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Exploring circular economies in the built environment from a complex systems perspective: A systematic review and conceptual model at the city scale

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Highlights

- Participatory approaches are key to ethical circular economy interventions in cities.

- Economics and decision sciences are lacking from circular economy research.
- Behavioral and policy issues remain understudied in the recent literature.

Abstract

As one of the globe's leading sectors for resource use and carbon emissions, the built environment could play a vital role in the circular economy (CE). This study aimed to understand and map the complex systems inherent to CE interventions in the built environment. We conducted a systematic literature review and thematic analysis to identify CE case studies in different cities around the globe that have considered systemic dimensions of CE and their interconnections and iterations. These include governmental, economic, environmental, technological, societal, and behavioral dimensions. The case studies informed a conceptual model that illustrates how CE functions in an urban setting. The model represents the interdependencies, flows, feedbacks, and unintended consequences that may result from the interaction between the CE research dimensions in cities. We hope to help policymakers, designers, and researchers to better understand how CE functions in urban settings, and to ethically design changes in the system to achieve circularity goals. The results suggest that meaningful stakeholder engagement is key to co-designing ethical CE interventions in the built environment. Finally, engaging disciplines like economics and decision sciences, and better understanding the role of public policies and human behavior are vital to future CE interventions in urban settings.

Previous Next

1. Introduction

The circular economy (CE) has been increasingly discussed as a potential solution to climate change and resource scarcity, problems that have been exacerbated by population growth and rising infrastructure needs (Blomsma & Brennan, 2017; Bocken, de Pauw, Bakker & van der Grinten, 2016; den Hollander, Bakker & Hultink, 2017; Geisendorf & Pietrulla, 2018; Ghisellini, Ripa & Ulgiati, 2018; Kalmykova, Sadagopan & Rosado, 2018; Munaro, Tavares & Bragança, 2020; Schroeder, Anggraeni & Weber, 2019; Stahel, 2016). The main goal of CE is to preserve resource value while decoupling economic growth from environmental degradation (Ellen MacArthur Foundation, 2013). Recycling alone has proven insufficient to reduce material use and carbon emissions around the globe (Circle Economy, 2019), and advocates for CE have emphasized the potential of circular strategies to narrow, slow, and close resource loops (Ellen MacArthur Foundation, 2019; Stahel, 2016). As one of the globe's leading sectors for resource use and carbon emissions, the built environment could play a vital role in the transition towards CE (Pomponi & Moncaster, 2017). “Built environment” refers to “the human-made surroundings that provide the setting for human activity”, which include buildings, parks, neighborhoods, and infrastructure such as transportation, water supply networks, and energy networks (Kaklauskas & Gudauskas, 2016). According to the Ellen MacArthur foundation (2019), CE strategies for the built environment could lower global carbon emissions by 38% in 2050.

A common way to synthetize CE strategies is through the ReSOLVE framework (The Ellen MacArthur Foundation, 2015), which describes six action areas to move towards CE: (1) Regenerate, (2) Share, (3) Optimize, (4) Loop, (5) Virtualize, and (6) Exchange. *Regenerate* refers to shifting to renewable energy and materials, restoring the health of ecosystems, and returning biological resources to the biosphere (The Ellen MacArthur Foundation, 2015). Examples in the built environment include using closed-loop water systems and green infrastructure (Braungart, 2020; Pearlmutter et al., 2020; Sassi, 2008). *Share* refers to sharing assets like vehicles, equipment, and facilities, and extending resource life through maintenance, design for durability, and reuse (The Ellen MacArthur Foundation, 2015). In the built environment, strategies like adaptive reuse (e.g., Assefa & Ambler 2017) and design for disassembly and adaptability (Cruz Rios & Grau, 2020; Durmisevic, 2019; Stahel, 2019) are key to extend the life of buildings and infrastructure. *Optimize* means to increase efficiency, eliminate waste during production, and leverage big data and automation. The principles of Lean Construction are an example of optimization in the built environment (Benachio, do Freitas & Tavares, 2021). *Loop* refers to remanufacturing, recycling, and anaerobic digestion. Besides the well-established practice of recycling construction materials, obsolete building products can be dismantled and remanufactured. For example, in 2010, the Empire State building had over six thousand windows remanufactured on-site (Stahel, 2019). *Virtualize* means dematerialize, or delivering value using a minimum amount of resources though digital solutions, for example, such as online shopping that substitute brick-and-mortar retail (The Ellen MacArthur Foundation, 2015). Finally, *exchange* refers to material, technology, and business model innovation. Examples of such innovations applied to the built environment are material passports, radiofrequency identification (RFID), building information modeling (BIM), and blockchain to enable material tracking and reuse of building and infrastructure components (Copeland & Bilec, 2020; Luscuere & Mulhall, 2018; Ness, Swift, Ranasinghe, Xing & Soebarto, 2015).

The circularity of the built environment can be analyzed through different levels or scales: the micro level (i.e., building materials and products), the *meso* level (i.e., individual buildings), and the macro level (i.e., neighborhoods, cities, built environment) (Pomponi & Moncaster, 2017). The larger the scale, the more complex and interdisciplinary the systems involved. For example, contrary to manufactured products, buildings are unique assemblies of diverse building materials, products, and systems with different lifespans (Pomponi & Moncaster, 2017). Cities, in turn, are extremely complex systems where social, ecological, and technical dimensions are deeply interconnected and affect each other in both desirable and undesirable ways (Nogueira, Ashton, Teixeira, Lyon & Pereira, 2020). McPhearson, Haase, Kabisch and Gren (2016) argued that understanding the transdisciplinary and complex nature of cities is key to advancing urban sustainability and resilience agendas. The authors highlighted the "need to better capture and understand the feedbacks, interdependencies, and nonlinearities" inherent to complex urban systems (McPhearson et al., 2016).

Similarly, authors have emphasized the need to understand CE as a complex system (Calisto Friant, Vermeulen & Salomone, 2020; Desing et al., 2020; Korhonen, Honkasalo & Seppälä, 2018; Laurenti, Singh, Frostell, Sinha & Binder, 2018). Laurenti et al. (2018) listed some of "unaddressed systemic challenges" to CE, including a lack of consumer awareness, regulatory and market barriers, and slow technological progress towards resource recovery. Calisto Friant et al. (2020) pointed out the lack of attention to issues of governance, justice, and cultural change in the CE literature, which reflects the little participation of social science and humanities in CE research to date (Calisto Friant et al., 2020). The authors warned that, "by overlooking social considerations, CE research is proposing a technological path to sustainability that many have criticized for being overly optimistic regarding the speed of technological transitions and the capacity of society to integrate disruptive innovations" (Calisto Friant et al. 2020, p. 6).

