Circular Economy practices in the Built Environment

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ABSTRACT

The aim of this literature review is to provide structured information for the basis of organizing the future cities through circular economy. The built environment is responsible for the majority of global greenhouse gases and raw material extraction. Climate efficiency in cities cannot be improved simply by replacing the old structures with new ones, because both the construction and operation phases cause major resource and energy consumption. The academia and practice have recognized circular economy as a key approach in sustainable urban development, especially in China and Europe. The main idea of circular economy is to retain the value of resources and to prevent the use of virgin materials and waste outputs, not only by recycling and reusing, but primarily by reducing the need for resources. This review aims to clarify the general view, identify research gaps and target further research by asking how the present body of literature sees cities getting organized in the transition towards low carbon circular economy. The review covers 282 journal articles, forming three approaches for the adoption of circular economy in the built environment: (1) Management for sustainable cities; (2) Urban services and consumer practices aligned with circular economy; and (3) Cleaner production and construction. In the results on consumer practices, requests on waste hierarchy indicate that further research is needed on strategies of reduction such as product-service systems in intensifying use and extending service life. The review also suggests a new concept of urban-rural symbiosis as a potential approach for resource recovery in integrated urban waste, water and energy systems. In the construction sector, the review notes shortcomings of buildings' life cycle assessment in the ability to reveal benefits in practices of reuse and reduction. In urban and industrial symbiosis, the review finds lack of carbon-free techniques and notices a risk of failing waste hierarchy. In the management of sustainable cities, the literature highlights self-correcting 'adaptive management cycle' with the phases of planning, implementation and evaluation. The review divides strategies for successful implementation under the categories of innovation-positive and inclusive politics, cross-sectoral integration, and cross-institutional capacity development. To promote cross-sectoral integration and cross-institutional capacity development, it is suggested that cities establish a database that consists of an interconnected set of best practices that are evaluated and continuously supplemented. This kind of a platform could support developing of built environment towards circular economy and delinking of environmental impact from economic growth.

Keywords: built environment, circular economy, sustainable development, urban development, cradle to cradle, waste hierarchy

Nomenclature

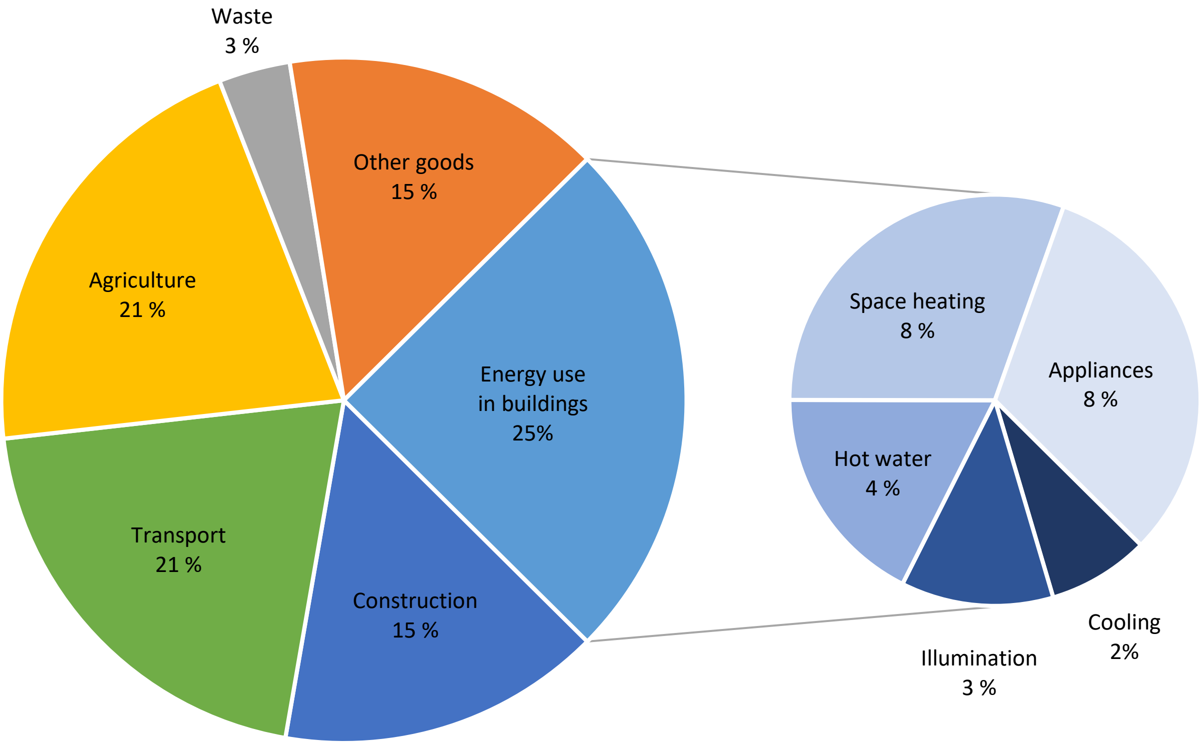
CE	circular economy	LCA	life cycle assessment
GHG	greenhouse gas	DfD	design-for-disassembly
C2C	cradle to cradle	PSS	product-service systems
C&D	construction and demolition	EPR	extended producer responsibility
MSW	municipal solid waste	WEEE	waste electrical & electronic equipment
MSWI	MSW incineration	IS	industrial symbiosis
MFA	material flow analysis	US	urban symbiosis
CO_2	carbon dioxide		

1 Introduction

This review provides a comprehensive insight into current scientific literature in the fields of circular economy (CE) and the built environment. The review leans on the notion that, due to the current major environmental impact of built environment, a large share of all sustainability problems could be solved if CE was applied. The review also looks at the built environment as a complex and multidisciplinary issue due to its sector-specific features and limitations, such as heavy environmental impact in multiple life-cycle phases, agglomeration into cities, and slow turnover of the building stock. A general view on the applications and implementation of CE in the field of the built environment is needed to provide urban planners with a better understanding on how the transition towards resource efficient and low carbon cities should be organized.

Construction, energy use in buildings and transportation play dominant roles in global climate emissions. Bajželj et al. (2013) reported the operation of buildings alone causing 25%, construction 15% and transportation 21% of global emissions (see Figure 1). New construction and urbanization would provide efficiency gains in residential energy but, simultaneously, the current construction material production may have the greatest role in urban energy consumption and also bring a significant contribution to the growth of urban energy consumption (Zhou et al., 2012). Improvements in energy efficiency will also rely on the current building stock for a long time because building stock is being renewed slowly, for example in Germany with 0.8% outflow and 0.5% growth rate (Schiller et al., 2017b). Even with a low outflow rate, building materials in waste streams are dominant and their value compared to their volume low (Salemdeeb et al., 2016). The slow regeneration caused by long service life contributes to lock-in and path-dependency with respect to material-, energy-, and carbon-intensive technologies and settlement patterns (Krausmann et al., 2017). The complexity of urban sustainability, originated from sector-specific realities including material intensive urbanization process, heavy energy use of buildings and slow turnover of the building stock, shows the urgency of adopting new sustainable practices to break the vicious circle and to avoid path dependency.

Figure 1 Global anthropogenic greenhouse gas (GHG) emissions by end use in 2010 (Bajželj et al., 2013)



One solution to the global sustainability problems could be CE. It is already adopted by some political programs, at least in China (World Bank, 2017) and the European Union (EU) (European Comission, 2018). In scientific discussion, CE has gained interest among researchers, especially in China and the EU, and these regions are also each other's primary source of co-authorship (Türkeli et al., 2018). The origins of CE date back to the 1960s and 1970s when Kenneth Boulding wrote his broadly referred seminal paper "The Economics of the Coming Spaceship Earth" that present the idea of the world as an interconnected, closed system (Boulding, 1966). Walter Stahel developed the notion of the looping economy further and compounded it into labor politics and service economy in his book "Jobs for Tomorrow: The Potential for Substituting Manpower for Energy", which was based on his project for the European Union (Stahel and Reday-Mulvey, 1981). The actual term 'circular economy' was presented by the environmental economists David W. Pearce and R. Kerry Turner in their book "Economics of Natural Resources and the Environment" (Pearce and Turner, 1990). Later, McDonough and Braungart popularized their cradle to cradle -concept (C2C), which shares objectives with CE but focuses on recycling and reuse, and emphasizes the role of product design as an enabler for a closed-loop material cycle (Braungart and McDonough, 2002). Braungart and McDonough (2002), and later the Ellen MacArthur Foundation (2015), categorized CE applications based on the type of material into technical and biological cycles. The biological cycle consists of all organic and biodegradable materials, while the technical cycle comprises inorganic materials that are not biodegradable (such as metals, minerals, or traditional plastics). Nature of CE as an approach can be concretized through operating principles such as 3Rs – which derive from the English words reduce, reuse and recycle in prioritized order – have been accepted as a starting point for scientific and political discussions in China (Yong, 2007). Some European scholars have expanded the model to include a fourth R that refers to the recovery of energy and materials from waste (Kirchherr et al., 2017). The principles and interpretations of CE may vary among theorists and across geographical locations, but share a clear and common target of decreasing the use of raw materials and preventing waste by sustaining the value of products as long as possible. The objective is to replace the take-make-dispose culture with the closed-loop system where all resources are used as many times as possible.

The urban population continues to expand on an international scale (United Nations, 2018). Cities where the built environment and any consumption and wastes are agglomerating could provide opportunities for successful CE applications and the utilization of waste streams as a resource. Several cities strive to make themselves role models in sustainable urbanism development and need an applicable vision on the basis of their initiatives (Marin and De Meulder, 2018). When implementing the vision, cities need to define the impacts of CE strategies to other urban elements and environment through integrating the new practices into their planning processes (Petit-Boix and Leipold, 2018).

This article looks at CE as a solution sustainable on the field of built environment, by interpreting the term ‘built environment’ as buildings and infrastructure. The term of built environment has been used in such meaning in the statistics of the anthropogenic stock with the aim of separating infrastructure and buildings from consumer goods (Schiller et al., 2017b). Fischer-Kowalski and Weisz (1999) include buildings and infrastructure in human-made technical structures under the influence of culture and nature by underlining the fact that built infrastructure, along with any human-made artefacts, needs to be maintained to avoid decay and becoming naturalized. Moffatt and Kohler (2008) develop the same framework by adding the dimension of time and space with the intention of building a framework for evaluating the environmental impact of the built environment. The literature provides a strong opinion saying that the built environment must be understood broadly, as buildings and infrastructure that are not only constructed, but also operated, maintained and used for different purposes, causing various environmental impacts over their life cycle and in the end of life phase. Pomponi and Moncaster (2017) highlight the multidisciplinarity of the topic of CE and built environment by claiming that CE expands building research on the dimensions of governing and behavior. Based on these notions this review looks at built environment as a technical, environmental and cultural system that is produced, used, managed and maintained by humans for humans, making it a topic the understanding of which calls for multidisciplinary knowledge.

