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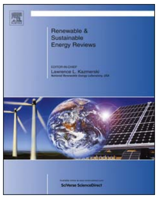

The history and current applications of the circular economy concept

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ABSTRACT

The challenges of balancing industrial development, environmental and human health, and economic growth in China and elsewhere in the world are drivers for recent resource use and low-carbon development strategies that include the application of the circular economy (CE) concept. A central theme of the CE concept is the valuation of materials within a closed-looped system with the aim to allow for natural resource use while reducing pollution or avoiding resource constraints and sustaining economic growth. The objectives of this study are (1) to review the history of the CE concept to provide a context for (2) a critical examination of how it is applied currently. Thematic categories are used to organize the literature review of current applications including policy instruments and approaches; value chains, material flows, and products; and technology, organizational, and social innovation. The literature review illustrates the variability in CE project success and failure over time and by region. CE successes, key challenges, and research gaps are identified. The literature review results provide useful information for researchers as well as multi-stakeholder groups who seek to define the CE concept in practical terms, and to consider potential challenges and opportunities it presents when implemented.

1. Introduction

In response to the United Nations Framework Convention on Climate Change, 196 participating countries created strategies for low-carbon development. Of these countries, China emits higher amounts of greenhouse gas (GHG) per year compared to any other country in the world, yet contributes less carbon dioxide (CO_2) emissions per capita compared to Russia and 68% of the Organization for Economic Cooperation and Development countries [1]. China produces the greatest amount of manufactured goods and has a historically rapidly growing economy. This pace of growth and consequental environmental damage, human health effects from pollution, and social justice issues in China and elsewhere in the world are drivers for recent low-carbon development strategies, including the the application of the circular economy (CE) concept [2–5].

The CE concept was popularized in China in the 1990s in response to economic growth and natural resource limitations [6–8]. The main point of the CE concept is to capitalize on material flow recycling and to balance economic growth and development with environmental and resource use [9]. Today, the concept of CE has been adopted more widely and organizations across the world such as the European Commission and the Ellen MacArthur Foundation are promoting certain aspects of it, including materials design and flow assessment [10], among others.

The objectives of this study are (1) to review the literature considering the history of the concept of CE to provide a context for (2) a critical examination of how it is applied currently. To narrow the scope and for purposes of this literature review, the following thematic categories are used to organize the results: policy instruments and approaches; value chains, material flows, and products; and technology, organizational, and social innovation. These thematic categories were in part selected based on the *Economie Circulaire dans l'Union Europeenne Resume Analytique* [11] and World Bank [12] findings and recommendations for applications of the CE concept. The literature review was conducted using searches of the journal databases Scopus and ScienceDirect as well as Google Scholar, and keywords including, but not limited to, industrial symbiosis, eco-industrial park, material flow analysis, and circular economy. Close to 1500 relevant papers were identified, over 150 of which were selected for inclusion in the review, covering a geographic scope of 20 different countries.

2. History of the circular economy concept

There is no clear evidence of a single origin or originator of the CE concept, but contributors include U.S. professor John Lyle; his student William McDonough; the German chemist, Michael Braungart; and,

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Abbreviations: CO_2, Carbon dioxide; CE, Circular economy; GHG, Greenhouse gas

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architect and economist, Walter Stahel [13]. The CE concept may also have been inspired by Rachel Carson's Silent Spring [14], the ‘limits to growth’ thesis of the Club of Rome in the 1970s, the ‘spaceship earth’ metaphor presented by Barbara Ward and Kenneth Boulding, and work by eco-economist Herman Daly [8]. Pearce and Turner developed conceptual frameworks for the CE concept such as the resource-products-pollution mode [15]. The principles of the CE concept include the 3Rs (reduce, reuse, recycle) [2] and the 6Rs (reuse, recycle, redesign, remanufacture, reduce, recover) [16].

The CE concept is interwoven with various other concepts, some of which predate it, like industrial symbiosis [17–19]. Eco-city is a CE related concept that is rapidly evolving in Japan, Singapore, and elsewhere [20]. In industrial ecology and systems theory, the CE concept is associated with a broad range of subjects such as thermodynamics and ecological economics. Important to note is the CE concept does not work for thermodynamics, in particular because no system can be 100% circular (or closed) due to the entropy law [8,21]. In systems theory and according to thermodynamics, application of CE concepts influences the production and consumption models in a way that causes a ‘degrowth phase’ not a ‘growth-oriented phase’ of the economic system [22–24].