Systems thinking is key to better understand complex systems like CE and the built environment (Jaradat, 2015). Systems thinking is a set of analytic skills that can help identify and understand systems, and design changes to produce desired effects (Arnold & Wade, 2015). Systems thinking include the ability to understand and conceptually map the system structure, including its elements, interconnections, stocks and flows, and cause-effect feedback loops (Arnold & Wade, 2015). To contribute to a systemic view of CE in the built environment, Pomponi and Moncaster (2017) created a framework with six interconnected dimensions of CE as found in buildings research: governmental, economic, environmental, technological, behavioral, and societal dimensions. The *governmental* dimension was concerned with policy instruments to support CE (e.g., tax breaks for salvaged building products). The *economic* dimension of CE research focused on circular business models such as product-service systems. Research within the *environmental* dimension assessed the environmental impacts of reuse and the development of environmental assessment metrics. Technology that can be used to create and connect demand and supply, along with managing CE data were within the scope of the *technological* pillar. Design strategies such as design for disassembly also fell under the technological umbrella. The *behavioral* dimension (e.g., people's attitude towards reused products) was identified by the authors as being a key element in current discussions around CE but lacking from CE research. Finally, the *societal* dimension included partnerships and collaborations to enable CE and raise awareness of CE strategies (Pomponi & Moncaster, 2017). Despite being an important contribution to approaching CE in the built environment from a systems perspective, Pomponi and Moncaster's framework did not explore the interdependencies between the CE research dimensions. The authors recommended future research on investigating the connections between dimensions, especially between technological and societal dimensions, and the role of policy measures to enable CE in the built environment (Pomponi & Moncaster, 2017).

Since the publication of Pomponi and Moncaster's framework (2017), the literature on CE and the built environment has grown exponentially, new case studies of CE implementations have emerged, and more topics have been included in the discussion of each CE dimension. In this paper, we build on Pomponi and Moncaster's framework to analyze the recent literature and ask the following questions:

RQ1. How are the different CE research dimensions represented in the growing built environment literature? What are the most present dimensions and disciplines, and what is missing?

RQ2. How do circular economies function within the complexity of cities? What are the interdependencies, feedbacks, elements, and flows between the CE research dimensions in the built environment?

To answer these questions, we conducted a systematic literature review and thematic analysis to identify case studies of CE interventions in the built environment that have considered the different dimensions of CE as proposed by Pomponi and Moncaster (2017), and their interconnections and iterations. The selected case studies informed the creation of a conceptual model that illustrate how CE functions in an urban setting. To our knowledge, this is the first attempt to use information from multiple case studies to synthetize and conceptualize CE in the built environment from a systems perspective. By identifying and mapping the interdependencies, feedback loops, elements and flows of CE interventions in the built environment, we contribute to understanding the complex systems inherent to both circular economies and urban settings. In the next section, we describe the methodology used to answer the research questions, followed by the results and discussion. Finally, we explain the limitations of this research and present our conclusions and recommendations.

2. Methods

In this section, we describe the methods used to answer the research questions in this study (Fig. 1).

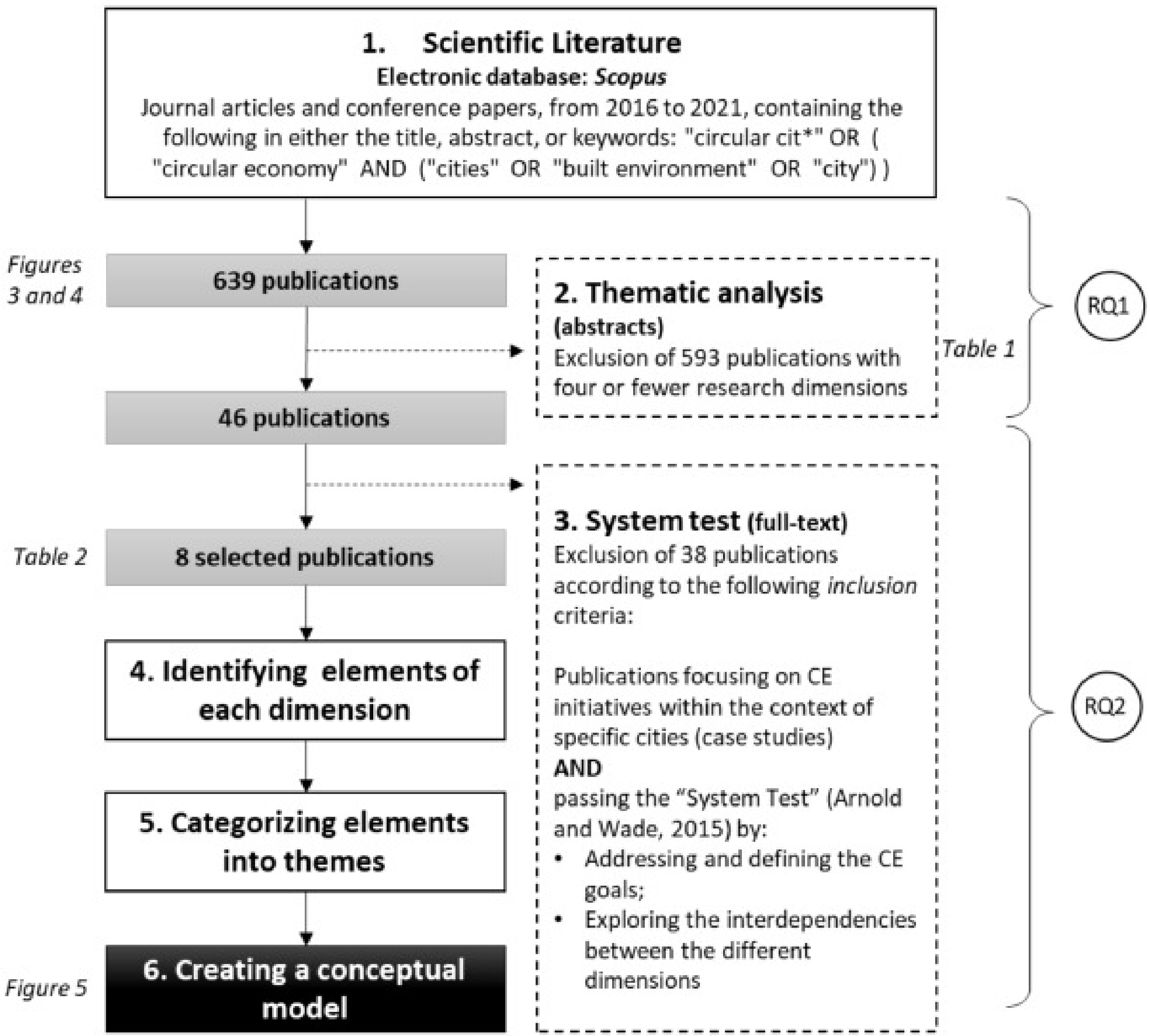

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Fig. 1. Methodology and research questions.

***RQ1*. How are the different CE research dimensions represented in the growing built**

environment literature? What are the most present dimensions and disciplines, and what is missing?

To answer RQ1, we conducted a systematic literature review. We used the Scopus database to search for the literature containing keywords such as "circular city" or "circular cities", "circular economy", "city" or "cities" and "built environment" (see Fig. 1 for exact searching criteria). After analyzing the growing trend of the literature over the years, we limited the search to publications from 2016 to 2021, where the number of publications started showing a steeper growth compared to previous years (Fig. 2).

