by-products

4.2. Pay-Per-Use

Business models where consumers pay for a service a given product can perform (e.g., wash) rather than own a product to have a desired service (e.g., washing machine) are widely known as pay-per-use business models. Clearly, these business models can be categorized as CE business models due to the consistent product ownership and the owners' aspirations to keep products, hence services, at their highest utility and value at all times. Bocken et al. [69] investigate how strongly pay-per-use business models foster sustainable consumption. They find a substantial discrepancy between consumers' behaviour in the first free month of their subscription to HOMIE, a provider of pay-per-use washing machines, and the subsequent ones. Since prices of each wash are determined by the temperature of the wash, consumers considerably reduced washing temperatures besides the number of washes. Noteworthy, HOMIE is not just another launderette, it combines the comfort of having an appliance at home with monetarily-encouraged sustainable consumption by charging consumers per wash while the product is still owned by HOMIE. Results show firstly that the average temperature per wash decreased from 40.2 °C in the first free month to 38.1 °C in the second paid month. Secondly, the average number of washes also decreased from the first free month to the second paid month by 12.9 to 10.3, respectively.

4.3. Product Sharing Platform

Peerby is a platform that allows neighbours to borrow or rent items from each other which was originally started as a simple Facebook group to enhance the sharing economy by offering an alternative for excessive consumption [70]. Due to the proximity to lending neighbours and the emotional connection one has when a possession is entrusted to one, item borrowers or renters feel naturally obligated to sustain the item quality on the highest possible level. Product owners have the freedom to decide individually if any charge should be applied to renting an item or the item can freely be borrowed by any neighbour. More than 100,000 neighbours are registered on the Dutch website and items range from electric wheelchairs to cameras and tables.

4.4. Summarizing the Empirical Positions

Empirical positions must be evaluated for relevance according to their offerings in a CE context. This means that there exists reflected considerations in resource consumption and potentials of studying information and technology. Following the cases presented by, e.g., the Ellen MacArthur Foundation [1], it is important to be ambitious to change "non-obvious" industries, as well as it is also significant to work with suggestions for improvements of "obvious" industries. In this respect, the obvious industries includes industries with opportunity to control the physical goods all through its life-cycles, e.g., laundry rentals, cars, construction materials. Non-obvious industries include companies where resources transition beyond potentials of re-use like food, oil, digital services, entertainment. It is argued that the presented empirical cases qualitatively represent a range of industries suited for a broader generalizability of the findings.

5. An EA Framework for a Circular Economy

EA practice is generally derived from EA frameworks, or EA models as they are also called. More than 70 frameworks exist for various purposes, for example ease, complexity, responsibility, IT orientation, investment orientation, or emphasizing formality and rigor versus flexibility and organizational aspects. This is a matter of design orientation, contrary to design stand domains. Here, dimensions of sustainability and social responsibility have been introduced gradually since 2011. The Smart Grid Architecture Model (SGAM) [71] has been developed to ensure positive balancing in the electricity sector to include more renewable energy sources, for example wind and solar power. The Smart City Infrastructure Architecture Model (SCIAM) [72] is an architectural model ensuring interoperability, integration, and balancing between critical elements of modern metropolises in terms of transportation, energy, security, water, and waste. The Electric Mobility Architecture Model (EMAM) [73] extends the SGAM to electric vehicles for the management of car fleets, consumer needs, the car as consumer, the car as storage, and the car as provider. Furthermore, architectural frameworks have been developed for (sustainable) building management (HBAM) [72], intelligent transportation systems (FRAME) [74], and industrial rethinking and integration (RAMI 4.0) [75]. Common to all the frameworks are a multidimensional approach, the top-down structuration of technologies, and the top-down structuration of the organizational context. In the following, EA frameworks are discussed and analysed in the context of CE.