The CE concept evolved differently in light of diverse cultural and social and political systems [25]. In Germany, in the early 1990's, the CE concept was introduced into environmental policy with the intent to address issues associated with raw material and natural resource use for sustained economic growth [26]. In China, in the late-1990's, an eco-industrial park model was promoted, and in the mid-2000's, the application of the CE concept was introduced in line with Hu Jintao's concept of a "harmonous society," which was later implemented with emphasis on waste recycling post consumerism and the development of waste-based closed loops within a company or among different processor and consumer groups [27]. In China, the concept of CE is used as a mechanism for profitable product development, new technology development, upgrading equipment, and improving industry management [28]. The CE concept is applied in the UK, Denmark, Switzerland, and Portugal for waste management, primarily, although there are also business models that apply material circular use (or reuse) concepts [29]. Some CE-related initiatives aim to increase consumers’ responsibility for material use and waste, which is evident in some parts of Korea and Japan [30,31]. In North America and Europe, corporations apply the CE concept with the aim to enhance reduce, reuse, and recycle programs, and to conduct product-level life cycle studies [32,33]. In the past decade, a range of government top-down, e.g., material flow analysis frameworks, and bottom-up, e.g., harmonious society, approaches emerged that include the CE concept and tools for quantitative assessment of new CE initiatives [12,34,35]. In Serbia, implementation of the CE concept is investigated to explore potential for and benefits of new CE initiatives [36]. With emerging CE initiatives, various tools are evolving to assess, e.g., material flows [37,38], and many of these tools do not evaluate the social or community context in which the initiatives occur [39].

3. Current applications of the circular economy concept

The three thematic categories used to organize the literature review results include (1) policy instruments and approaches; (2) value chains, material flows, and product-specific applications; and (3) technological, organizational, and social innovation.

3.1. Policy instruments and approaches

Policy instruments are regulatory and economic instruments implemented to achieve an effect that will not occur in the absence of governmental intervention. Note that there are different approaches to policy including but not limited to policy instruments, policy frameworks or top-down approaches, and government programs or bottom-up approaches. In the following sections, applications of the CE concept are presented along with the main objects or ideas, actors, and practices of each, which are the essential components of policy as defined by Jiao and Boons [40,41].

3.1.1. Eco-industrial park, eco-industrial network, and industrial symbiosis

Eco-industrial park initiatives include the exchange of water, energy, information, and or materials “to minimize energy and raw materials use, reduce waste, and build sustainable economic, ecological, and social relationships” [42,43]. Eco-industrial networks or industrial symbiosis networks also evolved with the same idea as eco-industrial parks but cover a broader geographic area within a region, a province, or a country. Sometimes the terms industrial symbiosis, eco-industrial network, and eco-industrial park are used in the literature synonmously. It is necessary to make a distinction between these terms, however, because the scale and scope of the objectives, actors involved, and practice are different, as are the potential synergies that may exist for each initiative. [44]. A critical point is that the spatial relationship, i.e. the distance between industries, influences energy and material flows between entities [45].

Eco-industrial park developments are the first manifestation of industrial symbiosis, occurring for the first time in the 1960's in the eco-industrial park in Kalundborg, Denmark [46]. Today, there are several examples of eco-industrial parks around the world– in India, Australia, Korea, Japan, Canada, the United States, and Europe– that build upon existing and potential linkages within a region [47,48]. Many of these eco-industrial park developments are supported by policy to encourage material and information interchanges [47,48]; however, some eco-industrial parks evolved without government intervention.

The eco-industrial park in Kalundborg, Denmark exemplifies natural physical linkages of material flow exchange between industries within a region. This eco-industrial park self-organized in that its economic feasibility resulted from bilateral agreements among industries without the participation of external forces [49,50]. The park continues to evolve and acts as a model system for new industrial symbiosis developments elsewhere in the world [49,50]. The eco-industrial park in Ostergotland (a region of Sweden) is another self-organized system that supports material flow and linkage between a sawmill, a pellet production plant, a pulp mill, and several municipality actors for purposes of reuse of and reduced waste of $CO_{2,}$ heat, and power within biofuel applications [51]. The Industrial EcoSystem project Rotterdam Harbour Industrial Ecology Project in the Netherlands started from the bottom-up, initiated by industry actors’ interests in the socio-economic welfare of new employees [52]. The Project culminated in 1994 with 69 industries involved, and now includes stakeholders from the government and academic sectors, as well as community members who are collaborating with the aim to reduce heat and CO_2 waste [52].