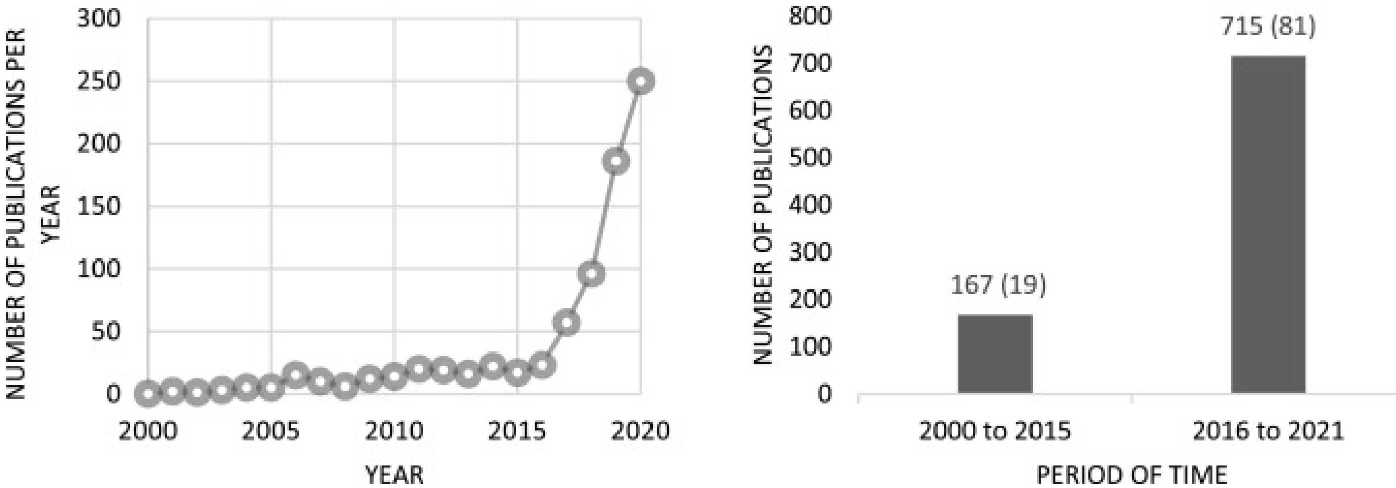

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Fig. 2. Literature growth over time, based on the systematic literature review results.

We also limited the literature search to journal articles and conference papers, which resulted in a total of 639 publications (Fig. 1). Next, we conducted a thematic analysis to identify the CE research dimensions present in each abstract. Based on the categorization and definition of each CE research dimension by Pomponi and Moncaster (2017) and on an initial screening of the abstracts, we created a list of keywords that were assigned to each dimension (Table 1). The keyword list does not intend to be comprehensive, but rather a snapshot of frequently used themes in the literature. We then used a web-based screening tool to search the abstracts for each keyword and assign the respective CE research dimensions. For example, an abstract containing the words "climate", "urbanization", and "design" was assigned the environmental, societal, and technological dimension, respectively.

Table 1. Keywords by CE research dimension used in the thematic analysis (step 2 in Fig. 1). Asterisks correspond to wildcards (e.g., cultur* includes words such as culture, cultures, cultural, and culturally).

Environmental	Environmental*; resource*; carbon; emissions; pollution; climate; ecolog*; waste; material flow analysis; life cycle analysis; life cycle assessment; greenhouse; energy; water
Economic	Market*; business*; profit*; cost*; trade*; investment*; economic
Societal	Social; society; justice; fair*; wellbeing; well-being; equit*; people; communit*; cultur*; health; educat*; aware*; learn*; urbanization
Behavioral	decision*; behavi*; attitud*; stakeholder*; bias*; trust; leadership; perception*
Technological	internet of things; technolog*; design*; planning; innovation; blockchain; 3D; smart; urban mining
Governmental	Polic*; regulation*; incentive*; mandate*; regulatory; tax*; subsid*; law*; government

RQ2. **How do circular economies function within the complexity of cities? What are the interdependencies, feedbacks, elements, and flows between the CE research dimensions in the built environment?**

To answer RQ2, we aimed to identify selected articles that have (1) demonstrated the implementation of CE initiatives in specific applications (case studies), and (2) approached circular built environments from a systems perspective. The first step was to screen the literature to include only examples of applications of CE initiatives in cities. Theoretical articles and reviews were excluded. Then, we conducted a System Test (Arnold & Wade, 2015) to verify which publications have approached circular built environments as systems. According to the System Test, each publication should have three components: (1) Purpose (describing the purpose of the CE initiative or intervention), (2) Elements (describing the characteristics and variables of each CE research dimension), and 3) Interconnections (describing the ways the CE research dimensions "feed into and relate to each other") (Arnold & Wade, 2015). After searching the full text of the publications for the three components described above, we selected eight publications to help answer RQ2. We then re-read each article to identify the elements, flows, interdependencies, and feedbacks among CE research dimensions. Next, we coded these elements into themes. For example, "greenhouse gas emissions" was labeled as a "negative impact from the technological dimension to the environmental dimension", and "gentrification" was labeled as an "unintended consequence" caused by the "revitalization of urban areas", which was in turn labeled as a "positive impact from the technological dimension to the societal dimension." Finally, we used the identified themes to create a conceptual model to represent the functioning of a complex circular urban system.

3. Results and discussion

In this section, we present the results from our systematic literature review and the conceptual model that emerged from it and answer the two research questions that guided this study.

***RQ1*. How are the different CE research dimensions represented in the growing literature? What are the most present dimensions and disciplines, and what is missing?**

As shown in Fig. 1, the initial search in the scientific literature resulted in 639 publications (i.e., journal articles and conference papers). To answer RQ1, we analyzed two different but often related aspects: the presence of the six different CE research dimensions in the literature (i.e., economic, governmental, technological, environmental, societal, and behavioral), and the representation of different knowledge areas or disciplinary fields (e.g., economics, engineering, social sciences) and subfields (e.g., environmental engineering, political sciences, urban studies). The breakdown of the articles by knowledge area or discipline is presented in Fig. 3. The literature on circular economy in the built environment was dominated by the environmental sciences, which according to the Scopus database classification, include subfields like ecological modeling, ecology, environmental chemistry, environmental engineering, waste management and disposal, pollution, water science and technology, among others. Environment-related management, monitoring, policy, and law are also included in this category. Together, the environmental subfields were present in 70% of the searched literature. These results are consistent with the results from the thematic analysis (Step 2 in Fig. 1) that showed that the environmental dimension of CE was represented in at least 88% of the articles (Fig. 4a).