There is still room for promoting the role of built environment in the field of CE. According to a bibliometric analysis on CE research in Europe and China by Türkeli et al. (2018), there is moderate interest towards construction and building technology in Germany, moderate interest towards planning development in the Netherlands and Italy, and moderate or minor interest towards urban studies in China and Netherlands. Some review articles on the field are available, such as Van Dijk et al. (2014) who compared the C2C theory with other environmental system theories from the angle of cycles in building. Ness and Xing (2017) reviewed and applied CE-related theories to the built environment, formed a process for improvement of resource efficiency in the built environment and concluded that empirical research is a crucial element in improving resource efficiency. Ghisellini et al. (2018) seems to lean on the same empirical basis when they suggest applying CE strategies along economic, environmental and social indicators in their review on the construction and demolition (C&D) sector in China. Environmental indicators are investigated by Petit-Boix and Leipold (2018) in their review that focuses on environmental assessment in practices of CE. Previous studies are valuable but seem not to systematically review the available applications and look at CE from a methodological or abstract perspective and may limit the scope to a limited number of aspects of CE or built environment.

A research gap remains for a comprehensive and multidisciplinary review on concrete applications of CE in the built environment to understand the complexity of sustainable development in the field and to support development of successful policies and planning practices. Advancing urban sustainability requires a general view of the possibilities of the CE presented in the scientific literature. This literature review contributes to bridging the gap by providing a cross-sectoral general view with the focus on potential applications. A review on CE in the built environment would support development of the planning processes and the capacity development of professionals by helping in avoiding conflicting policies and finding successful ones. This review aims to respond to the demand by asking “how would the buildings and the infrastructure be constructed, used and managed in the transition towards resource efficient and low-carbon CE?”

2 Literature and structure

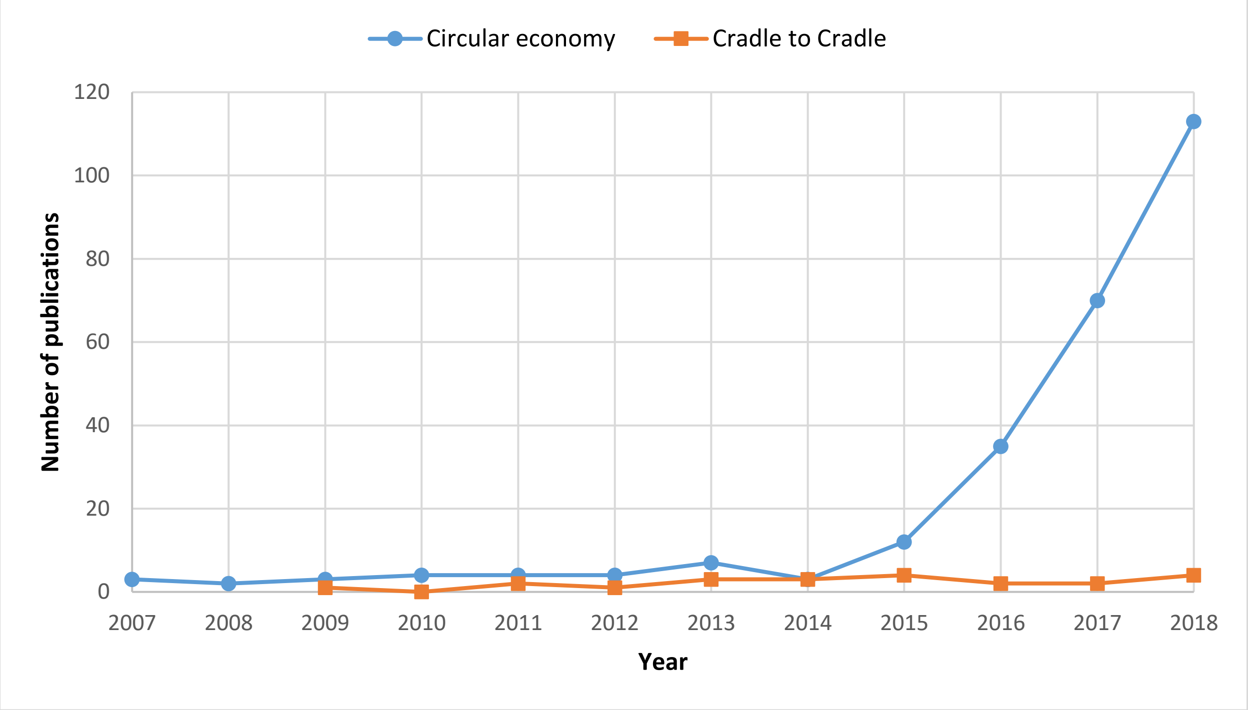
This literature review contains papers from scientific journals containing the term ‘circular economy’ as it appears alongside terms that commonly describe the built environment. The rationale for selecting the terms of search connected the phenomenon of CE to the field of applications; that is, the built environment. Since a goal of this review was to identify solutions based on CE for urban development projects, the perspective broadened beyond building and construction to include terms like city, urban, district, neighborhood and infrastructure as keywords in the literature search. “cradle to cradle” was also accepted as one of the search terms in this study as it is one of the most influential background concepts of CE (Franco, 2017).

This review was based on searches in the Web of Science, a citation indexing service launched by a company called Clarivate Analytics in 2002. The platform contains over 90 million records and supports 256 disciplines (Clarivate Analytics, n.d.).

The final search string in the search was: (“circular economy” OR “cradle to cradle”) AND (building OR urban OR city OR district OR neighborhood OR construction OR infrastructure)

Only papers published before January 2018 in scientific journals were included. The total amount of papers found was 499 out of which 217 were excluded due to irrelevancy. The excluded papers mainly used building in other ways such as “capacity building” or “theory building”. The final number of relevant papers totaled 282 where 260 papers originate from the search term “circular economy” and 22 papers from the search term “cradle to cradle”. Figure 2 shows that that interest in CE is rapidly increasing in the field of the built environment but interest in C2C seems to be stable. Additional sources that provide more detailed background information on some specific ideas of the search results were not included in the statistics.

Figure 2 Number of publications in the search results of this review by year.



2.1 Thematic categorization of the papers

To enable coherent discussion on the reviewed papers, there is a need to find a way to classify the findings on CE and the built environment from the existing body of literature. This paper's categories are based on the analysis of the material in this review, as well as previous reviews and theories. Existing literature on CE provides two main approaches to categorizing sources, called scale-based taxonomy and thematic categorization in this review.

The first possible categorization is the universal, scale-based taxonomy, which splits materials into the micro-, meso-, and macro-levels. A notable review that uses this scale-based taxonomy is Ghisellini et al. (2016). Another is by Su et al. (2013) who used a table in which they combined a scale-based taxonomy with thematic categories of CE applications. Pomponi and Moncaster (2017) also used micro-, meso-and macro-scales combined with scientific disciplines in their framework for the built environment. Pomponi and Moncaster (2017) placed buildings on the meso-scale, while other authors have classified district-scale actions on this scale. Due to the contradictions between different interpretations of the scale taxonomy, this review does not underline the aspect of scale but rather addresses the meaning of the urban scale when it is relevant from a practical perspective. Comprehension of the difference between bigger and smaller structures is visible in the contents of this review.

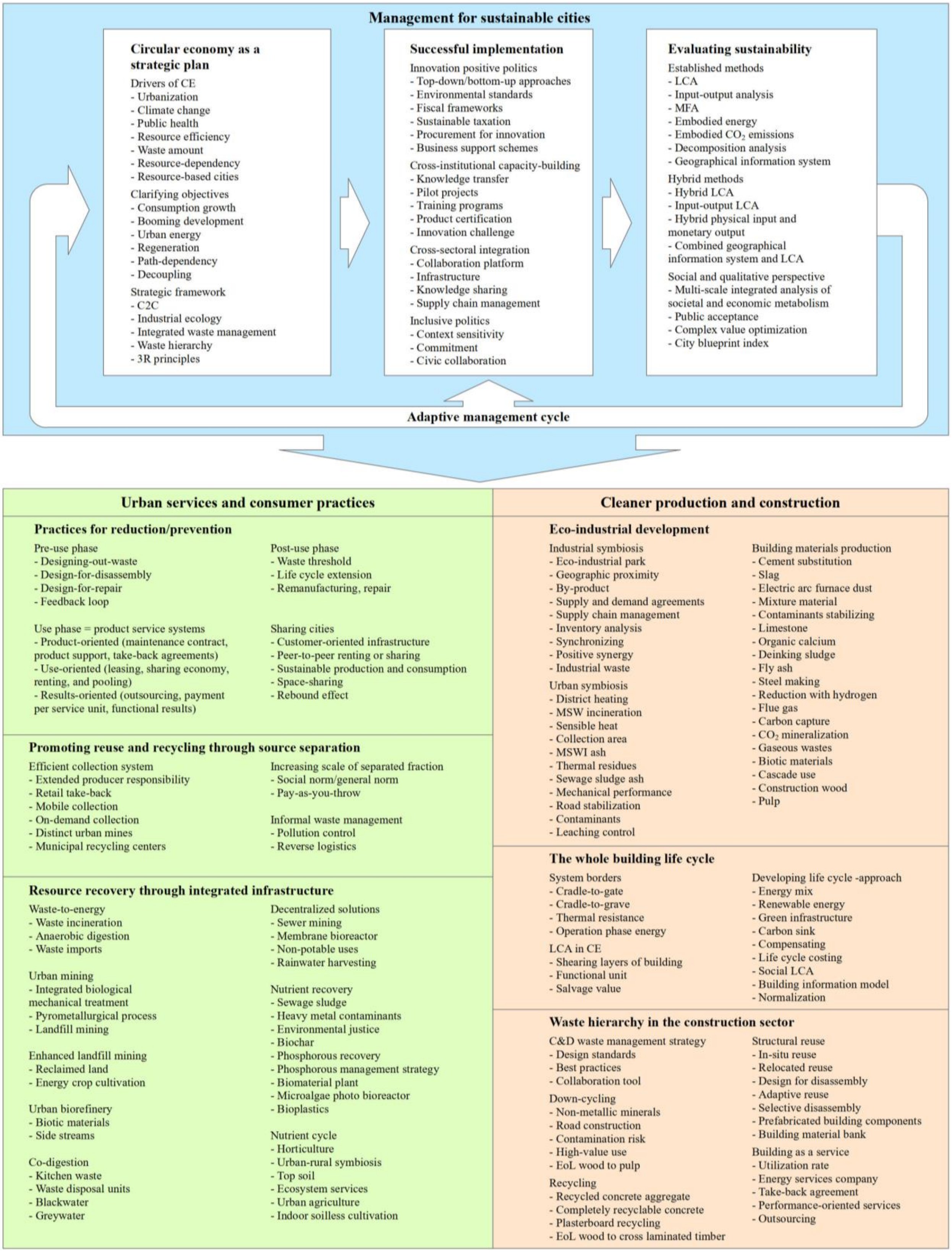
Another option is thematic categorization. In their review on CE in the manufacturing industry, Lieder and Rashid (2016) presented a framework of stakeholders (industry, governments, and society). Su et al. (2013) placed applications under the topics of waste management, consumption, production, and supporting actions. The stakeholders' perspective shares similarities with the public-private-people partnership (4P) model, a process framework that Majamaa et al. (2008) propose for large-scale building projects and property management. Winans et al. (2017) categorized the literature on CE into three groups: (1) policy instruments and approaches; (2) value chains, material flows, and products; and (3) technology, organizational, and social innovation.