Most eco-industrial parks or networks and industrial symbiosis initiatives are not self-organized and are instead inspired and supported by policy. In Italy, the eco-industrial park concept was introduced in 1997 under Italian law *Area produttiva ecologicamente attrezzata*, Law No. 57/1997 (article 26), entrusting regions to develop industrial zone initiatives according to the definition “industrial zones equipped with infrastructure and systems able to guarantee health, safety and environment protection” to which 15 regions responded. One region (Emilia-Romagna) instituted a regional law (Planning Law no. 20/2000) to develop the eco-industrial parks with sustainability principles [53]. Within Emilia-Romagna region, the Raibano eco-industrial park has been assessed by Conticelli and Tondelli [53] using a strategic environmental assessment, but the project has not been implemented to date. In the United Kingdom, several eco-industrial programs started under the banner of the National Industrial Symbiosis Program [54], a program which is now an independently owned commercial enterprise [55].

In the United States, the President's Council on Sustainable Development established three eco-industrial parks after the June 1992 United Nations Conference on Environment and Development. Heeres et al. [56] evaluated these eco-industrial parks (in Baltimore, Maryland; in Brownsville, Texas; and in the Cape Charles Sustainable Technologies Industrial Park in the town of Cape Charles), along with similar eco-industrial parks in the Netherlands (the Industrial Eco-System project, the Rietvelden/Vutter sustainable revitalization project, and the Moerdijk eco-industrial park). Heeres et al. [56] concluded that for an eco-industrial park to succeed, both economic incentives from the government and a community-based, bottom-up approach to participation are required. An awareness of the benefits to current operations and the sharing of resources (water, energy, and wastes) rather than a mere exchange of resources is also required for an eco-industrial park to succeed [56].

In China, the community-based, bottom-up approach to eco-industrial park development is common practice. However, top-down government agencies and initiatives support CE to form an integrated approach for implementing new CE initiatives. Unlike other countries, China seems to embrace the CE concept as a viable economic reform model. The National Development and Reform Commission is in charge of CE related initiatives [57]. In China, the core ideology of the CE concept is the 3Rs principles that encourage full life cycle utilization of products to reduce waste and save resources [8]. Waste exchange or byproduct exchange is implemented or planned in almost every eco-industrial park because it is economical to do so, in particular for metal scraps, waste plastics, paper or wood scraps, ash, and sludge [58].

China's CE-related initiatives are implemented at three levels: the enterprise level, the eco-industrial park level, and the social level. China's eco-industrial park initiatives are in part led by the government, and three ministries influence their establishment–the Ministry of Environmental Protection, the Ministry of Commerce, and the Ministry of Science and Technology [59]. China first promoted industrial development sites in the form of Economic and Technological Development Areas in 1984 and then High-Tech Parks in 1988 [59]. Among the 210 Economic and Technological Development Areas and 113 High-Tech Parks, 85 serve as eco-industrial park pilot projects, and 23 of them are considered to be under the auspices of China's national eco-industrial park initiative. The State Environmental Protection Administration started a pilot operation to construct exemplary eco-industrial parks in China in 1999, as a mainstream policy approach model adapted from Germany and Japan [60]. China's augmentation of eco-industrial parks is a bottom-up model [8,40]. Other policy instruments introduced by the Chinese government to support the CE concept include the Law of the People’s Republic of China on Promotion of Cleaner Production initiated on January 1, 2003. This law was the first in China to provide an explicit definition of CE. In 2004, the CE concept was written into the 11th Five-Year Plan for National Economic and Social Development, which made it the fundamental principle and an important target of National Economic and Social Development. Also, the Law on the Prevention and Control of Environmental Pollution by Solid Wastes (2004 revision) laid a good foundation for the future legislation of CE initiatives in China [61]. In 2007, the first resource recovery management measure (the Administrative Measure for Renewable Resource Recovery) was issued by the government of China [61]. The Circular Economy Promotion Law, approved in 2008 and enforced since January 2009, helped to initiate other environmental programs and CE initiatives [62]. Tianjin Economic and Technological Development Area, one of the first of three national eco-industrial parks approved by China's Ministry of Environmental Protection in 2008, motived the establishment of the Industrial Symbiosis Innovative Technology Alliance (in 2011). The Alliance benefited 81 inter-firm symbiotic relationships involving utility, automobile, electronics, biotechnology, food and beverage, and resource recovery clusters [63]. Beginning in January 2009, the Circular Economy Promotion Law took effect, supporting further consideration of the relationship between economic development and environmental problems [61]. To date, China promulgated cleaner production standards for more than 30 industries like the oil refining industry and the monosodium glutamate industry [57].