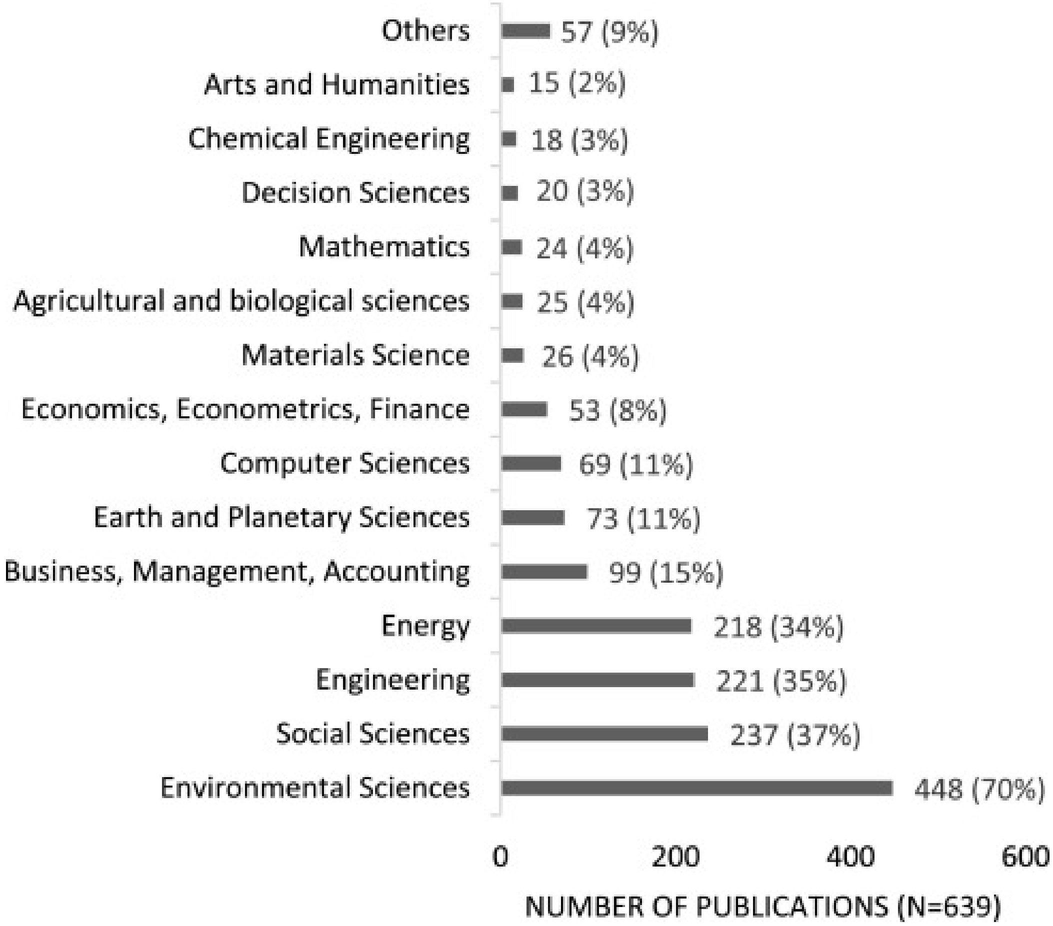

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Fig. 3. Articles by discipline. Note: the sum of individual disciplines does not correspond to the total number of articles ($n = 639$) due to the articles that have more than one discipline involved.

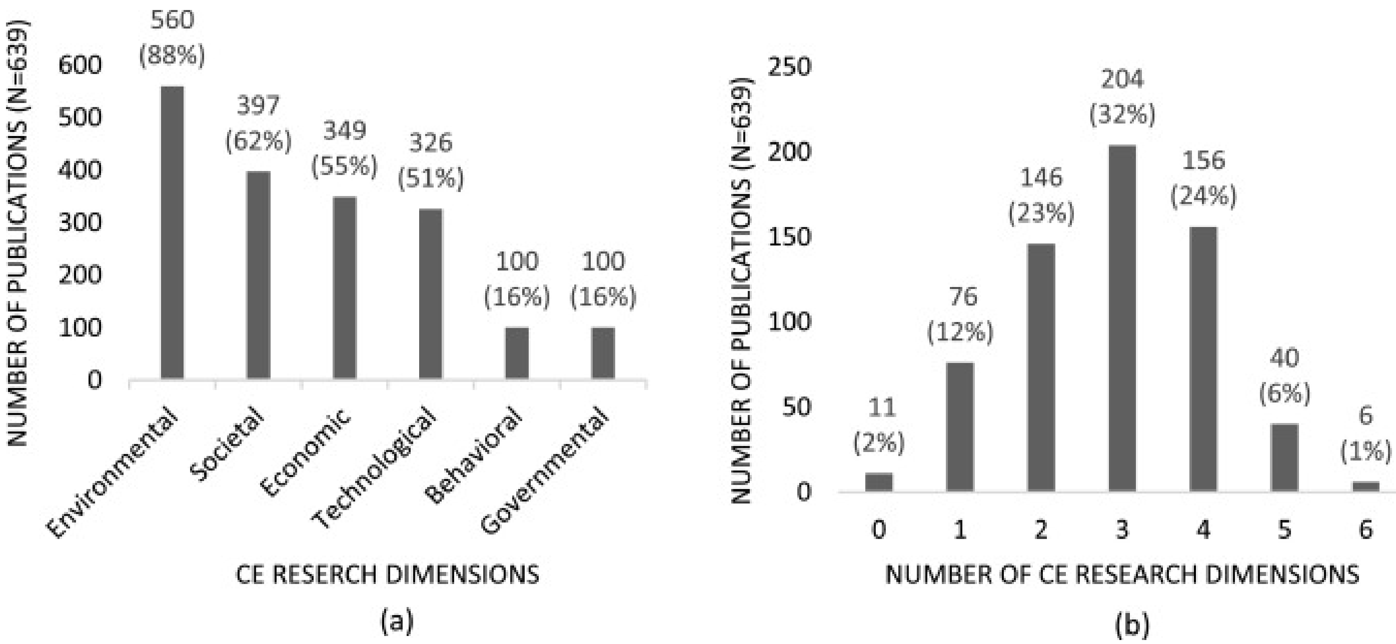

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Fig. 4. Representation of the six CE research dimensions in the searched literature (a), and the number of CE research dimensions considered by publication (b).

Social sciences, engineering, and energy disciplines were also present in a significant share of the literature (each being present in approximately one third of the literature). Social sciences include subfields such as education, geography, health, law, sociology and political science, anthropology, communication, and cultural studies. Urban studies and transportation are also included under the social sciences umbrella (as categorized by the Scopus database), which may explain the large presence of social sciences among the searched literature. The results of the thematic analysis shown in Fig. 4a also highlighted a strong presence of the societal dimension in the searched literature: at least 60% of the articles had keywords such as "communities", "culture", and "urbanization" in their abstracts, probably because of the focus on the city scale. The energy discipline includes energy engineering and power technology, fuel technology, nuclear energy and engineering, and renewable energy, sustainability and the environment. Finally, engineering includes several engineering subfields like aerospace, automotive, biomedical, civil and structural, control and systems, electrical and electronic, industrial, and mechanic engineering. Architecture and building and construction are also categorized as engineering subfields by the Scopus database. A strong engineering presence in the literature may explain the significant representation of the technological dimension (Fig. 4a), present in at least 51% of the publications.