With the knowledge from previous scientific literature in mind, this review aims at categorizing the papers into three thematic main topics, under which the literature falls naturally. These are:

- Management for sustainable cities
- Urban services and consumer practices aligned with CE
- Cleaner production and construction

The first main section discusses the objectives of CE as a strategic plan for the public sector and also provides management strategies for successful implementation of the plan. The second section discusses the possibilities of detailed applications of CE from a service-sector perspective. The third section looks at how CE transforms the construction industry sector. Figure 3 shows how the topics on the overlapping fields of CE and built environment are categorized under the thematic categories of this review.

Figure 3 Topics discussed under thematic categories of this review.



3 Results

3.1 Management for sustainable cities

In order to provide knowledge on how to enhance the transition towards sustainable practices in cities, the first section collects and discusses the notions in the literature related to management for sustainability. In the search results, Ness and Xing (2017) present their management model for a resource-efficient built environment that contains an idea of continuous improving. Their model is reminiscent of a more generic model of adaptive management cycle that includes a three-phase loop that starts from a plan where management objectives, actions and indicators are determined, continues towards implementation, ands in the phase of evaluation and learning that provides the basis for development of the next strategic plan (Jones, 2009). Following the approach, this review discusses the management of sustainable cities under three themes: (1) a strategic plan with definition of the main objectives; (2) implementation-related issues and (3) methods for evaluating sustainability.

3.1.1 The objective of circular economy as a strategic plan in management of sustainable cities

The CE is expected to solve many of the problems of urban sustainability. CE has been suggested as one of the responses to megatrends such as urbanization, climate change, and inadequate infrastructure causing problems such as water scarcity, flooding, water pollution, adverse health effects and rehabilitation costs (Koop and Leeuwen, 2017). Ilić and Nikolić (2016) find multiple drivers towards CE in municipal solid waste (MSW), including public health, resource efficiency and waste amount. CE is also expected to reduce resource dependency in urban areas by Liu et al. (2018) who examined in Zengcheng that the city is dependent on external nonrenewable energy. Respectively, in Birmingham, Lee et al., (2016) propose CE after demonstrating through material flow analysis (MFA) how the city heavily relies on its hinterland as a source of food, water, material and energy but also as an area for waste disposal. They claim that, in addition to local sourcing and more efficient transport, CE would have the potential to transform the city towards more sustainable and resilient metabolism. The other side of the coin in cities' resource scarcity is material extraction in rural areas that do not get the most out of economic benefits but rather suffer from pollution and other negative impacts of industry (Geng et al., 2011). As a side effect, industrial activity produces depleting and resource-based cities where CE has also been perceived as an environmental or economic development strategy (He et al., 2017). Expectations for the CE as a strategy to solve the problems of sustainable urban development are extremely high.

The main objective of CE seems to require clarification. Ramaswami et al. (2017) estimated through a bottom-up modeling technique that their set of strategies, including utilization of industrial excess heat in urban areas and utilization of wastes in construction, could carbon dioxide (CO_2) emissions in 637 Chinese cities by 15-36%, and help avoid 25,500–57,500 premature deaths annually. Still, this would not be enough to reverse the total environmental impact of human activities, as improvement in technical efficiency can only partially offset consumption growth, caused by growth of gross domestic product, urbanization and lifestyle changes (Peters et al., 2007). Emissions related to lifestyles and urbanization actually play a big part in environmental footprint of cities, as researchers in the city of Shenyang noted that commercial and residential sectors emitted the largest proportion of GHGs at 28.5% (Xi et al., 2011). Analysis of the urban metabolism in Shanghai showed that the industrial growth causes booming development of the service originated from lifestyle changes (Lu et al., 2016). This would create a reinforcing loop that continuously increases resource consumption. New and more energy-efficient buildings improve the urban emissions but construction materials production in new construction may offset the savings (Zhou et al., 2012) Energy intensive buildings and settlement patterns cannot be easily replaced because of material-intensive construction and slow regeneration of the built environment (Krausmann et al., 2017). Getting rid of this path-dependence is necessary if cities wish to respond to a challenge of absolute decoupling between environmental impact and economic growth (Krausmann et al., 2017). The results indicate that there is a call for development of new consumption practices for reducing not only wastes but also the demand for industrial production.

Cities need a strategic plan of how the whole built environment can be developed to simultaneously create value and reduce the need of resources. CE provides various developing strategies for infrastructure, such as 3R, C2C, industrial ecology and integrated waste management (Kollikkathara et al., 2009). A large number of optional strategies may confuse decision-makers when deciding what concrete steps they should take. Ribić et al. (2017) present a simple vehicle to overcome the problems of indecision called the waste hierarchy that has already been applied in the waste framework directive of European Union (European Union, 2008) and is actually very similar to the 3R principles (Yong, 2007). Waste hierarchy aims to prioritize the prevention of waste generation and to minimize processing which may provide costs savings opportunities in the extracting of raw materials and the disposal of wastes (Ribić et al., 2017).

3.1.2 Achieving success in the implementation of sustainable urban development

Finding appropriate practices for implementation is one of the main challenges of CE. In the literature, practical political interventions for the purpose are available such as public procurement, infrastructure, fiscal frameworks, knowledge development, business support schemes and collaboration platforms (Prendeville et al., 2018). A typical way to categorize different types of leadership approaches is a dichotomy of top-down and bottom-up approaches. In the context of built environment it was used by Pomponi and Moncaster (2017) in their research framework for CE and by Prendeville et al. (2018) in their comparative study on cities' CE initiatives. Prendeville et al. (2018) define bottom-up and top-down approaches as follows:

- Top-down change is institution-driven change (in this case municipal/local government) such as strategy and policy decisions including public-private partnership projects concerned with developing and facilitating market initiatives
- Bottom-up change describes social movements and social innovation such as initiatives and entrepreneurial activities initiated and run by civil society, non-governmental organizations, communities and businesses

As the literature indicates that management of the transition towards sustainable urban development and CE is an issue of finding balance between top-down and bottom-up approaches, the functionality of political interventions needs to be analyzed through both perspectives. Both of the approaches may provide competitive advantage because latecomers may reap the benefits through top-down approaches while new innovations are formed through spontaneous and self-organizing processes, which is why a market-driven approach remains essential (Mathews and Tan, 2011). Top-down command-and-control policies may not be avoided in industrial production where the main motivators for participation in symbiotic activities are economic advantage not only from benefits in material substitution but also tax preferences, financial subsidies and pressures from stricter environmental standards (F. Yu et al., 2015).

The risk in top-down policies is facing serious problems such as the different agendas of two government organizations that confuse the various actors, ignoring geographical variation, missing or conflicting policies, missing guidelines that might cause whitewashing at the operational level, and misunderstanding of the objectives of CE (Zhang et al., 2010). These problems could be avoided by taking the bottom-up perspective through simplifying regulations in which an example is the sustainable taxation, whereby government taxes non-renewable resources instead of labor and renewable resources (Stahel, 2013). Another example is procurements that are traditionally officials' straightforward decisions guided by strictly defined features, but procurement for innovation makes it more interactive and leaves detailed solutions for business to advance new CE innovation (Milios, 2018). The results indicate that innovation-positive politics which defines border conditions through simple rules would facilitate successful implementation by giving understandable objectives for stakeholders and leaving room for inventions.

Objectives or regulations alone do not guarantee successful implementation if there is a lack of capability among stakeholders. For example Tianjin Eco-City ended up in problems with a lack of expertise among professionals, greenfield development and diverging from the original vision of CE, which indicate that without capacity building, success in implementation could not be achieved (Chang et al., 2016). Referencing developed countries, as suggested by Zhijun and Nailing (2007), would provide a proper starting point in capacity building, but it alone will not enable getting rid of latecomer status. This is why there is a call for knowledge development where flexible roles between high education, industry and government, following the ideas of triple-helix model of innovation, could effectively facilitate cross-institutional knowledge transfer to accelerate urban development towards CE (De Medici et al., 2018). In practice, knowledge development could be effectively advanced by mixing approaches of education for sustainable development and sustainable consumption and production for example in C2C product certification, innovation challenge, sharing of productive capital and training program (Petry et al., 2011). Also, a pilot project may act as a tool for institutional capacity-building (Abreu and Ceglia, 2018). A large variety of detailed practices could be further investigated to enable cross-institutional capacity-building for increasing the probability of successful implementation in sustainable urban development.