3.1.2. *Eco-industrial parks today*

Eco-industrial parks now act as innovation platforms for environmental management and have in some ways created a paradigm shift from the end-of-pipe treatment to a more system-assessment oriented one. With the advent of eco-industrial parks, interest in life cycle assessment [64,65] and materials flow analysis increased to provide opportunities to improve the product value chain [66]. Evolutionary, multi-object system optimization models that integrate life cycle assessment and industrial symbiosis also developed [67]. Thus, systematic assessment of supply chains improved in that there is more emphasis on the valorization of wastes and resources and possible exchange of resources between different supply chains.

3.1.3. *Eco-industrial estates and networks*

Thailand established the Industrial Estate Authority of Thailand as a state enterprise within the Ministry of Industry in 1972 to develop eco-industrial estates. The goal of these estates was to decentralize industrial development within provinces by utilizing and obtaining value from waste through reuse, recycling, and waste minimization [68]. Note that an eco-industrial estate is similar to an eco-industrial network in that they have the shared objective to create circular economies and industrial symbiosis at a regional scale. In Thailand, in 2000, five industrial estates were selected as pilot projects for eco-industrial estate development [69]. These projects failed due to the government rescinding financial support. The government's actions have been attributed to a lack of government-industry dialogue, information exchange, and effective economic instruments that support waste removal [70].

In 2006, a separate initiative developed in Thailand referred to as the *Map Ta Phut* Industrial Estate [71]. It had a different set of actors including the industrial sector and the academic research sector, as well as a framework for eco-industrial evaluation [72]. The *Map Ta Phut* Industrial Estate was the start of the second phase of eco-industrial estates initiatives in Thailand, and with it, in general, there was a shift from a top-down to a bottom-up approach to new CE initiatives [72]. Panyathanakun et al. [72] provide a careful review of eco-industrial estates and the bottom-up and top-down approaches to new and ongoing eco-industrial estate initiatives in Thailand.

In South Africa, in 2000, the Nuclear Energy Corporation of South Africa [73] and the Cape Metropolitan Council, through its Integrated Waste Exchange program, developed eco-industrial networks with the idea to reduce and to manage waste [74]. Following initiation of those programs was the development of mechanisms to integrate dematerialization and decarbonization strategies along with the use of life cycle assessment and material flow analysis [75]. Results from the evaluation of these programs and others around the world (e.g., Puerto Rico) showed that a lack of community involvement influences industrial productivity and industrial symbiosis that in turn generates economic constraints and social disparities between different regions in a country that inhibit the success of CE-related initiatives [76–80]. For example, in Australia, the Kwinana Industrial Area and Gladstone mining areas have many possible synergies between multiple actors for energy, material, and water flows, which could facilitate innovative and new industry opportunities; however, policy instruments are not in place to mobilize these initiatives [81,82]. Mattiussi et al. [82] and other studies conducted about industrial symbiosis and CE initiatives in these regions [83] identified the need for an integration of a bottom-up and a top-down approaches to industrial symbiosis network development.

3.2. Value chains, material flows, and products

In this section, peer-reviewed published literature on applications of the CE concept to specific systems are reviewed. The priority materials categories identified in the United Nations 2014 scoping study aimed to discover "potential priorities and policy options to support the CE concept in the European Union" are used to organize the literature review results into subsections: wood and paper, plastics, metals, agricultural products and waste, and phosphorus (and other chemicals) [84]. In the United Nations study, chemicals and compounds are not categorized as priority materials, however they are included as important “cross-linkages” within priority material categories [84], whereas water and land are considered priority resources [85].

3.2.1. Wood and paper

The forest, pulp, and paper industry typically consumes a large amount of energy. Yet, in an industrial symbiotic setting, this industry can share heat and electricity with municipal power plants [86]. Few studies have evaluated actual industrial symbiosis systems for wood and paper industries. Sokka et al. [87] present a case study of Kymi plant of the UPM Kymmene Corporation in Finland and its industrial symbiosis with a power plant, a water purification plant, a waste water treatment plant, and a landfill. The Sokka et al. [87] study show that there are GHG emission savings due to the industrial symbiotic relationships. Other studies [88–91] demonstrate potential synergies between energy, waste, and water flows within a hypothetical circularity mode, where the CE concept is applied to enhance material exchange for the forest, pulp, and paper industries. Li and Ma [92] evaluated the potential benefits of the creation of the Guangdong Silver Island Lake Papermaking Park in China, showing potential savings on the water utilization rate for that Papermaking Park industry.