Conversely, disciplines like economics, material sciences, and decision sciences were underrepresented in the searched literature (8%, 4%, and 3% of the articles, respectively) Fig. 3. That includes subfields like economics and econometrics, finance, biomaterials, materials chemistry, metals and alloys, polymers and plastics, information systems and management, and statistics, probability, and uncertainty. The behavioral dimension represented in Fig. 4a includes topics like decision-making and stakeholders, thus its low representation compared to other dimensions may be a consequence of the low involvement of decision sciences in the literature. The results of the thematic analysis also suggest that, although economics is an underrepresented discipline in the literature, topics like markets, business models, and costs were present in at least 55% of the literature. Such an apparent discrepancy can be partly explained by the presence of disciplines related to business, management, and accounting, that do not fall under the economics category, but also address topics labeled as economic dimension (e.g., business models, profits). Another possible explanation is the discussion of economic aspects (see Table 1 for a complete list) in general terms from authors outside of economics and business disciplines. The results suggest a need for an increased participation of economists and business specialists in the CE in the built environment literature to either validate or find inconsistencies in the current economic-related discussions. Finally, topics like policy, regulations, codes, and standards were present in approximately 16% of the literature (see governmental dimension in Fig. 4a). Policy and law-related subfields are categorized by the Scopus database under both environmental and social sciences disciplinary fields.

Fig. 4b illustrates the number of CE research dimensions by publication. According to the results of our thematic analysis, approximately one third of the publications considered three CE research dimensions, and only six publications had elements of all CE research dimensions. To answer RQ2, we aimed at selecting the studies with the largest number of CE research dimensions to go through a full-text analysis. Due to the low number of publications with six dimensions, we included publications with keywords from either five or six CE research dimensions in the abstract.

***RQ2.* How do circular economies function within the complexity of cities? What are the interdependencies, feedbacks, elements, and flows between the CE research dimensions in the built environment?**

The eight publications resulting from the full-text analysis (step 3 of Fig. 1) are summarized in Table 2. They represent case studies of CE initiatives and interventions in different cities in India, United States, Canada, Australia, and European countries. Despite the specificities of each city and case study, we expected to see patterns in the way the different CE research dimensions were connected to each other. Our goal was to represent such patterns in a conceptual model that described how CE interventions are inserted in an complex urban system, by illustrating the interdependencies between elements, feedbacks, and flows that influence circular built environments.

Table 2. Summary of the case studies selected to inform the conceptual model.

Citation	City	Objective	Main conclusion
(Fiksel et al., 2021)	Pune, **India**	Presenting the results and lessons learned from the implementation of CE principles to an urban regional community.	"An integrated systems view is necessary to understand the interplay of economic, environmental, and social forces."
(Russell et al., 2020)	Amsterdam and Rotterdam, **The Netherlands**	Investigating the critical factors influencing the implementation of 12 bottom-up CE initiatives.	The critical factors "do not act in isolation and form a complex web of interconnecting critical factors."
(Nogueira, Ashton & Teixeira, 2019)	Chicago, **United States**	Developing a framework based on participatory action research methods to co-create hard and soft CE infrastructures.	The framework can help to understand how infrastructural interventions are influenced by the intersection of social, ecological, and technical systems, and the interactions and iterations involved in the complex urban system.
(Cerreta et al., 2020)	Naples, **Italy**	Presenting an adaptive decision-making process for implementing CE principles in the redevelopment of a commercial port.	Circular transitions require a broader engagement of multiple stakeholders including government officials, researchers, entrepreneurs, NGOs, and active civil society members.
(Della Spina, 2019)	Catanzaro, **Italy**	Assisting decision makers in choosing CE solutions considering "the role of cultural heritage in a systemic landscape perspective."	"Only with the support of integrated assessment approaches and inclusive processes is it possible to build shared actions in a long-term vision and effectively develop and build public decision-making."

(Longato et al., 2019)	Eight European cities in **Italy, Spain, Portugal, and Romania**	Creating a methodology for developing strategic plans for waste prevention and resource management.	"The participatory approach led to the legitimization of the strategic plans, as well as to raise awareness among stakeholders."
(Keough & Ghitter, 2020)	Manchester and Calgary, **Canada**	Identifying barriers and mitigation strategies to transforming an industrial area to a sustainable low-carbon city district.	"Creating a durable path for a sustainable, low-carbon transition is… predominantly a social, cultural and political [challenge]."
(Newton & Frantzeskaki, 2021)	Melbourne, Sydney, Brisbane, and Perth, **Australia**.	Introducing a new platform for urban innovation that engages multiple stakeholders and allows for "real time synchronous collaboration, visioning, research synthesis, experimentation, and decision-making."	The collaborative platform can become a "critical institutional space and enabling space" by "providing the knowledge infrastructure" needed for innovative urban interventions globally.

Besides the six CE research dimensions, several elements resulted from the analysis of the case studies: environmental, societal, and design goals, physical and digital infrastructure, material and information flows, social resources, multi-stakeholder networks, positive and negative impacts, and unintended consequences. The resulting conceptual model is presented in Fig. 5. In the next subsections, we describe the elements and flows for each of the CE research dimensions, and how they interact with each other. We illustrate our results with examples from the case studies.