Besides suggesting an advanced framework for balancing in energy systems, SGAM is important for its introduction of enterprise architecture in between resiliency and consumption. Resilience is encompassing a range of methodologies including reliability, adaption capacity, elasticity, and evolvability [76]. Resilience must be based on algorithmic approaches to manage demand-response and central-decentral connectivity through rightful functional decomposition and database designs [76].

The pressure on organizations to divert their business strategy to embrace CE calls for a review of the key elements of EA to scrutinize the technological fit of the existing operating models to the CE as a strategy. By considering EA as a model of the key business enablers and a framework for documentation and planned change, a number of requirements can be refined from the above. The requirements must aim to create persistent information across any context of judicial ownership and spatio-temporal context throughout the life cycle of a set of resources until safe reclamation of these resources is accomplished. RAMI 4.0 contributes well to the understanding of the product in its 'active' life cycle of development, manufacturing, and use, but it does *not* focus on the cross-cutting responsibilities, end-of-life responsibilities, and potential for the preservation of resources. The theoretical position of extended enterprise architecture (EEA) [29] is interesting, as it discusses cross-organizational barriers and enablers for designing architectures involving multiple actors; Tambo [29] highlights a range of focal points for ensuring qualitative EEA with imprecision, imbalance, heterogeneity, transformation, temporality, and operational maturity. The CE adds specific needs for:

- Materiality: Understanding resources ecologically and as future resources.
- Ownership: Responsibility in appropriate forms of meaningfulness, such as judicial, ethical, practical, and power.
- Relationships: Collaboration across life cycles and supply chains.
- Documentation: Knowledge about the quality, age, and place of products or parts.

The CE is mostly interorganizational and is dependent on preserving the capital of resources at any life cycle stage [38]. Furthermore, it needs persistence in the form of long life cycle management and requires control elements to assure high quality of the resources throughout any given stage of the product's life cycle. CE is dependent on interoperability to disseminate information on a resource and its handling, collect information on resources for taking back, pass a resource to business partners for handling, and eventually source new materials from other CE actors.

A Circular Economy Enterprise Architecture Framework (CEEAF) is introduced, encompassing dimensions of the life cycle value stream, hierarchy levels, and layers, which are derived in accordance to RAMI 4.0 and SGAM. Bernard's [21] five basic layers are increased to seven to involve all the required aspects. The proposal is presented in Figure 4, whereas Table 2 examines its relatedness to the RAMI 4.0 and SGAM architectural frameworks.