3.2.2. Plastics

Plastics make up approximately 20–30% (by volume) of global municipal waste flows, the result of an average per capita consumption of 40 kg of plastic material yr^{-1} [93]. Various initiatives are underway to manage plastics recycling and reuse [94,95]. Lee et al. [96] critically examined material flows of phthalates (chemicals used to make plastics) in Europe and Denmark to address “upcycling” or maintained quality, “downcycling” or decreased quality, and “risk cycling” or the presence of contaminants in waste streams. The authors present a conceptual framework for implementing the CE concept based on “clean” resource flows and principles of sustainability linked to policy instruments [96].

3.2.3. Metals

Metal industries like iron and steel can exchange energy, water, and waste materials with other sectors, most notably as a cement blending material [97]. Active iron or steel industrial symbiosis initiatives exist in Sweden [98]; in Kwinana, Australia [45]; in Mipo and Onsan industrial complexes in Ulsan, South Korea [99]; in Japan [100]; and more extensively in China [101]. Dong et al. [101] identified several key challenges to the circularity of steel and iron and related industrial symbiosis networks including excess waste material of one kind (e.g., plastic) that does not meet the supply and demand needs of another industry within the same system (e.g., steel). Also, naturally, the exchange of materials requires transport and infrastructure; however, if the necessary infrastructure is not in place, then materials can not be transferred within an industrial symbiosis network. It is important to note that new initiatives need policy instruments like economic incentives to provide initial invests in infrastructure development and maintenance that support the exchange of resources [97]. Pauliuk et al. [102] and Wubbekea and Heroth [103], in their studies of the steel industry, concluded that the main barriers to CE application are economic instruments, i.e. tax incentives for taking back end-of-life products, waste recycling, and management in secondary vs. primary production steel that changes its quality or grade. In some cases, the available technologies may also prove to be a challenge. For example, in a study of China's iron and steel industry, the researchers concluded that sulfur dioxide would be difficult to reduce within the supply chain, due, in part, to the available desulfurization technologies [104].

3.2.4. Phosphorus and other chemicals

The chemical industry plays a vital role in the economy as a source of fine and bulk chemicals. However, there are few thorough studies of specific chemicals or related value chains in the CE literature. Ma et al. [104] used material flow analysis to assess phosphorus in chemical industries, and discovered that utilization of phosphor-gypsum can increase to 100% by implementing CE principles [104]. Zhang et al. [105] and Tian et al. [58] demonstrate the utility of assessing the metabolism of one element at a time, i.e. sulfur and carbon, respectively, to identify barriers to the circularity of chemicals between industries, as well as within industries. Carbon is the base element for many organic chemicals. As such, Tian et al. [58] focused on carbon metabolism and efficiency in chemical industrial parks in China, concluding that improvements can be achieved through green chemistry and green engineering with the aims to increase energy efficiency, environmental regulation, and physical exchange of chemicals. Zhang et al. [105] evaluate an eco-industrial park in China called Lubei, and sulfur used within “three chains for recycling materials and energy: the ammonium phosphate sulfuric acid cement chain, the stepped utilization of seawater chain, and the cogeneration of salt, alkali, and electricity chain.” The authors’ in-depth analysis of sulfur revealed disparate beliefs about system organization, e.g., cement clinker production versus sulfuric acid plant production, two processes that are equally important in that network, actually. Further research on chemicals used and reused within closed-loop systems in, e.g., industrial settings, is needed.

3.2.5. Agricultural products and waste

The CE concept is applied to support resource reuse in agricultural industries like tanneries [106]. However, there are a limited number of studies about actual CE application to agricultural and aquacultural systems. A study on the animal-husbandry breeding industry in Jilin Province of China includes pharmaceutical, fertilizer, and agricultural industry in material reuse and recycling to reduce and manage waste streams and increase annual income [107]. In Vietnam, Mol and Dieu [108] assessed a potential eco-industrial network for a Vietnamese tapioca industry with the aim to minimize waste within and from the Industry. For a different system, Anh et al. [109] applied a tri-network model developed by Mol [110], where ‘tri’ refers to economic, policy, and social network factors, to identify potential barriers to implementing a proposed shrimp production and eco-industrial network in Vietnam. In conclusion, the authors found economic, technology (wastewater treatment), as well as policy instrument challenges to implementation of the proposed eco-industrial network [110].