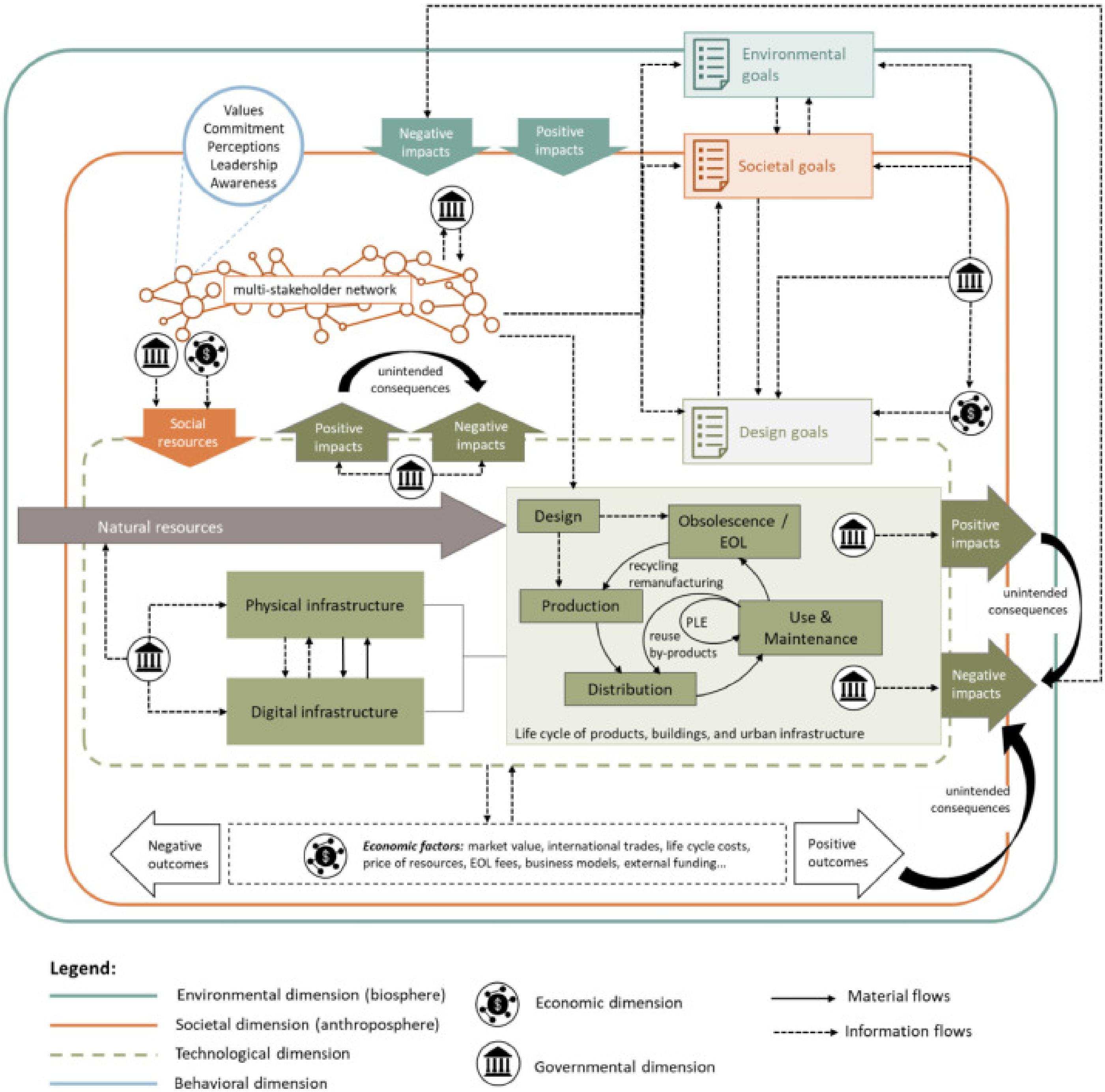

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Fig. 5. A conceptual model for circular built environments from a systems perspective. EOL = end of life; PLE = product life extension.

3.1. Societal dimension

In the conceptual model, the societal dimension represents the anthroposphere and is illustrated by an inner boundary nested in the environmental dimension (i.e., biosphere). The economic, behavioral, governmental, and technological dimensions, though separate dimensions, are part of the anthroposphere (see for example, International Labour Organization 2019). For this reason, the boundaries surrounding the technological dimension are represented as dashed lines. The key elements of the societal dimension are the multi-stakeholder network, societal goals, and social resources. Notably, all case studies of circular interventions in cities had one common aspect: the presence of a *multi-stakeholder network* formed by several members of the society: private companies, NGOs, government officials, media representants, members of community organizations, start-up companies, financial institutions, research institutions, philanthropic foundations, educators, members of the informal sector, professional associations, volunteers, small and local business, among others (Cerreta, di Girasole, Poli & Regalbuto, 2020; Della Spina, 2019; Fiksel, Sanjay & Raman, 2021; Keough & Ghitter, 2020; Longato, Lucertini, Fontana & Musco, 2019; Newton & Frantzeskaki, 2021; Nogueira et al., 2020; Russell, Gianoli & Grafakos, 2020). This multi-stakeholder network is at the core of the CE interventions in the built environment. While networks and collaborations are essential to the success of urban based projects, applied research in the built environment and design disciplines are currently dominated by disciplinary silos (Newton & Frantzeskaki, 2021; Nogueira et al., 2020). As a result, urban interventions are often implemented by few stakeholders who do not understand the daily life, habits, and values of the local community (Nogueira et al., 2020). Such a democratic deficit was described by Keough and Ghitter (2020) as a barrier to low-carbon transitions like CE interventions. Democratizing the transition towards CE demands engaging individuals and organizations that are going to be involved or impacted by CE interventions to actively participate in the design and creation of circular infrastructure from early stages (Nogueira et al., 2020). Russell et al. (2020) argue that the future of CE depends heavily on its multi-stakeholder and collaborative nature.

Hence, in our conceptual model, the multi-stakeholder network is the central part of the societal dimension and of the model itself (Fig. 5). Each network member is influenced by behavioral aspects and connected to each other by meaningful social relationships (Della Spina, 2019). Innovative participatory approaches and technologies can leverage the exchange of knowledge and skills, speed up innovation, and build consensus around *environmental, societal, and design goals* and targets (e.g., Della Spina 2019, Newton & Frantzeskaki 2021). For example, a multi-stakeholder network has decided on societal, environmental, and design targets for the city of Manchester, including 100% renewable energy, zero waste to landfill, automobile optional living, and the optimization of local sourcing of materials, goods, and services (Keough & Ghitter, 2020). Examples of societal, environmental, and circular design goals identified in the case studies are listed in Fig. A1 (Appendix A).

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Fig. A1. Examples of environmental, societal, and design goals identified by stakeholders in the case studies.

Finally, multi-stakeholder networks can blend top-down and bottom-up approaches and drive public acceptance of CE policies and positive behavioral changes (Fiksel et al., 2021; Longato et al., 2019; Newton & Frantzeskaki, 2021). Besides deciding on societal, environmental, and design goals, the multi-stakeholder network generates key *social resources* such as synergistic partnerships, services, social enterprises, capacity building, and multiple sources of funding (Della Spina, 2019; Keough & Ghitter, 2020; Longato et al., 2019; Russell et al., 2020), as well as sociocultural associations, creativity and innovation (Della Spina, 2019), and even citizen-led infrastructure like material reuse and recycling centers (Nogueira et al., 2020). Another example described by Keough and Ghitter (2020) was a cooperatively operated facility that aims at identifying synergies between enterprises and creating a local industrial ecology. These social resources function as inputs to the technological dimension (e.g., partnerships to fund innovative circular design).

3.2. Behavioral dimension

The behavioral dimension includes behavioral factors that affect stakeholders in an individual and collective level. The behavioral factors identified in the case studies were *leadership, activism, and commitment* to CE and sustainability (Fiksel et al., 2021; Nogueira et al., 2020; Russell et al., 2020), *awareness levels and expectations* (Cerreta et al., 2020; Della Spina, 2019; Fiksel et al., 2021; Longato et al., 2019; Nogueira et al., 2020; Russell et al., 2020), *values, interests, and beliefs* (Cerreta et al., 2020; Della Spina, 2019; Nogueira et al., 2020), and *perceptions* (Longato et al., 2019; Nogueira et al., 2020). Raising public awareness about CE was a widely discussed topic among case studies. For example, Cerreta et al. (2020) described using role playing games to raise awareness within neighborhoods, while Fiksel et al. (2021) described multiple levels of awareness campaigns, from sensitization workshops with 12 or fewer participants, to mass awareness events with over 500 residents. Values and beliefs are influenced by the larger community, that determines what types of values and behaviors are encouraged, discouraged, or tolerated (Nogueira et al., 2020). Della Spina (2019) described a multi-stakeholder decision analysis methodology aimed at harmonizing different stakeholder interests and priorities when deciding circular design goals for the city of Catanzaro. According to Longato et al. (2019), engaging the multi-stakeholder network contributed to increase awareness, change attitudes, and positively affect stakeholder behavior.