CE is also an issue of cross-disciplinary development. Practical problems originated from missing cross-agency management were documented in Dalian where the Environmental Protection Bureau established a source separation system for MSW at the community level, while the infrastructure bureau still used the traditional waste collection system and mixed all the separated wastes together (Wang and Geng, 2012). In the case of developing sustainable tourism, Pan et al. (2018) found that lack of cross-disciplinary communication channels and information platforms causes barriers for developing resource recovery in infrastructure, conserving of nature and cultural heritage, and improving socio-economic conditions. An example of such information platform could be the CE strategy database, developed by Kalmykova et al. (2018). The results show that information platforms for networking, knowledge sharing, and supply chain management would provide premises for interoperability that is needed in CE for cross-sectoral integration.

Implementation of any CE initiative without a large enough commitment of key stakeholders carries a high risk of failure. In the worst case, officials can disable favorable development (Swagemakers et al., 2018). In Tianjin Eco-City Flynn et al. (2016) revealed through a questionnaire that the main motivator for moving into the area is not ecology but rather the high standard of living or value for money, leading to above average energy consumption and failure to reach sustainability goals. To avoid commitment-related problems in implementation of CE, Xue et al. (2010) conducted a survey on interest and awareness, which would be an applicable method in the preliminary phases, but actual implementation calls for public participation. Guidelines and principles regarding public participation are actually included for example in the legal framework of waste management in China but the procedures do not back it up (Wang and Geng, 2012). European cities may have bottom-up initiatives to overcome financial barriers for implementation of CE but they may lose credibility when only relying on major urban business actors and missing the citizen perspective (Prendeville et al., 2018). Bottom-up civic collaboration will also fail if the initiators cannot convince all key stakeholders and do not understand the characteristics of the context (Aguiñaga et al., 2018). The importance of contextual sensitivity in successful implementation was highlighted by Marin and De Meulder (2018). They claim that certain kinds of spatial structures are embedded in certain kinds of political positions, but their unclear framework raises questions on the predictability of the results. Many authors seem to agree that interactive and inclusive politics are needed in any sustainable urban development process to ensure that stakeholders are capable and motivated enough to help avoid any gaps between policymaking and practice.

3.1.3 Methods for evaluating sustainability

According the idea of continuous improvement and adaptive management cycle, the performance of the implemented plan should be measured to ensure that the intended effects will be achieved, and necessary improvements will be recognized. When developing new innovations of CE as well as measuring the progress in main goal of resource efficiency, reliable quantitative assessment of the environmental and economic impacts is needed, to which purpose the literature presents a diverse set of established scientific methods. Life cycle assessment (LCA) appears as a well-received bottom-up method that provides a comprehensive picture of the environmental impact of urban investments over time, while the popular top-down method is an input-output analysis that can reveal inter-regional and inter-sectoral consumer-producer relationships (Finnveden et al., 2009). MFA is a reliable method for understanding the flow of materials in complex, large-scale systems, and has also been utilized in the first steps of other methods (Dong et al., 2016). Embodied energy analysis defines the total amount of available energy needed directly and indirectly to generate a product or service that can make different solutions comparable (Liu et al., 2015). Respectively, embodied CO_2 emissions can be used in the comparison of solutions, as the emissions do not always correlate with energy consumption (Xi et al., 2011). When comprehension of the role of structural changes in total resource use or other impact is unclear, the decomposition analysis could provide clarity (Guo et al., 2016). These quantitative methods with different advantages show how the suitability of certain method depends on the nature of the investigated case, the research in question and available data.

The evaluation may face challenges when CE practices differ from business as usual, of if they are systemically complex or there is limited data available. To reveal the synergetic nature of CE concepts, there is a call for hybrid methods (Liu et al., 2017). One of the used hybrid methods is the hybrid LCA where the idea is to complete the process-based LCA with input-output LCA to take into account impacts caused in the supply chain outside system borders because process-based LCA alone suffers from a truncation error and input-output LCA employs historical averages which cannot reveal the nature of unconventional synergistic processes (Dong et al., 2016). Dong et al. (2016) overcame these problems by using a hybrid LCA method that employed MFA to compose the local process, LCA to analyze the environmental impact, and input-output analysis to complete data and define the streams over system borders. By employing an input-output method based ‘hybrid physical input and monetary output’ analysis they were able to convert monetary flows into physical flows and reveal a relationship between economic sectors in an industrial and urban symbiosis. Another direction for the development is broadening of the LCA approach as a bottom-up method that combines LCA results with statistical data of a geographical information system with the aim of predicting resource flows and the environmental impact when building-scale solutions multiply on an urban or national scale (Stephan and Athanassiadis, 2017). The literature shows that hybrid approaches of environmental assessment are built almost without exception by complementing LCA with other statistical methods.

Economic and environmental performance alone cannot legitimate new design solutions or techniques that have extensive effects on environmental values and quality of life, which is why interest in social aspects is increasing in the literature. Method of 'multi-scale integrated analysis of societal and economic metabolism' is broadening the discussion on urban metabolism by gauging working hours as a measure of social sustainability, along with economic and environmental indicators (Geng et al., 2011). A social aspect that also needs to be evaluated to avoid barriers for implementation of CE practices is public acceptance (He et al., 2018). Some of the barriers of social acceptance could be crossed by engaging stakeholders with an evaluation method that is socially, economically, and politically integrated, transparent, easy to understand, scalable, not too detailed, clearly defined and realistic (Iacovidou et al., 2017). When assessing qualitative and quantitative aspects, Iacovidou et al. (2017) claim that evaluation methods should avoid aggregating values into a single dimension, which is exactly what Nadal et al. (2018) are doing when they combine weighted quantitative data with weighted subjective score about qualitative issues into a single index number, basically indicating only an assessor's opinion on sustainability. An example of a safer approach in multi-criteria assessment could be a complex value optimization method that enables community engagement, utilizes the LCA and combines bottom-up and top-down approaches (Iacovidou et al., 2017). These results indicate that assessment methods should be not only reliable but also inclusive to enable defining the broadly shared objectives.

Some researcher chooses to build a method for monitoring of progression from scratch with varying degrees of success. One way for monitoring progression was presented by (Koop and Leeuwen, 2017) who compared the progress of cities in waste and water management systems by calculating the number of applied state-of-the-art technologies using an index system built with a panel of experts. The index system would simultaneously enable the sharing of best practices and ranking cases but would benefit mainly latecomers and not necessarily support bottom-up innovations. Koop and Leeuwen (2017) underline the importance of available and applicable data in enabling of the index system. Likewise, in the case of fully quantitative national CE indicators in China, Geng et al. (2012) noted that a lack of valid and accurate data created a barrier to the implementation of indicators but they found the indicators to be incomplete as well. Wang et al. (2015) noticed that pre-set indicators problematic also because they were not able to properly indicate the delinking of economic growth and environmental impact in the Chinese Ecological Province Construction initiative. The results show that cities and governments should primarily ensure that their data on resource flows through cities is diverse, accurate and applicable. That would enable them to develop and apply indicators at any later point of international co-operation between cities and scientists along the City Blueprint index presented by Koop and Leeuwen (2017) or any established methods presented in this study.

3.2 Urban services and consumer practices aligned with circular economy

As noted in section 3.1.1, climate change mitigation calls for developing infrastructure and the consumer practices of cities with a continuously improving and commonly shared vision of CE that enables the delinking of resource consumption from economic growth. da Silva (2018) sees CE as an issue of urban planning and management which is why there is a call for compiling knowledge of how cities and buildings should be designed, planned and operated to help the tertiary sectors to create more value with less resources. Having the main objective of waste hierarchy to avoid material processing, the next subsection will be discussing the studies related to waste management and urban infrastructure under the topics of reduce, reuse, recycle and recover in prioritized order.

3.2.1 Reduction of waste and consumption calls for new consumer practices

Reduction is prioritized highest in the waste hierarchy. The priority of reduction in the waste hierarchy refers to waste prevention that Hutner et al. (2017) defines as any measure taken before a resource crosses the waste threshold, claiming that, despite its priority, prevention activities have so far been hesitant. The same notions were made in a comprehensive review by Ghisellini et al. (2016) who claim that the principle of reduction remains one of the most poorly discussed topics in the scientific literature on CE and the emphasis should move from end-of-pipe activities towards smarter design and use of products.

Literature provides an appropriate starting point for investigation of potential applications to promote the priority of reduction. Hutner et al. (2017) categorize types of prevention into phases of pre-use, use and post-use, according to which life cycle phase the strategy applies to. The pre-use phase consists of acts such as designing-out-waste, where products are designed from recycled materials, designed with minimal material or harmful substance, designed to be manufactured with minimal loss, and apply design-for-disassembly (DfD) or 'design-for-repair' for enabling expanding life cycle of component or product. Feedback from recycling experts or services and environmental assessment can in the pre-use phase help in waste prevention through better design of a product or a production process (Esmaeilian et al., 2018). In the use phase, reduction could be achieved through more intense utilization of resources such as sharing economy to increase the number of users or through extending the life cycle of a product through repair and maintenance. The idea of prevention in the post-use phase is that the user will not discard the product after use but directs it to re-use to enable continuing the use, after checking & cleaning, repairing or remanufacturing if needed (Hutner et al., 2017). Hutner et al. (2018) has been able to show through LCA that some of these practices would effectively promote the principle of reduction. The results show that there is a call for closer research on how the successful implementation of reduction practices can be promoted.

A framework for facilitating reduction of consumption and waste with the same or higher level of service could be provided in the concept of product-service systems (PSS). The core idea of PSS is to focus on customer needs instead of physical products, and create a mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling the final customer needs (Tukker, 2015). A similar approach with the PSS is introduced in the performance economy where the customer pays for utilities instead of ownership (Stahel, 2017). The tactics in PSS are divided into three main categories (Tukker, 2015):

- Product-oriented (maintenance, product support, and take-back agreements);
- Use-oriented (leasing, sharing, renting, and pooling);
- Results-oriented (outsourcing, payment per service unit, functional results).

The paradigm of PSS gives a large variety of options for satisfying the customers’ needs. An example of PSS would be an urban laundry service (Retamal and Schandl, 2018). In the same demand, another type of PSS would be a washing machine rented with payment-per-use and maintenance contract (Lieder et al., 2018). One of the most comprehensive interpretations of PSS in urban context is provided by Ness (2008) who present customer-oriented infrastructure systems where the utilities for citizens are provided through holistic service. In this context, Knoeri et al. (2016) categorize the citizens' needs into the classes of thermal comfort, illumination, hygiene or cleanliness, sustenance, communication and mobility. The idea of customer-oriented service is already embedded in infrastructure services, but PSS is broadening the idea to products and goods that previously have been included in the sphere of private consumption or retail.