3.2.6. Water

In Australia, in the Kwinana industrial area, the circular use of water proved to be economically beneficial, in particular because the cost of water has increased over time due to the decline in groundwater and surface water stored in reservoirs in the Perth potable water supply network [111]. In Jordan, application of the CE concept is applied to water use due to the water scarcity issues that lead to the need to close the loop and recycle water through wastewater treatment, i.e. for select reuses [112]. Schetters et al. [113] explore some strategies for water reuse within industrial settings. Schetters et al. [113] studied the circular use of ground calcite pellets produced from industries in Amsterdam as an alternative seeding material for Garnet sand in pellet softeners for the drinking water treatment process. They showcase the potential economic and material reuse benefits for the industries and water treatment facilities, and more importantly the ability to maintain the water quality within the industry using the technology. Li and Ma [92] studied water along with energy and solid material utilization in the Guangdong Silver Island Lake Papermaking Park in China. Each of these studies shows some of the potential benefits the circular use of water and other materials in creating a competitive advantage for the industries involved in the Park over other industries that have no circularity to explore potential for resource exchange(s). Overall, these papers all conclude that the cycling of water within a closed-loop system is possible if the materials added to the water throughout its use (and reuse) consider the long-term potential applications and quality of the water. Similar results were found in an assessment of the application of the CE concept to water tourism [114].

3.2.7. *Land*

The opportunity to apply waste to the land, e.g., from bioenergy industries to create closed-loop systems that use the CE concept is a topic of research interest lacking detailed analyses to date [91]. However, the critical importance of land as the "basic source of biomass, energy, and mineral reserves" cannot be overstated [115]. The land is linked directly to agricultural product and in some cases bioenergy production which has been explored to a limited extent within the contexts of supply-chain analysis [116–120].

3.3. *Technological, organizational, and social innovation*

Innovation can be stimulated by government and industry actors [45], by economic geography and value chains, or by feedbacks between ecological and economic systems [111]. Overall, the barriers to implementing the CE concept are often technical and economical, and are sometimes due to a lack of stakeholder involvement in a shared vision, as was shown in assessments of the printed circuit board industry [121] and the electric vehicle industry [122]. Organizations like the Ellen MacArthur Foundation and the McKinsey & Company are creating mechanisms for technical and social innovation.

The Ellen MacArthur Foundation developed a list of priority research themes to include product and materials innovation in biological and technical materials and processes, economic and business models, material flows and reverse cycle systems, and enabling conditions and systems for the energy sector [13]. These priority research themes (except material flows and reverse cycle systems) are examined briefly in this section through the observation of peer-reviewed literature that investigates one or more aspect of each theme. One additional category is added to provide a brief overview of innovative assessment models for various CE-related initiatives.

3.3.1. *Product and materials innovation in biological and technical materials and processes*

Cohen-Rosenthal [123] describes entropic effects and materials and flows that should be part of a how "stuff" works and the analysis of material manufacturing, design, and reuse. Conventional industrial manufacturing is used to convert a conglomerate of raw materials into processed goods and products that often do not have the same structure or function as the parent raw materials chemically, physically, or biologically. Theoretically, the CE concept suggests materials can be designed to be cycled through industrial systems as if they are in natural systems [124]. Yet, this idea is impractical when there are engineering and technological limitations to manufacturing and designing products that are akin to the structure or function of their parent (raw) materials.

3.3.2. *Economic and business models*

Most existing empirical assessments of the economic and business model dynamics of CE initiatives can be characterized using comparative studies, e.g., [125]. Some researchers use a dynamic systems assessment approach whereby conceptual time-space conditions of CE concepts applied to industrial systems are considered. In a comparison of early and advanced industrial symbiosis projects operating within the Dutch stimulation program, Boons and Spekkink [126] found differences in the capacity of the industries involved to handle the projects. Boons and Spekkink [127] developed a conceptual framework for assessing industrial symbiosis using the event sequence analysis method. They suggest that outcomes of the event sequence analysis need to be evaluated using indicators such as energy consumption and social network analysis. Overall, these studies [65,125–127] agree that the actors involved and events that occur over a time period of ~10 years show distinctive patterns with respect to the CE concepts applied to industrial symbiosis systems, such that how these systems evolve can be predicted with some accuracy. As such, the researchers iterate that if a set of industries or a government has a goal in mind, then an effective industrial symbiosis network can be designed to meet the objectives based on models and lessons learned from previous systems.