Understanding stakeholder values and perceptions is key to promote CE in the built environment, as individual and collective behavior influence the way people design, use, and abandon buildings and infrastructure. For example, modernity and freedom are deep cultural meanings attributed to the automobile, and these meanings can be more important than the automobile's function (Keough & Ghitter, 2020). Thus, the demand for automobiles - an important driver for designing urban transportation systems and infrastructure -, is highly influenced by cultural values. Consequently, one cannot propose sustainable transportation solutions without understanding how to effectively change the public behavior to switch from automobiles to public transportation, for example.

3.3. Technological dimension

In our conceptual model, the technological dimension includes the physical and digital infrastructures in an urban setting. The *physical infrastructure* (Nogueira et al., 2020) includes the building and infrastructure stocks needed to provide essential services to the society (e.g., housing, food, healthcare, education, mobility, energy, water, communication, culture and recreation), produce and distribute goods and services (e.g., manufacturing facilities, commercial buildings, retail, transport), and promote the recirculation of natural resources (e.g., renewable energy infrastructure, green infrastructure) or human-made resources (e.g., recycling centers, salvage yards, repair and remanufacturing facilities). The *digital infrastructure* includes digital technologies needed to provide and support the services described above, which includes information and communication technologies, digital media, automation and data exchange technologies, software, and innovative technologies like 3D printing, Internet of Things, cloud computing, asset track technologies, artificial intelligence, among others (Newton & Frantzeskaki, 2021; Nogueira et al., 2020; Russell et al., 2020). Both digital and physical infrastructures involve the *design, production, and distribution* of goods, from products to buildings and urban infrastructure. These goods then are purchased, leased, or shared by members of the society, who *use, repair, and reuse* them until they become *obsolete*, at which point products can be disassembled and remanufactured, buildings and infrastructure can be retrofitted or deconstructed, neighborhoods can be revitalized, and materials can be recycled, utilized as by-products by other industries, or returned to the environment. These processes require *natural resources* from the biosphere (e.g., raw materials, energy, and water used in manufacturing and construction, and soil, vegetation and wetlands used to enhance the urban landscape), and generate positive and negative impacts for the environment and society (Fiksel et al., 2021).

Positive impacts from the technological dimension to the environment are impacts that restore damages caused by human action or, preferably, create net positive impacts by improving the environmental conditions. Examples of positive impacts found in the case studies are flood control through green infrastructure, carbon sequestration, energy and water conservation (Fiksel et al., 2021) and the nutrients generated by composting organic waste (Keough & Ghitter, 2020). Examples of *positive impacts from the technological dimension to society* are the essential services provided by urban infrastructure as mentioned above, along with energy and water security, inclusive and accessible buildings and urban infrastructure (Fiksel et al., 2021), and food security through urban agriculture and community gardens (Keough & Ghitter, 2020). For example, one of the goals for the city of Manchester is to create land banks to increase the proportion of public owned lands and the offer of public infrastructure and societal services like affordable housing (Keough & Ghitter, 2020). Other examples of positive impacts to society are the revival of historic city centers and preservation of architectural history and cultural heritage (Cerreta et al., 2020; Della Spina, 2019; Nogueira et al., 2020), and regeneration urban development and redevelopment (Cerreta et al., 2020; Della Spina, 2019; Newton & Frantzeskaki, 2021).

Negative impacts from the technological dimension to the environment happen when there are failures in the circular economy model. For example, when the government fails to regulate and limit industrial waste and air or water pollutant emissions, when manufacturing and construction companies fail to implement resource efficient measures, or when the public behavior and traditional business models lead to increased consumption of products, quick obsolescence, and generation of increasing amounts of municipal solid waste (Fiksel et al., 2021; Keough & Ghitter, 2020; Longato et al., 2019; Russell et al., 2020). These failures can also lead to *negative* *impacts to society,* such as negative health impacts caused by pollution and waste especially to underrepresented communities who are more vulnerable to the negative impacts of waste proliferation (Fiksel et al., 2021). Similarly, unregulated urban developments with deficient water and sewer systems have caused diseases (Keough & Ghitter, 2020). Failures in the physical and digital infrastructures can also cause inequities in the distribution of the essential societal services mentioned above, like food, energy, water, culture and recreation, education, and housing. Finally, social inequities can also be caused by *unintended consequence*s of positive interventions. For example, the revitalization of urban areas (a positive impact from physical infrastructure to society) may attract wealthier populations and new businesses, which may lead to the displacement of local populations to suburbs and exacerbate social inequities (Keough & Ghitter, 2020). Nogueira et al. (2020) described another example of unintended consequence: when urban food infrastructure scales up food distribution through large corporations, which on the one hand provides more people with access to food, but on the other hand creates difficulties to small producers and increase social divide.

Understanding and quantifying the social and environmental life cycle impacts of products, buildings and infrastructure, and the material and energy flows in an urban setting (also called urban metabolism) are key to inform environmental and *design goals* in a circular built environment (Longato et al., 2019; Nogueira et al., 2020). As discussed, the built environment at a city scale provides critical physical infrastructure for other sectors. Examples include food production and distribution; manufacturing and distribution of products and materials, end-of-life management of products and materials centers, entertainment; and research and education. These sectors, in turn, can generate positive or negative impacts to society, economy, and the environment.

3.4. Economic dimension

Economic factors influence and are affected by the technological dimension and generate both negative and positive outcomes to society. *Circular business models* such as product-service systems and sharing economy platforms (Fiksel et al., 2021; Newton & Frantzeskaki, 2021; Russell et al., 2020) directly influence the design goals and consequently, the technological dimension. For example, car and bike sharing systems influence the design of transportation infrastructure (Newton & Frantzeskaki, 2021). Keough and Ghitter (2020) proposed to transform the transportation system in circular cities by completely substituting automobile ownership with public transportation, walkable neighborhoods, bicycling infrastructure, and carshare systems. Similarly, product-service systems require reverse logistics infrastructure and product life extension strategies (Fiksel et al., 2021), such as designing products and buildings with more durable materials to increase their long-term value. Besides business models, several *market factors* impact the design, use, and end of life of products, buildings, and infrastructure. For example, the availability, quality, and appropriate pricing of resources (including both natural resources and existing resource stocks to be reused) directly influence the profitability and feasibility of circular design and business models (Russell et al., 2020). The quality of the urban infrastructure also directly affects market factors by encouraging or discouraging real estate investments (Cerreta et al., 2020; Della Spina, 2019). Finally, the economic dimension can create positive or negative impacts to society.

Examples *of positive impacts to society* are the provision of affordable housing, energy, water, and other societal services, the creation of cooperative enterprises and permanent jobs linked with circular business models (Della Spina, 2019; Fiksel et al., 2021), and the integration of informal workers into the formal economy while providing them with safe and decent working conditions (Fiksel et al., 2021). However, when local businesses thrive and create more job opportunities and increased purchasing power among residents, that can create *unintended consequences* such as an increase in consumption and waste generation, which contributes to negative impacts to the environment like resource scarcity and land, air, and water pollution (Fiksel et al., 2021). Finally, *negative impacts to society* include economic inequality manifested in unequal access to jobs and services, which is influenced by the distribution of physical infrastructure like housing and by "housing markets that increases suburbanization of social disadvantage, often combined with racial/ethnic inequalities" (Newton & Frantzeskaki 2021, pp. 1).