In the sources one of the most broadly discussed sub-category of PSS is the sharing economy. Hutner et al. (2017) also suggested the sharing economy as a strategy of prevention in the phase of use and interpret it as a practice to enable multiple users for a single product. Nobre and Tavares (2017) linked urban CE to discussions on smart and sharing cities where digitalization enhances the sharing economy by providing new, effective marketplaces for producer-consumers (prosumers) to rent out goods. In the context of built environment, they examined Airbnb and Über as cases illustrating ongoing changes. While the modern sharing economy is narrowing to represent commercial platform online platforms for facilitating peer-to-peer practice in renting or sharing, Cohen and Muñoz (2016) also include uncommercial community-based practices in the concept. They viewed the sharing economy as an integral part of CE and as a potential way to promote sustainable production and consumption in multiple resources such as energy, agro-food, and the production and consumption of transport and space. Despite its origins it seems that smart technologies promote sharing economy as a rapid transition in consumer practices towards more intensive use of spaces and goods.

There is a lack of consensus on the potential for climate benefits of the sharing economy. Hutner et al. (2018) have demonstrated that it is possible to prove through life cycle impact assessment that preventative strategies such as sharing economy contain radical potential for reduction in waste and climate emissions. In space-sharing, of which AirBnB is a well-known peer-to-peer concept, outsourcing of everyday spatial needs could enable space-saving with the same higher functional quality. Hobson and Lynch (2016) take a critical stance and propose examining assumptions about the environmental benefits of sharing economy more closely, arguing that Airbnb fails to fulfill the agendas of sustainable consumption because of a 'rebound' effect where low cost actually promotes the escalation of tourist-based consumption. They ignore a possibility of sustainable taxation that emphasizes the heavy emissions of air travel to steer consumer behavior. Since modern sharing economy applications are quite new phenomena, it is difficult to find empirical proof of the benefits while negative impacts have also evolved. The results highlight the need for further research on how the service sector, including real estate business, could move towards holistic operation and maintaining of resources with the strive for the highest possible energy efficiency and utilization rate of products.

3.2.2 Promoting reuse and recycling in the waste collection system through source separation

Reuse and recycling are the second and third priorities in the waste management hierarchy. Reuse is a preferable principle in general and found to be an effective way of reducing the volume of waste, for example in case of waste electrical & electronic equipment (WEEE) (Veenstra et al., 2010). Theoretically, reuse overlaps with priority of reduce while trying to motivate users not to discard a product in the post-use phase. The first barrier for promoting reuse is the product design of which an example is lithium-ion batteries where Busch et al. (2014) found low potential for reuse due to uncertainty in battery chemistry, proposing the concept of down-cycling by using electric car lithium-ion batteries in grid-attached electric storage where performance requirements are lower. To overcome barriers caused by the current take-make-dispose culture it would be essential to apply waste prevention practices in the pre-use phase, such as DfD and design-for-repair.

Reuse shares the same barrier with recycling of establishing a source-separating collection system with supply chains for different materials or reusable products and components. In practice it means that that for example in the case of WEEE, collection systems should be designed to promote separating of functioning devices from broken ones (Pierron et al., 2017). Recycling process suffers from low quality of material in China where Hu and Poustie (2018) suggest establishing a legal framework that obligate inhabitants to source separation. In a European context, the main political tool to force the transition to proper facilities is extended producer responsibility (EPR) where the underlying idea is to make the manufacturer of a product responsible for its entire life cycle, and especially for take-back, reuse, recycling, and final disposal (Lindhqvist, 2000). Multiple authors in the results discuss EPR as it is mandatory for WEEE in the European Union (European Commission, 2015). Detailed practice for organizing source separating supply chain vary case-by-case, because EPR does not specify whether recycling facilities should be outsourced for example to a producer community or organized in-house.

Researchers have suggested a broad variety of practices to advance source separation in the waste management system. Mo et al. (2009) note that the key factors affecting recycling patterns and the main actors are the value and scale of waste generation. With the aim of improving efficiency of recycling facilities by increasing the share of source separated fractions, researchers have investigated possibilities to influence citizen behavior. Using legislation to force source separation may not be an effective strategy, as Tong et al. (2018a) find social norm more effective than general norm. A solution might be setting an economic incentive such as the pay-as-you-throw scheme, with higher charges of residual waste, that has been found to increase the amount of recycled waste and reduce residual waste but not to affect the total amount of waste (Morlok et al., 2017). Retail take-back systems might increase the amount of source separation in non-reusable fractions such as light bulbs but it would have a small impact in municipalities where proper recycling centers already exist (Richter and Koppejan, 2016). Scale of the recycled fraction and efficiency of the collection could be improved through distinct urban mines where the idea is to place the collection points at places where most e-waste is generated (Ongondo et al., 2015). Climate emission comparison of three optional WEEE collection systems revealed retail take-back system the most effective, mobile collection the second best and municipal system the most ineffective (Nowakowski and Mrówczyńska, 2018). New opportunities to improve the efficiency of collection systems may lay in digital solutions where an example is a genetic algorithm in the route optimization of on-demand e-waste collection (Nowakowski et al., 2017). The results indicate that reaching the critical mass through larger scale of source separated fractions and improved efficiency of the waste collection system could enable reuse and recycling in the waste management. Making source-separating waste management systems more accessible, attractive, and effective calls for research on new smart technologies and transformative policies.

Involving the informal waste management sector would support improving the efficiency of source separating waste management system. Especially in reusable fractions, take-back systems should be facilitated through dealers and retailers because they are the most effective agents of refurbishment and reselling (Veenstra et al., 2010). In China, the informal sector has traditionally played a significant role in facilitating reuse and recycling in waste collection systems but recent developments in the sector have led to a deterioration of the working environment due to reduced profits and increased regulation (Steuer et al., 2018). Some of the regulations are favorable as the primitive recovering processes contain a risk of releasing heavy metals into the soil and rivers (Han et al., 2018). Still it would be highly counterproductive to exclude the informal recycling market from the system (Tong et al., 2018b). To enable both pollution control and inclusion of informal actors, Tong et al. (2018b) suggest developing creative market-based business models among various stakeholders for effective reverse logistics. The results indicate that the local culture and the stakeholders' capability need to be carefully considered when establishing systems for recycling and reuse.

3.2.3 Integrated infrastructure towards a closed biotic cycle and recovery of valuable resources

Despite a developing process of reuse and recycling, a notable share of end-of-life products end up in disposal when the last option for CE is recovery of the valuable resources and energy. Waste incineration looks like a climate-friendly solution compared to coal-fired plants and landfilling (Islam and Jashimuddin, 2017), which is why many cities end up investing in waste-to-energy plants. Some cities struggle with the uncontrolled increase of waste incineration because it is a suboptimal solution that causes inefficiency in waste reduction and recycling (Farmer et al., 2015). Climate benefits of incineration are also uncertain due to development of low carbon techniques in other power generation sources (Pizarro-Alonso et al., 2018b). In Denmark where other energy sources are available, Pizarro-Alonso et al. (2018a) found temporal mothballing of incineration plants economical during overcapacity in power generation. They assume that a coherent European strategy would help to avoid waste imports, originated from tax competition. New approaches are needed for getting more value from waste but causing less environmental impacts.

Researchers discuss the principle of recovery in waste management systems through the concept of urban mining. It is a universal term that represents the idea of recovering metals and other resources from anthropogenic sources (Krook and Baas, 2013). Urban mining has been demanded by Xianyang Zeng et al. (2018) who noted through MFA that 60% of the nickel in China ends up in landfills. The main barrier for the urban mining is the feasibility of the metal recovery for example in case of lithium where efficient process is still lacking (Swain, 2017). The profitability is improving but varies between metals as recovery of gold and copper from e-waste is becoming competitive compared to virgin mining (Xianlai Zeng et al., 2018). Zinc recovery from MSW could already be profitable using an integrated biological mechanical treatment (Ng et al., 2016). Improving the efficiency of CE system of metals through internet of things, including a loop of digital monitoring, simulation and optimization has been suggested by Reuter (2016). Efficiency could be also improved through urban planning by placing facilities near an urban area to enable thermal energy recovery from pyrometallurgical processes and to minimize transportation costs (Tesfaye et al., 2017). If scientific efforts on metal recovery lead to a breakthrough and a paradigm shift in waste hierarchy, optimal positioning of increasing number of metal recovery facilities in the urban fabric should be explored as part of the recovery process.

The paradigm of resource recovery is moving towards a holistic perspective also by integrating multiple processes. Jones et al. (2013) place urban and landfill mining under the same approach of a long-term recovering perspective whereby material agglomerates excluded from ongoing and historical anthropogenic cycles are once again brought back into social systems. Enhanced landfill mining further develops the idea of landfill-mining process through the concept of waste-to-energy, and utilization of reclaimed land in energy crop cultivation (Schneider et al., 2017). The paradigm of recovery is developing towards larger wholes also in biotic materials in which researchers discuss the concept of urban biorefinery, referring to a plant that could produce various chemicals, fuels, and intermediates from different types of biomass feedstock by combining different processing methods (Satchatippavarn et al., 2016). It looks like waste management is evolving towards a larger integrated process whereby the side streams generated by the treatment of different fractions are utilized in the processes of other waste streams to maximize the value generated from the materials.

Biowaste treatment could be partly integrated with the wastewater treatment system as a share of the urban biomasses originates from wastewater. van der Hoek et al. (2017) found climate and economic benefits in recovery of chemical and thermal energy through integrated wastewater and waste-to-energy processes. Co-digestion of biomasses from various sources could even improve the process of anaerobic digestion (Pan et al., 2015). To enable kitchen waste and wastewater co-digestion, Verstraete and Vlaeminck (2011) suggest installing waste disposal units in kitchen sinks for collecting biowaste through sewage. They analyze also decentralized neighborhood-scale energy and nutrients recovering system with separated blackwater and greywater treatment but end up suggesting a centralized end-of-pipe scenario for over 100 000 inhabitant equivalents. Still, Giezen (2018) argue that CE drives energy and water infrastructure not only towards system integration but also decentralized solutions. Development of contemporary technologies such as membrane bioreactor could enable concepts like sewer mining, where the idea is to recover water from sewer for non-potable uses (Makropoulos et al., 2018). Rainwater harvesting could be another water-saving solution, especially in cities suffering from drying aquifers (Espíndola et al., 2018). As there is no consensus on the level of centralization in resource recovering infrastructure, and as new technologies are transforming the field, a decentralized scenario in the future wastewater treatment might as well be possible.