Dong et al. [101] developed a network analysis framework with a defined system boundary to assess economic and environmental gains based on a material flow analysis. Zhang et al. [105] conducted a study on sulfur metabolism, and developed a network model that includes the enterprises or industries as nodes and the exchanges amongst them as the paths. The model includes a structural distribution and functional attributes that allow for the assessment of the existence of flows between nodes and the magnitude (characteristic) of each flow. The researchers conclude that the methods they employed in their studies are data intensive, yet the results of the work are useful in that they provide a basis to improve and to stabilize industrial symbiosis operations.

Park et al. [128] used ecological modernization theory as a lens through which to evaluate three firms in China and contextualize the firm-level and industrial-level value streams, concluding that technological and innovative practices increase in value within a company or an industry that stimulates CE-related initiatives. Park et al. [128] and Zhu et al. [129] assess supply-chains from upstream and downstream, using a statistical approach to evaluate environmental supply chain cooperation from three perspectives (or dimensions): internal environmental management, eco-design, and corporate asset management and recovery. Both studies [128,129] highlight the importance of bottom-up, customer cooperation, and top-down, moderating or mediating effects of manufacturers, managers, and government agencies. Heuristic algorithms and neural network models were used to assess iron and steel industry initiatives in China that apply the CE concept [130,131]. These studies show the importance of using models as tools to evaluate current CE initiatives to systematically improve the design of new CE-related initiatives.

3.3.3. *Enabling conditions and systems for the energy sector*

Zhou et al. [130] assessed energy in three sectors in China (residential households, transportation, and the building materials industry) to create a conceptual framework to evaluate links between urbanization and energy consumption in line with CE principles. The authors conclude that energy savings is possible in each sector, e.g., through the use of higher quality building materials (cement, steel, aluminum, and glass) and improved energy performance of buildings. Sokka et al. [87] assess industrial symbiotic relationships in Finnish forest industry with the idea to reduce GHG emissions and energy consumption in biofuel production systems. The authors highlight the importance of not perceiving energy production systems (in this case the authors refer to a pulp and paper industry used in part for fuel production) as stand-alone systems, in particular when there are cross-linkages within an eco-industrial system.

3.3.4. *Models used to assess CE related initiatives*

Several different models have been created to assess CE-related initiatives. This section highlights selected models that provide a careful assessment of specific applications of the CE concept. For the most part, the models alluded to in this section are not noted in previous sections of this article.

Eco-industrial parks like Kulundborg in Denmark that have been around for a long time provide opportunities to study and to develop models that can be used to systematically assess new CE-related developments. Such models include the planned eco-industrial park model developed by Chertow [132], the three-step model presented in Chertow et al. [17], and the strategic environmental assessment model used by Conticelli and Tondelli [133]. The three-step model introduced in Chertow et al. [17] includes sprouting (initial exchange of resources, e.g. between industries), uncovering (i.e. regional learning), and embeddedness and institutionalization (i.e. self-organization, consideration of scope or geographic proximity, development of social capital, and expansion of initial exchange or resource and idea). This three-step model allows for an adaptable approach, i.e. it is neither a top-down nor a bottom-up approach. It does not emphasize the importance of a particular institutional structure or actor group, but rather depends on self-organization and allows for observation of regionally specific system dynamics, e.g., including specific conditions such as those described in Chiu and Yong [134] for Asian developing countries. The strategic environmental assessment used by Conticelli and Tondelli [133] includes step two and step three of the Chertow et al. [17] model (i.e. uncovering, and embeddedness and institutionalization) with a top-down approach to implementation and evaluation and monitoring of eco-industrial parks.

Soft science approaches to CE project assessment includes, yet is not limited to, the strengths, weakness, opportunities and threats (SWOT) analysis employed by Veiga and Magrini [135] for Brazil and by Chiu and Yong [134] for Asian Developing Countries. This type of soft science approach can be used to assess corporate social responsibility schemes, and knowledge and information exchange. Soft science approaches can be employed before a new CE project starts to provide useful information for stakeholders, e.g., about the social dynamics within a firm.