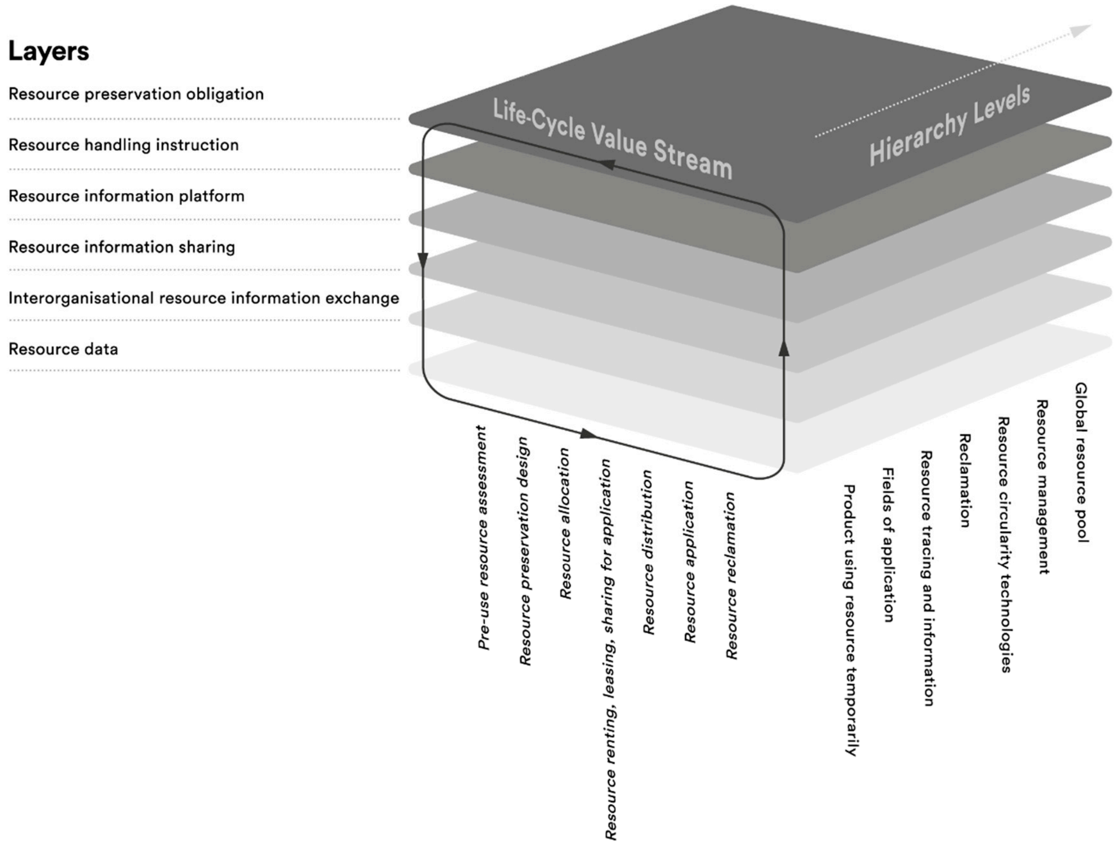

Figure 4. Circular Economy Enterprise Architecture Framework (CEEAF).

Table 2. CEEAF in comparison with RAMI 4.0 and SGAM.

Dimension	RAMI 4.0		SGAM	CEEAF
Life Cycle Value Stream				Pre-use resource assessment
	Type	Development	Generation	Resource preservation design
		Maintenance/usage	Transmission	Resource allocation
	Instance	Production	Distribution	Resource renting, leasing, sharing for application
		Maintenance/usage	Demand–response	Resource distribution
			Consumer premise	Resource application
				Resource reclamation

Table 2. *Cont.*

Dimension	RAMI 4.0	SGAM	CEEAF
Hierarchy Levels	Connected world	Market	Global resource pool
	Enterprise	Enterprise	Resource management
	Work centres	Operation	Resource circularity technologies
	Station	Station	Reclamation
	Control device		Resource tracing and information
	Field device	Field	Fields of application
	Product	Process	Product using resources temporarily
Layers	Business	Business	Resource preservation obligation
	Functional	Functional	Resource handling instruction
	Information	Information	Resource information platform
	Communication	Communication	Resource information sharing
	Integration		Interorganizational resource information exchange
	Asset	Component	Resource data

6. Discussion

6.1. Considering Implementation

The proposed CEEAF offers a theoretical basis for organizations to operate according to CE principles on a large scale using standard (enterprise) architectural management frameworks. Implementation efforts can be conducted following the industry standards of TOGAF as a dominant framework for the transition of the technology architecture. TOGAF, with its proposals for business, data, application, and technology architectures, provides a comprehensive ensemble of all domains, for which our proposed CEEAF must be the guiding principle. Precisely, the business architecture, which includes the definition of business processes, must be construed to facilitate the circulation of materials (through, for example, a disassembling phase, as described in Section 4 on electronics manufacturing). The data architecture must encompass the supplier, age, materials, transformations, usages, and so on to efficiently document the material properties or product component quality and hence their optimal utilization. Technologies that are capable of long traces without the possibility of being amended, like block-chain, escrow-style services, or the passport regime from the shipping case, would be ideal to use for this purpose. The application architecture aims to define which sub-systems are deployed and thus needs to comprise, for example, sub-systems documenting the dissembling processes in conjunction with the CEEAF. Intelligent design must be placed in the interactions of all the sub-systems, because the circulation of goods requires the transferring of data among multiple stages and loosely related stakeholders. The technology architecture must be designed to trace quality aspects throughout the lifetime of any goods; that is, the aforementioned block-chain technology seems to be capable of vast advancements in this endeavour. Ross' [77] perspective of seeing EA on different maturity levels might provide support, whereas the technology architecture must aim to be *modular*. Jonkers et al. [57] describe a well-observable problem of merging business strategists and digital architects for a respected, appreciated among all the stakeholders, and thus successful implementation. Crucial to solving this problem is the applied implementation methodology, that is, the definition of *how* the proposed changes are satisfactorily realizable. At this point, the difficulties no longer arise from technological challenges; the management of people with its required persuasion of scepticism account for more obstacles [78].