The potential for nutrient recovery is gaining special interest in the development of wastewater systems. The problem is the phosphate rock used in agriculture which is a geographically concentrated, nonrenewable resource with significant environmental impacts. A solution may lay in biomasses from urban sources that contain significant potential for nutrient recovery (Tampio et al., 2017). To capture the potential, a large variety of technologies for nutrient recovery from wastewater have been investigated (Egle et al., 2015). Case et al. (2017) also investigated farmers' interest in the utilization of fertilizers originating from urban residues. The greatest barrier for utilization of sewage sludge as a fertilizer results from heavy metal contaminants. (Mosquera-Losada et al., 2017). The same problem applies to biochar originated from urban residues (López-Cano et al., 2018). It has also become an issue of environmental justice in the United States (Mason-Renton and Luginaah, 2018). Skeptical views were expressed by Macintosh et al. (2018) who consider the recovery of phosphorous an expensive option and claim that a broad waste hierarchy following management strategy is needed for saving the critical phosphorous resources. Some of the economic issues in nutrient recovery could also be resolved through some novel technologies such as microalgae photo bioreactor and membrane bioreactor that move the idea of wastewater management towards a plant that produces multiple valuable resources such as energy, clean water, bioplastics and nutrients (Uggetti et al., 2018). As technology and understanding of nutrient recovery processes evolve, there is a need for a continuously improving holistic view of healthy, safe, and effective nutrient recycling and use.

Nutrient recycling has a link to facilitating sustainable food production, which has gained interest also in the urban context. Nutrient recovery leads to integrative links that close the loop between urban and rural areas, improving the sustainability of both agriculture and wastewater treatment (Masullo, 2017). This development has the potential to cause landscape changes due to expanding applications of horticulture, energy crops and urban gardening (Jedelhauser and Binder, 2018). In urban agriculture, quite holistic concepts have been investigated such as the Norwegian pilot project "Food to Waste to Food". It is a soap bubble insulated greenhouse that utilizes heat, power, nutrients and CO_2, from biogas generator and anaerobic digestion of bio-waste (Stoknes et al., 2016). These new solutions need careful comparison to current open field agriculture options because earlier results indicate that indoor soilless cultivation is water and space efficient but more energy intensive (Gwynn-Jones et al., 2018). It means that basically non-renewable top soil will be a critical ecosystem service for human activities for a long time and CE strategies for soil and land management including brownfield development, urban mining, urban planning and urban agriculture are needed (Breure et al., 2018). These results indicate that a new kind of symbiosis between urban and rural areas, enabled by integrated waste, water and energy infrastructure for sustainable biotic cycle and recovery of valuable resources, could be considered as a new synergetic practice for sustainable urban development.

3.3 Cleaner production and construction

This section aims to look closer at the solutions that the current CE literature in the field of built environment can offer to construction industry in order to improve environmental efficiency. The built environment plays a crucial role in global climate emissions but because of high resource consumption in both phases, construction and use, the climate efficiency cannot be improved by simply replacing the existing cities with new ones. To decrease the environmental impact in the construction industry, Krausmann et al. (2017) suggest more intensive utilization of existing building stocks, longer service life, and more efficient design and technologies. Hara et al. (2011) suggest as implementation of the concepts industrial symbiosis (IS), including urban waste utilization as energy and material sources especially in the steel and cement industries. Esa et al. (2017) consider CE concepts such as waste hierarchy and 3R in their waste management strategy for construction industry and note that waste prevention strategies are applied to the design and planning stage while recycling and reuse are applied during the stages of procurement, construction and demolition.

3.3.1 Achieving a low-carbon built environment through broadening the life cycle approach

LCA has been well-established as a key method for assessment and management of sustainability of construction projects. It is useful method especially in buildings that cause significant resource consumption in both material production and operation energy over time. CE cause in buildings’ LCA a paradigm shift from cradle-to-gate or cradle-to-grave to C2C and whole life cycle approaches where the phases of planning and design, materials production, materials distribution and construction process, maintenance and renovation, deconstruction and disposal, to the material reuse and recycle phase are taken into account (Ng et al., 2012). Still, in the construction sector, LCA has been applied to a single material with cradle-to-gate system borders, such as in recycled insulation materials with different thermal conductivity, by varying insulation thickness to achieve certain thermal resistance (Nasir et al., 2017). While insulation thickness also affects surrounding structures in the building, evaluations on different wall compositions would help to avoid some of the misleading results from narrow system borders (Slavković and Radivojević, 2015). Still, the results on single component should only be applied as a part of decision-making through the whole life cycle assessment of an entire building (Silvestre et al., 2013). Buildings’ emissions result not only from wall composition but multiple technical systems, structural composition and local energy mix (Hossain and Ng, 2018). Information on thermal conductivity and environmental impact of single components will be still useful when the LCA of the whole building is composed.

Multiple improvements have been suggested for the buildings’ LCA. One direction for recent development is taking into account any compensating elements on the property, with the aim of promoting renewable energy and green infrastructure as a carbon sink (Renger et al., 2015). A significant role of operation phase energy consumption in building's life cycle emissions require harnessing upcoming renewable energy techniques that are applicable in urban environment (Barragán-Escandón et al., 2017). Also, in review by Hossain and Ng (2018) multiple improvements for developing buildings' LCA were suggested, such as noticing context's effect on energy consumption, energy mix and upstream processes, implementing LCA in building information model, combining the LCA with social LCA and life cycle costing, and starting industry collaboration to develop an LCA database. They note that one of the problems in buildings' LCA is to make the results from different cases comparable as the service lives and functional units between different cases vary. Broadening of the approach in buildings' LCA calls for standardization and a normalization method to improve its applicability outside case-specific decision-making (Hossain and Ng, 2018).

The current LCA has shortcomings with revealing the benefits of waste prevention strategies that should be prioritized highest in CE. From this perspective the problem in buildings' LCA is using fixed, typically 50-year, service life for the whole building (Hossain and Ng, 2018). The problem in fixed whole building service life is that it applies poorly to revealing the benefits of waste prevention strategies such as sharing economy and DfD. Basically new design strategies with the objectives to intensify the use of building or its components call for special attention on relationship between matter and time (Campioli et al., 2018). For example in case of DfD Campioli et al. (2018) refer to the idea of shearing layers of building presented by Brand (1995) who demonstrates the importance of paying attention to the fact that each structural or technical system in the building would have its own service lives. The approach should move from LCA with fixed whole building towards an approach focusing on unique service life for each component. In this case, the whole building LCA could be composed by using a functional unit in which the lifecycle emissions of each component are divided by its historical and expected service life in years. Another option for promoting reuse could be applying remaining service time as a compensating element in buildings' LCA, following the idea "salvage value" that has been used in life cycle costing (Akanbi et al., 2018). These shortcomings show that more research on promoting priorities of reduce and reuse in buildings' LCA are needed.

3.3.2 Improving the eco-efficiency of building materials through industrial and urban symbiosis

One solution to cutting the heavy short-term environmental impact of building material production could be a concept of IS that has emerged from the resource recovery paradigm of the field of eco-industrial development. It is a concept that has been noted to be able to improve socio-economic indicators and decline energy consumption in Chinese eco-industrial parks (Zhang et al., 2009). The key aspects of IS are collaboration and the synergistic possibilities offered by geographic proximity (Chertow, 2003). It is a principle that engages traditionally separate industries in a collective approach to ensure competitive advantage, which involves the physical exchange of materials, energy, water, and/or byproducts. A successful IS is capable of avoiding byproduct quantity uncertainties with long-term supply and demand agreements for example by utilizing a management and inventory analysis tool in synchronizing byproduct exchanges between multiple suppliers and buyers (Herczeg et al., 2018). Mathews and Tan (2011) suggest criteria for successful eco-industrial development according to which development must improve the eco-efficiency of a group of companies, while also enhancing the profit position of at least one without damaging that of the others. In other words, IS is development practice to achieve positive synergies and improve environmental performance of whole industrial area.

A common form of IS is the utilization of industrial waste in production of building materials to improve their environmental performance. An effective and established practice to cut emissions of steel and concrete industries is substituting cement with steel slag (B. Yu et al., 2015). A novel technique in steel industry would be carbon capture from flue gas by CO_2 mineralization with electric arc furnace slag, and by employing the carbonized slag as construction material (Pan et al., 2017). Also, brick production has found applicable uses for some industrial wastes, such as electric arc furnace dust, as a mixture material due to its potential for stabilizing contaminants (Karayannis, 2016). A mixture material in bricks can also originate from biotic sources such as olive oil production residues (Díaz-García et al., 2017). Limestone in cement, too, could be substituted with materials from organic sources, such as eggshells (Ferraz et al., 2018). An organic source to be utilized in cement with even greater potential is deinking sludge from a paper mill that could substitute 49% of fuel and 2.7% of limestone when incinerated along cement production (Deviatkin et al., 2016). The bio-economy has its separate tradition in establishing processes of CE where the term of 'cascade use' refers to symbiotic process such as combined use of harvested wood in the form of pulp, construction wood, and energy, to save GHG emissions, compared to single use (Sikkema et al., 2013). The results indicate that involving in IS not only steel and concrete but also industries with biotic materials would provide innovative solutions for cutting environmental impact of construction materials.

Some of the practices of IS will be outdated when current carbon intensive techniques are replaced with climate neutral ones. B. Yu et al. (2015) estimated that the symbiotic activities of steelmaking industry contain nearly a 60% CO_2 reduction potential in which reuse and recycling of solid waste/byproducts contribute 16%, the comprehensive use of gaseous wastes/byproducts contribute 41% and the recovery and cascade use of sensible heat contribute 3%. While utilization of gaseous wastes and use of slag in concrete are business as usual practices, the actual future potential of IS would be only 20%, which is why more radical techniques to cut emissions in steelmaking are still needed. One such technique would be steel reduction with hydrogen, as suggested by Reh (2013), which would also change practices of IS because of a potential reduction of gaseous wastes. Use of coal ash as an alternative raw material in concrete is another example of IS practice related to construction materials that is getting out of date after shutting down of coal power plants (Dong et al., 2017). The results show that when applying the concept of IS there must be awareness of the most advanced technologies of cleaner production to avoid wasting efforts in establishing of outdated processes.