Employing models such as SWOT and the strategic environmental assessment for new CE-related initiatives helps stakeholders to examine the practicality of the initative before investing in it. These types of models are essential when it is believed that recycling and reusing wastes are an economical option for businesses [136]. Tools like an economic input-output (EIO) analysis can be used to quantify potential economic benefits [137], or to be aware of potential barriers to the success of a new CE-related initiative, e.g., government policy or waste management fees that prohibit or incentize waste disposal rather than waste reuse [8,138]. Other models developed for the assessment of the CE concept for water use and reuse within industrial and natural systems include Rubio-Castro et al.'s [139] discretized, integrated model, which "could be applied to any CE development project" scenario, yet has not been tested to date.

4. Discussion

4.1. Circular economy successes and challenges

The CE concept has influenced policy and innovation in some of the world's largest economies such as China, Germany, Japan, and the UK. One finding of this review is that CE-related initiatives need to be well designed and evaluated regularly. Whereas many new CE-related projects fail, others have operated for decades, for example, in China [140] and Denmark [45]. In some cases, there is an opportunity to learn from the projects that succeed as well as those that fail. Appropriate policy instruments contribute to the success of [2,70,141] and to the innovation and network synergies that help stakeholders to meet the multiple objectives or environmental, economic, societal/managerial, and topological challenges of CE-related initiatives [81,82,142]. Policy that supports standardized use and recycling of products (or materials) is required to encourage industries to adopt the CE concept [143].

Social innovations that allow for community involvement, wider public education, and broader media coverage are essential to the success of an initiative that applies the CE concept [144]. Further, without knowledge resources (i.e. informaiton), stakeholders either "do not know how to respond to recycling pressure or may employ tactics that do not effectively reduce their waste" [56,70,145]. Also, successful implementation of the CE concept requires that the stakeholders have a clear idea of the potential economic benefits, social disparities, waste reduction, reduced environmental burden, and reuse of materials [76–80,105,121,122].

Specific value chains, material flows, and products need to be assessed to show the value of applying the CE concept. There are potential barriers to product-level use and reuse in a closed-loop system, including the lack of information about specific products [146] and the perceived risks associated with refurbishing or reusing materials like plastics [147] and food wastes [148]. However, there is evidence that the consumer demand and the market for reused and recycled products is increasing [31], and dialogue between procurers and suppliers can further support a business model for this market that can be sustained [149].

A key challenge related to the use and reuse of materials (e.g., steel) in an application of the CE concept is the quality of these materials over time [102,103]. This challenge was discussed in the 1990s by Leontief [150] who considered the value of materials over time after use and reuse using mathematical principles. Leontief concluded that economic as well as physical material value can be estimated depending on the stakeholder need(s) [150]. In a more recent study, Franklin-Johnson et al. [151] provide a dynamic model for assessing material use for finding the maximum value of a material over time. Further investigation of the quality of materials used and process and product design that supports reuse of materials over time, e.g., through green engineering, is needed.

5. Conclusions

The body of literature and real-world cases of successes and failures of the CE concept show that CE-related initiatives require integrated bottom-up and top-down approaches to implementation and evaluation. Policy instruments (economic and regulatory instruments) such as subsidies and tax incentives work when governments have clear objectives for policy processes that are evaluated and regulated, iteratively, to achieve short- and long-term goals. Without an evaluation framework or bottom-up support from the industry or the community, CE initiatives are not sustained.

Consistently, information exchange is cited as a constraint to the success of CE initiatives. In-depth assessment of ongoing CE initiatives highlight barriers to sustained circularity due to material flows that exceed or do not meet demand, and transport and infrastructure, e.g., for energy exchange. Many CE-related initiatives take advantage of yet can be limited by proximity–the industries or resources available within the economic geography. Several CE-related initiatives are constrained by a lack of regulation, incentive(s), and infrastructure required for resource exchange.

Critical research gaps observed in this study include the CE concept application to and assessment of the biological systems (e.g., agricultural industries) and the chemical / biochemical industry products and value chains. Plastics are less studied, yet there are several European-based research initiatives underway to address this research gap. It is still unclear how land use can be integrated into CE-related initiatives, design, and evaluation.

The quality of materials circulated in, for example, an eco-industrial park or industrial symbiosis network is of critical importance. However, this topic is highlighted in only a few studies. The studies that consider this topic do so in the context of downcycling, upcycling, and risk cycling in the metal and plastic industries, and to some extent with respect to water cycling, however it is often underemphasized or ignored in the chemical industries and agricultural products and waste cycling.

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