As another tool for the enhancement of the chances of successful EA implementation, a capability model [26] can be constructed to visualize not only the functions that the organization *wants* to achieve but also the functions that *are possible* with its internal capabilities. It facilitates strategic decision making through the provision of a common language and a shared understanding of the objectives of the enterprise. That gives the architect expertise, firstly, to identify and structure capabilities rapidly that are unique, stable, and abstracted. Secondly, the so-called strategic architect [79] is then qualified to change the entire enterprise. Prahalad and Hamel [79] define strategic architecture as 'a road map of the future that identifies which core competences to build and their constituent technologies.' Knowledge about residual products, components, or materials that could theoretically be reused or recycled will enter the spotlight through that procedure. Building an initial capability model is achieved by pursuing a threefold process as visualised in Figure 5. To begin with, all the entities that are important to the organization need to be identified. Accordingly, the customer, supplier, and product and especially the processes operating in a linear economy model count as relevant objects. Secondly, those entities are turned into capabilities by adding the word 'management', that is, customer management, supplier management, product management, and process management. Lastly, within each capability, the verbs must be identified that represent the actions that must be conducted for successful exploitation of each capability. The application of those three steps with the ultimate goal of transforming an organization operating in a linear economy model into one operating in a CE model are visualized in the following Figure 5.

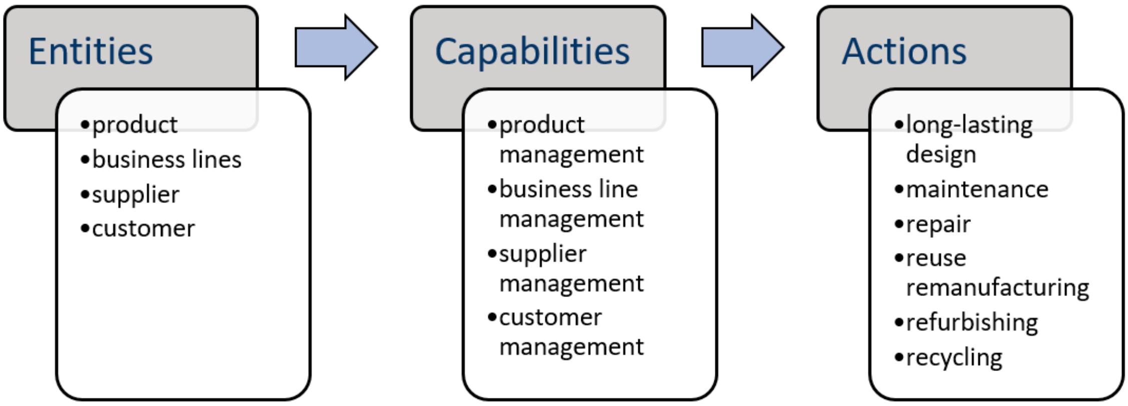

Figure 5. Capability model for circular economy business models and designs.