In recent studies, researchers have also suggested the concept of urban symbiosis (US) to provide resource-saving, reduction in mining, waste disposal and CO_2 emissions, as well as to generate revenue for companies and to create local business opportunities (Li et al., 2015). The term refers to an extension of IS that entails exchanging materials and energy between industrial and residential areas (Van Berkel et al., 2009). A typical construction material that could be involved in IS is cement where any non-toxic urban and industrial solid wastes that contain energy have been utilized as an alternative energy source, and thermal residues have been utilized as an alternative material source (Supino et al., 2016). In steel, the down-cycling of high-quality cold-rolled steel into construction steel would avoid losses in steel stock (Pauliuk et al., 2017). IS could also bring climate benefits, as recycling of every kilogram of steel scrap can also help to avoid 0.8 kg of CO_2 emissions (Lanfang et al., 2015). Carbon neutral steel reduction with hydrogen could make some of the US practices out of date, such as the use of waste plastics as a substitute for steelmaking coke, as suggested by Dong et al. (2016). The planning issues of US appear the same as with MSW management of finding optimal collection area and plant size for different fractions (Chen et al., 2012). This makes it look like simply an IS integrated to the urban mining facilities, waste-to-energy systems and district heating.

Current applications of US and IS are basically energy and material recovery plants which is why the same criticism as in waste incineration – that it impedes proper waste hierarchy – applies to US. A good example of problems of US on the field of construction industry is the utilization of MSW incineration (MSWI) ash as a construction material (Vandecasteele et al., 2013). The problem in use of MSWI ash as a substitute of cement is its weaker mechanical performance compared to cement that limits the use of thermal residues to road stabilization (Deviatkin et al., 2017). The same problem applies to substituting cement with sewage sludge ash which is why Molina-Moreno et al. (2017) suggest its use in concrete structures that do not support heavy loads. Another great barrier to the utilization of MSWI ashes in construction is finding a viable solution to remove or control leaching of toxic and corrosive contaminants (Verbinnen et al., 2017). If contaminants cannot be removed effectively, sewage sludge ash and MSWI ash could only be safely used in the production of ceramics and bricks (Smol et al., 2015). Basically, a high quantity of contaminated sewage sludge ash and MSWI ash indicates that urban waste problems should primarily be solved by following the ideas of C2C through designing maintainable, recyclable, biodegradable packages and consumer products (Braungart and McDonough, 2002). It is even more favorable to put more effort on waste prevention strategies such as designing-out-waste, PSS and remanufacturing (Hutner et al., 2017). The results show that there should be awareness of latest carbon neutral CE strategies when applying IS, US or any material recovery.

3.3.3 Transition towards a proper waste hierarchy in the construction sector

Implementation of CE in the C&D sector is in its early stages and causing high rates of low-value waste generation (Salemdeeb et al., 2016). C&D wastes originate from relatively high turnover of buildings and infrastructure in developed countries (Tisserant et al., 2017). According to the review by Huang et al. (2018) lack of building design standard for reducing C&D waste, low cost for C&D waste disposal and inappropriate urban planning are the primary barriers of reducing C&D waste in China. A questionnaire for six experts shows that the main barriers for CE in the C&D sector are improper dismantling, sorting, transporting, recovering processes, and finitely recyclable materials (Mahpour, 2018). To overcome the barriers, researchers suggest documentation of best practices (Gálvez-Martos et al., 2018). Getting results may need also a broader vision on CE-supply chain to which purpose Leising et al. (2018) developed a collaboration tool. The results show that, in the C&D sector, CE has been largely discussed as an issue of waste management.

A well discussed topic in the C&D waste sector is the concept of "down-cycling", which refers to material recycling where the material value declines (Vandecasteele et al., 2013). The use of different kinds of recycled and down-cycled non-metallic minerals is a popular solution in road construction, due to heavy and growing demand for non-metallic minerals, but a typical way of using crushed concrete in road structures looks more like a solution for disposal of demolition waste, as its proportion in the road construction material is not statistically significant (Miatto et al., 2017). There is a risk of contaminants leaching into the ground when using concrete aggregates, but this risk can be somewhat controlled with a larger grain size (Coudray et al., 2017). In the literature, unusual down-cycling ideas for construction wastes include utilization of materials as a filter for wastewater (Grace et al., 2016). Another creative use for construction waste is as a substrate in green roofs (López-Uceda et al., 2018). As the environmental benefits in down-cycling are weak, and better technical possibilities are available in many building materials, it is easy to understand why Vandecasteele et al. (2013) claim that the discussion on C&D waste should move towards high-value use. From this perspective, advantageous material would be an end-of-life construction wood with multiple high value uses including utilization as raw material in the pulp industry (Husgafvel et al., 2018). In the C&D sector, future research on down-cycling could put more emphasis on facilitating high value uses of end-of-life wood.

Recycling is the most investigated topic in the field of C&D waste (Ghisellini et al., 2018b). In plasterboards, the main benefit from recycling is avoiding conditions in landfills where gypsum produces hydrogen sulfide, but also 10% climate benefits can be achieved by preventing uncontrolled methanation of the cardboard (Jiménez Rivero et al., 2016). In the case of concrete, recycled aggregate is appropriate from the perspective of mechanical performance (Yao, 2018). Recycled aggregate in concrete may also save one-third of raw materials (Schiller et al., 2017a). Still, climate benefits cannot be achieved in use of recycled concrete aggregate (Ding et al., 2016). Climate benefits resulting from recycling in the concrete sector would derive fully from cement production. Completely recyclable concrete made with using limestone aggregates could reduce the life cycle CO_2 emissions of normal strength concrete structures by 7-35%, depending on service time, whilst a cubic meter would cause over 0.4 t CO_2eq of climate emissions (De Schepper et al., 2014). In steel, recycling can cut energy intensity by 29%, GHG emissions by nearly 45%, and air and water emissions by 90%, but still every kilogram of recycled steel consumes 18.1 megajoules of energy and causes over 1 kg of climate emissions (Lanfang et al., 2015). A promising application of recycling is using end-of-life construction wood as raw material in cross laminated timber (Rose et al., 2018). The results show that most of the recycling building materials can bring typically moderate but not game-changing climate benefits.

Limited benefits of recycling and down-cycling maintain the logic of waste hierarchy strong in the building sector, which is why an increasing number of sources discuss solutions of reuse. Different types of structural reuse could be classified into the categories of in-situ reuse or relocated reuse and into the levels of whole building, component system and element (Densley Tingley et al., 2017). Angrisano et al. (2016) suggest extending the service time of buildings through adaptive reuse where spaces are transformed for a new function. It will be the primary solution of CE on the construction sector for a long time, due to the current slowly renewing building stock (Schiller et al., 2017b). In some cases, selective disassembly would be an appropriate solution where fluid sequential process can be achieved with a building information model -based tool with expert rules for choosing, ordering and defining disassembly directions of parts, based upon physical constraints (Sanchez and Haas, 2018). An exception in the current building stock are some prefabricated building components that may be reusable (Minunno et al., 2018). Despite its potential for extensive environmental benefits, low resale value compared to high labor costs can create a barrier for building component reuse (Zaman et al., 2018). The concept of DfD would help reduce labor costs in reuse of future buildings to which purpose Pavlović and Veljković (2017) developed, modeled, and tested bolted shear connectors in a concrete flat slab. Densley Tingley et al. (2017) claim in the case of construction steel that barriers for reuse are not primarily technical but systemic, including obstacles related to cost, availability, customer demand, traceability, and supply chain gaps. To overcome the barriers, they suggest government leadership, a demonstration of client demand, technical guidance, and education for the construction industry as well as a database of available reused sections. Such a digital 'material bank' for component reuse can be efficiently composed by taking its construction component database from the building information model (Nobre and Tavares, 2017). Establishing a supply chain for reusable components and especially establishing a building material bank could be included in an EPR for construction industry, as suggested by Ghisellini et al. (2018a) in their review. The results indicate that, in the future, the construction sector should put a lot of effort on multidisciplinary research that emphasizes advancement of reuse and DfD.

As discussed earlier in Section 3.2., the reduction of consumption and harmful waste is the most important priority in the waste hierarchy. According to Krausmann et al. (2017) more efficient design and technologies needed in the construction sector to reduce its environmental impact promote a higher utilization rate and longer service life. For phase of use, PSS is a distinct paradigm in literature that could provide solutions to achieving the objective of reduction, by getting more value from resources and focusing on customer needs. The applications of PSS are, for example, maintenance contracts, sharing, outsourcing and performance-oriented services (Tukker, 2015). An early infrastructure-related example of performance-oriented PSS could be an ‘energy services company’ that sells energy at a higher price per watt, but provides energy savings for customers by combining expert services and installations (Ness, 2008). A hypothetical PSS application in the construction sector could be a service that rents out or sells reusable structural components for buildings by take-back agreements and utilizes components multiple times. In the construction industry, too, the paradigm of PSS provides potential ideas to create more value with less physical resources, the focus of CE research in the sector should move to finding out if enterprises could help to reduce waste and consumption by concentrating on end user needs.

4 Discussion

The concept of CE is a set of principles that collects a large variety of practices under the same objective of cutting the production of waste and consumption of resources by retaining the value of resources for as long as possible. The value of this kind of sensible umbrella term is that it enables the building of a broadly shared vision of a sustainable society by strengthening communication. This review shows that the number of different, sometimes optional and not always efficient CE solutions to be applied in built environment is large and growing with accelerating speed.

The term ‘cradle to cradle’ was accepted as one of the search terms along ‘circular economy’ because it is one of the most influential background theories looking at sustainable material cycles from the perspective of product design. Basically, adding this term did not radically change the outcome of the study but the emphasis on recycle and reuse in C2C is clearly visible, as the term did not provide any studies on waste prevention. 11 studies out of 22 in the results provided by the term “cradle to cradle” discuss LCA because researchers tend to use C2C as a phrase to state the fact that a closed-loop supply chain is evaluated in the study. In this context, term ‘C2C’ does not seem to literally refer to the theory of "cradle to cradle" by Braungart and McDonough (2002). The main theoretical contribution of Braungart and McDonough (2002) in the field of CE is the division of materials into biological and technical nutrients, claiming in their famous book that the use of technical materials can make many consumer products difficult to recycle or reuse, and even toxic.