3.5. Governmental dimension

In our conceptual model, the governmental dimension encompasses the several roles of policymakers identified in the case studies. These roles include (1) creating laws, regulations, and mandates to promote CE practices, (2) creating codes, standards, and certifications to inform the design and operation of physical and digital infrastructures, (3) offering incentives to promote circular business models, (4) funding CE initiatives, (5) co-creating targets and benchmarks to move the city towards CE goals, (6) creating guidelines, frameworks, and information campaigns to raise awareness about CE initiatives, (7) providing benefits and assistance, and 8) engaging stakeholders. Examples of *laws, regulations, and mandates* include safety regulations (Nogueira et al., 2020), landfill bans (Russell et al., 2020), extended producer responsibility (Fiksel et al., 2021) and the regulation of solid waste generation and management (Fiksel et al., 2021; Russell et al., 2020). In the CE interventions in the cities of Amsterdam and Rotterdam, regulations have caused barriers for initiatives that aimed at utilizing waste as resources, which led to the recommendation of creating "novel conceptualizations of traditional waste streams" that are aligned with circular models (Russell et al., 2020).

Urban, building, and product design are regulated by *codes* (Keough & Ghitter, 2020), *design standards* (Fiksel et al., 2021), and *certifications* like green building rating systems (Keough & Ghitter, 2020). The inert and fragmented nature of planning and regulatory processes that regulate land use and development have resulted in entrenched urban planning codes that pose a barrier to CE initiatives in Canadian cities (Keough & Ghitter, 2020). Keough and Ghitter (2020) proposed a "democratic and regulatory reform" to enable circular interventions in the built environment. Design standards that include resource efficiency and material reuse were proposed in Fiksel et al. (2021), as well as green procurement schemes that pre-approve certain materials for design and construction.

Besides codes and regulations, *market-based incentives* such as subsidies and tax exemption schemes can make CE initiatives economically feasible and stimulate the use of more sustainable technologies and products (Fiksel et al., 2021; Keough & Ghitter, 2020; Russell et al., 2020). Additionally, Fiksel et al. (2021) identified several areas that can benefit from *government funding*. These include baseline studies to assess the current state of sectors and opportunities for CE, impact assessment studies to analyze social, environmental, and economic impacts of improper handling of waste, CE research, feasibility studies for circular business models and their supporting networks and infrastructure, and the creation of infrastructure to support CE (Fiksel et al., 2021). Additionally, Nogueira et al. (2020) recommended grant funding from federal, state, and local governments to support small businesses that contribute to CE.

Finally, the government can participate in *engaging stakeholders* to *raise awareness* about CE practices and co-create societal, design, and environmental *goals and targets* that will inform the municipal agenda and directly impact the implementation of bottom-up CE initiatives (Fiksel et al., 2021; Longato et al., 2019; Russell et al., 2020).

3.6. Environmental dimension

In our conceptual model, the environmental dimension represents the biosphere. The main elements in the environmental dimension are natural resources, environmental goals, and negative and positive impacts from the environment to society. *Natural resources* comprise air, sunlight, water, soil, raw materials, biodiversity, and natural heritage (Della Spina, 2019; Fiksel et al., 2021; Longato et al., 2019; Nogueira et al., 2020). Natural resources are used as input from the technological dimension to create energy, products, building, and infrastructure to support society. *Environmental goals* include the conservation, efficiency, renewability, enhancement, and resilience of natural resources (Fig. 6) to support sustainable development. Examples of *positive impacts from the environment to society* are positive health impacts from food and nutrition (Nogueira et al., 2020), contact with nature, and carbon sequestration and pollutant absorption (Fiksel et al., 2021). *Negative impacts from the environment to society* are exacerbated by the negative impacts from the technological dimension to the environment, and include natural disasters, climate change, resource scarcity, and poor air and water quality (Fiksel et al., 2021; Newton & Frantzeskaki, 2021).

4. Limitations

This study had some key limitations. First, as inherent to systematic literature reviews, the literature search was limited by the specific term "circular economy" and the built environment-related keywords, with emphasis on the city scale. The decision to narrow the scope to CE-specific literature meant excluding publications related to CE strategies but that do not explicitly mention CE (e.g., urban regeneration design). However, while these individual strategies are part of circular design, we aimed at selecting studies that understood CE as a complex system to gain insights about the interactions between CE strategies and the built environment. Second, we focused on the macro scale of CE in the built environment (i.e., cities) due to their largest degree of complexity when compared to buildings and building products or materials. However, our model focuses on urban areas and does not explore potential links with rural communities. More research is needed to test the appropriateness of our conceptual model across scales, and the interdependencies and iterations of the built environment with adjacent rural areas. Additionally, since the built environment provides critical physical infrastructure to other industries, it is reasonable to assume that the conceptual model presented in this paper could be applied to other sectors. However, more research is needed to validate this assumption. For example, a similar study could investigate and how circular initiatives in the food sector work at a city scale, and whether our model can be applied or modified accordingly. Third, our model does not emphasize the adaptive nature of the system over time, nor does it assess the system resilience to possible disruptions over time. Finally, when trying to understand and conceptualize complex systems, there will always be a gap between the perception of the system and the actual system. Dynamic methods like agent-based modeling may be useful in testing the model structure in different scenarios.

5. Conclusion

This paper reviewed case studies of CE interventions in the built environment from a complex systems perspective. First, the authors built on the framework created by Pomponi and Moncaster (2017) to identify how diverse CE research dimensions and disciplines are represented in the recent literature. Second, a multistep selection of the literature resulted in eight case studies of CE initiatives in different cities. These case studies have addressed elements of several CE research dimensions, as follows: governmental, economic, environmental, technological, societal, and behavioral. Next, the authors performed a thematic analysis to identify and categorize the elements of each research dimension, their interactions and iterations as reported by the case studies. The patterns that emerged from this analysis informed the creation of a conceptual model to represent the complex systems inherent of CE interventions in the built environment. The model offers insights into the interdependencies, flows, feedback loops, and unintended consequences that may result from the interaction between the CE research dimensions and their elements in an urban setting.

The results suggest that the behavioral and governmental dimensions were the least represented among the searched literature, which is consistent with the results from Pomponi and Moncaster (2017), despite the methodological differences from this study. Similarly, key disciplines are still lacking from the recent literature, like economics and decision sciences. Future research studies that aim at addressing the combined complexities of both CE and the built environment will require deeper convergence across scales, dimensions, and disciplinary fields.

Finally, leveraging the societal dimension is key to ethically designing CE interventions in the built environment. Specifically, all case studies reviewed in this paper have successfully engaged a network with multiple members of the society and adopted innovative participatory or shared decision-making approaches. Engaging with the local community and co-creating goals, targets, and design solutions was an effective way to blend top-down and bottom-up approaches, gain public support, promote positive behavioral change, and raise awareness about CE.

In conclusion, mapping the complexities inherent to CE and the built environment is an important contribution to understanding how CE interventions function in an urban setting and how to design changes in the system to generate desired outcomes. We hope that the conceptual model and examples presented in this paper will inform policymaking, design, and applied research to promote circular, regenerative, and resilient built environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Stakeholder goals for the circular cities

Appendix A

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