Beyond that initially built capability model, apparently similar capabilities may appear under various headings, the requests refining the initial model. The services or processes behind those headings that implement the specific capability together with the corresponding stakeholders must be identified first. Then, several approaches can be utilized depending on the explicit case. Exemplarily, the architect could combine multiple instances as the capability model does not see the necessity for a hierarchy. Otherwise, a new higher-level capability could be created as an umbrella for all the similar capabilities identified earlier. Conversely, one precise capability could be selected as that aforementioned umbrella with references to it in other capabilities. Multiple iterations of this refining process should be applied but can be stopped when the benefits are flattening regarding the impact of mergers, acquisitions, divestment, strategic differentiation, the leverage of new markets, resource investments, strategic value-adding technology, or cost-decreasing technologies.

6.2. Critical Reflections

The proposed interpretation of the five basic levels of EA analysis and design according to Bernard [21], as well as its implementation, requires an extraordinarily fervent desire of organizations to transform themselves into ones operating within a CE model. Noteworthy are the substantial interdimensional relations between the resources of the *life cycle value stream*, the *hierarchical levels* of the tangible matters, and the *layers* of the organization in focus. Architectural frameworks have their strength in the systemic and generic approach to organizations with both descriptiveness of current states and aspirations for guidance for transformations to prospective states. By connecting the flow of resources to relevant business strategies, operational processes and technological systems, the CEEAF is supposed to be used as a generic and comprehensive organizational transformation tool.

Critical to the proposed framework and a clear limitation is temporality in the form of high variation between life cycles ranging from hours and days to decades; short cycles are demonstrated as manageable in SGAM, whereas CE overall propose responsibility to the long cycles. Additionally, the universal information access and societal enablement in responsible resource reclamation are prone to be critical. The conviction of all the involved stakeholders regarding the necessity for that transformation must be given, and persistence during the whole process is essential. Furthermore, the organization must deal with certain financial losses during the transformation process itself, which is nothing unusual when considering any change processes [80]. This loss will ultimately be redeemed by the profits gained from new business models. Even cases in which not all the involved stakeholders are convinced to the fullest extent, the increasing request of customers for products with low negative environmental influences [81] and NGOs' efforts to achieve transparency in the entire value/supply chain [82] will most likely lead to the eventual transformation of those organizations as well.

Another large limitation is the aspect of product or product part ownership, which is particularly noteworthy in industries like energy, food, or textile. Certainly, tracing a part of an assembled hardware (e.g., washing machine, automobile, or computer) is accomplishable with certain technologies. However, ensuring that food or textiles, often produced far away from their place of consumption in less technologically developed circumstances embodies a major challenge. Attaching the aforementioned tracing technologies like, e.g., a bar code or chips with a saved blockchain, to a product or product part can surely facilitate implementing CE business models for many of the consumable goods. However, the majority of food and textile products, or electricity can most likely not be adequately and quantitatively be measured. To summarize, the proposed CEEAF is more accessible to enterprises and extended enterprises producing only theoretically reusable hardware, hence it can generalized and applied to those straightforwardly. Nevertheless, enterprises and extended enterprises in the aforementioned industries of food and textile products, or electricity might have major difficulties, which is aligned with the six limits and challenges Korhonen et al. [83] outline.

7. Conclusions

The circular economy (CE) is experiencing corporate and political momentum as resources run scarce and reclamation technologies improve. The CE offers answers in dealing with the future complexities of resource acquisition, reuse, and waste. This article has discussed the shortcomings of the strategic design of enterprises and the technological operating models using enterprise architecture (EA) as a fundamental construct for corporate management. The Circular Economy Enterprise Architecture Framework (CEEAF) has been proposed, which provides the theoretical basis of an EA designed to facilitate the transformation of organizations that are aiming to operate in a CE model but are currently operating in a linear economy model. The activities involved in designing long-lasting products that can be maintained, repaired, reused, remanufactured, refurbished, and recycled must be executable immediately in such an EA. Rather, fundamental and strategic guidelines are defined that necessitate personalized EA designs for each organization in future work. The CEEAF is, as any EA framework, made to be implemented in corporations with large amounts of data and numerous stakeholders who manage these. The enterprise-wide commonalities of data handling and accessing allows transparency throughout the organization which is particularly required for any business acting according to the CE.

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