The fundamental difference between C2C and other approaches with the aim of closing the material cycle is that it does not emphasize minimizing energy or material consumption at all (van Dijk et al., 2014). Still the results of this review show that, in the field of built environment, also CE has been effective mainly in promoting the concepts of recycling and recovery materials from waste and the use of byproducts as sources of new material. Despite several theorists’ view that the concepts for prevention of waste and consumption should be prioritized as the most important in CE, only 12 of 282 sources discuss in-depth concepts where buildings or assets are used smartly to reduce the need for resources. Also, the principle of reuse is high in the waste hierarchy but only 24 sources seriously discuss extending the lifespan of assets, buildings or structures through renovation or reuse.

More concepts should be discussed in the broader framework of CE to get a more comprehensive picture of the possibilities of the approach. Some established topics in the field of built environment that are compatible with the principles of CE did not emerge in the results such as open building (Juan and Hsing, 2017) and heat recovery from various urban sources such as supermarkets (Arias and Lundqvist, 2006) or data centers (Lu et al., 2011). Even the logic of waste hierarchy that was used as one basis of this review may become threatened by development of new technologies such as the production of synthetic fuel from the CO_2 emissions of waste incineration (Hansson et al., 2017) or the use of biodegradable polymers (Siracusa et al., 2008). This means that the vision of CE in the built environment is always incomplete and should not be seen as an infinitely stable truth, but as a fruitful and developing paradigm that can potentially generate sustainable new solutions. This review provided a large set of issues that call for deeper scientific discussion on the fields including management of cities for sustainable development, infrastructure and services for CE and enhancing resource efficiency in the construction industry.

4.1.1 Developments needed in management for sustainable cities

This review uses the ideas of ‘adaptive management cycle’ as a framework for successful implementation of CE in the built environment as explained in the subsection 3.1. The framework includes the following phases: 1) planning with determining the objectives, actions and indicators of the development 2) implementing the plan and 3) evaluating the success of the plan to show necessary improvements in the previous phases and to learn to provide the basis for development of the next strategic plan (Jones, 2009). Similar approach, known as continuous improvement cycle (or PDCA-cycle) with the phases of plan, do, check, and act, has been adopted for a core of the ISO9001 quality management standard (ISO 9001, 2015).

Expectations are high on the potential of CE to solve a large variety of resource-related problems. Facing the current information overload, scientists and urban developers should remember the main objective in CE of delinking environmental impact from economic growth. The improved efficiency from urbanization and more efficient buildings may turn into increased total environmental impact due to lifestyle changes and resource intensive construction. Long service lives increase the complexity of improving buildings' efficiency. More effort should be spent on researching for developing a strategic plan with the objective of creating more use value with less environmental impact and reducing waste and industrial processing.

The literature on implementation indicates that a successful plan with the main objectives of CE could be achieved with inclusive and location-sensitive politics functioning from bottom-up and top-down perspectives. This would be possible by developing positive political practices with simple regulations that leave room for inventions, by building capacity through cross-institutional knowledge transfer, and by developing communication platforms to enable cross-sectoral integration. To enable better communication, knowledge-sharing, better-informed decisions and better skills for all the stakeholders, it would be beneficial to establish a continuously updated best-practice database with proper assessment tools as suggested by Kalmykova et al. (2018). As the results of this review show that CE practices are not separate entities but outputs of one process may be inputs for other processes, the best-practice database should be built as a cross-sectoral system of interconnected functions by applying the approach of integrated resource management that is familiar from earlier projects of sustainable urban development (Chang, 2017).

The cities should put focus on collecting valid and accurate data that is the key enabler for developing evaluation methods for objectives of CE in the future. Evaluation of sustainability in CE innovations differing from business-as-usual practices, calls for developing of hybrid methods built by combining well-established scientific methods. More attention needs to be paid also on social aspects which call for developing evaluation methods for social acceptability, and inclusive easy-to-understand methods for presentation of the results. Appropriate methods for evaluation would help in starting a self-correcting process and establishing next broadly shared strategic plan.

4.1.2 Issues of services and consumer practices

Implementing CE in urban services and consumer practices is an issue of urban planning and management where researchers have suggested waste hierarchy as an effective framework for development of waste management systems. According to waste hierarchy, this review discusses reduce, reuse, recycle and recover in prioritized order as tools for delinking of economic growth from environmental impact.

The waste hierarchy put the highest priority on reduction of consumption and waste through smart design and use of products with practices such as DfD to enable reuse in the post-use phase and PSS to intensify the phase of use. PSS would move focus in development of infrastructure and manufacturing from tangible goods and ownership towards fulfilling of customers' needs and has potential to reduce consumption by providing more value with a smaller amount of spaces, vehicles and consumer products. As the implementation of the concept of PSS is in its early stages, more experience and empirical data in real-life conditions are needed to prove its environmental benefits.

In the waste management systems, reuse and recycle share the same goal of establishing a supply chain that enables source separation where EPR has been investigated as a practice to involve manufacturers in the system. Affecting consumer practices to increase scale of sorted wastes and enhancing efficiency of the collection system with smart technologies could be further investigated as options for improving the feasibility of the source separating supply chain. Also, research on inclusive practices for the development of waste management would be needed to achieve both pollution control and benefits in involving informal actors such as secondhand markets.

Research in the paradigm of recovery should emphasize reaching for high value. Improving the efficiency of urban mining calls for developing a broad approach for planning that would include finding optimal positioning of metal recovery facilities in the urban fabric to enable heat recovery and to reduce logistic costs and exploring of options for synergetic integration with other waste management facilities and infrastructure systems. Another topic of research in the infrastructure is exploring the optimal level of centralization and integration options between wastewater, waste and energy systems to enable efficient recovery of energy, nutrients and water. A new kind of idea on a symbiosis between urban and rural areas is evolving with objectives of sustainable food production, recovering valuable materials, saving water and harvesting of renewable energy.

4.1.3 Further research for cleaner production and construction

In built environment, the use and the construction both cause a heavy environmental impact, even with a slow renewal of building stock. This is why both of the phases call for solutions for improving resource efficiency and the problems cannot be fixed by simply replacing the existing buildings with new ones.

In construction industry, LCA is a well-established method for environmental management. CE is moving LCA towards the whole life cycle approach, but also the shortcomings in revealing the benefits in strategies of reduction, such as DfD and sharing economy, call for methodological development. In buildings, each component that has an effect on thermal performance could be reliably assessed only as a part of the whole building in local conditions. There is also a call for research on broadening approach to buildings' LCA for example through integration to life cycle costing, social LCA and building information model, development of LCA database through industrial collaboration and taking compensating elements such as integrated renewable energy into account. When the LCA approach is broadening, improving of normalization methods and standardization is needed.

A largely discussed practice for cutting environmental impact of building materials production is the concept of IS with the idea of building positive synergies among industries. IS seems to carry a risk of greenwashing as many examples apply the practice to industries that are based on burning of coal, causing heavy climate emissions. The concept of US expands that of IS by also involving the urban areas in the symbiotic activities, for example by providing excess heat but it also carries a risk of wasting efforts on practices that are getting out of date such as replacing coke with waste plastics or finding solutions for contaminated MSWI ash. The research on IS and US should be better aware of carbon neutral techniques such as steelmaking with hydrogen and utilization wastes from biotic sources.

In the construction sector, CE has been applied mainly as a solution of waste management and should move towards high-value uses while construction wood seems to provide a potential for high-value use to be explored. In recycling construction materials, climate benefits mainly vary between moderate and negative, as material processing still causes heavy energy consumption. More effort should be spent on on researching possibilities to establish a supply chain and marketplace for reusable DfD-components through EPR and building material bank. Primary solutions to be investigated for cutting climate emissions in buildings include PSS practices to intensify use and adaptive reuse to expand the service life along with technical improvements for energy efficiency.

5 Conclusion

This literature review provides a comprehensive, multidisciplinary and structured picture of practices and applications from overlapping fields within CE and the built environment. By asking how the present body of literature sees cities getting organized in their transition towards low-carbon CE, this review aims to understand the complexity of sustainable urban development to help avoiding conflicting policies and finding successful ones in developing the urban planning process.

This review discusses practices for successful implementation of CE through framework of ‘adaptive management cycle’ with the phases of plan, implementation and evaluation. The main objective of cutting reinforcing loop of increasing industrial production originated from urbanization could be achieved by developing consumption systems towards a commonly shared vision of waste hierarchy. The successful implementation of supply chains for CE in both industrial and consumption systems would need commitment, capability and interoperability, which is why more research on innovation positive and inclusive practices in politics, cross-institutional capacity development and cross-sectoral integration is needed. The last phase of the cycle is the evaluation where methods, including the buildings’ LCA, needs further developing to reveal all the benefits of CE. More attention in the evaluation methods should be paid on the inclusive presentation of the results and the assessment of qualitative aspects.

The priority in waste hierarchy is the reduction of need for waste management and industrial processing, which require smarter and more intense use of products and buildings. The reduction could be promoted through product-service systems where maintaining, sharing, renting or outsourcing could create value and avoid resource consumption by limiting the growth of building stock and extending its service time. Practices of reduction and product-service systems are a relatively new and poorly discussed paradigm in the field of built environment and therefore needs more attention. Empirical proof on effects of sharing economy is especially needed.

Secondary option for achieving goals of CE is the service life extension through practices of adaptive reuse, design-for-disassembly, design-for-repair and remanufacturing. To overcome the systemic barriers of missing markets and the supply chain in reusable components, there could be research on EPR of the building industry with the objective of establishing a virtual building material bank as a marketplace for reusable building components.

The scientific literature indicates that useful applications of waste through industrial symbiosis, recycling and recovery cannot bring game-changing environmental benefits to the construction industry. To get more benefits, industrial symbiosis and urban symbiosis should be developed by applying state-of-the-art carbon neutral technologies. The integrated infrastructure and symbiotic links among urban and rural areas could be investigated to enable the recovery of energy, nutrients and other valuable materials from urban biotic cycle.

This review shows that the number of different and sometimes optional CE solutions to be applied in built environment is large and growing with accelerating speed, highlighting multidisciplinarity and complexity of the field. To stay up to date on development of the paradigm, cities need a database that consists of an interconnected and continuously supplemented set of best practices along with proper evaluation methods. The value in the CE paradigm is strengthening communication on practices and broadly shared vision for sustainable cities.

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