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CIRCULAR ECONOMY IN CONSTRUCTION SECTOR

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\textbf{Abstract}

In the last few years Circular Economy (CE) is receiving increasing attention worldwide as a way to overcome the current production and consumption model based on continuous growth and increasing resource throughput. The concept of the CE is increasingly seen as a major policy agenda item and a testing challenge, for the construction sector. Nowadays, an omnipresent problem of resource scarcity and a need for reduction of waste generation make a discussion about eco-friendly production models more serious than ever before. Construction sector is one of the world’s largest waste generators. Fortunately, the Circular Economy can help to diminish an environmental impact of the construction sector. The paper provides an overview of the literature on Circular Economy theoretical approaches, strategies and implementation cases, in construction sector. Finally, the suggestions for future development are also discussed in this paper.
1. Introduction

The concept of the Circular Economy (CE) is increasingly seen as a major policy agenda item and a testing challenge, for the construction sector. It is an economic system aimed at minimising waste and making the most of resources. This regenerative approach is in contrast to the traditional linear economy, which has a 'take, make, dispose' model of production. In a circular system resource input and waste, emission, and energy leakage minimized by slowing, closing, and narrowing energy and material loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, recycling, and upcycling (Geissdoerfer et al., 2017). Proponents CE suggest that a sustainable world does not mean a drop in the quality of life for consumers, and can achieved without loss of revenue or extra costs for manufacturers. The argument is that circular business models can be as profitable as linear models, allowing us to keep enjoying similar products and services. To achieve models that are economically and environmentally sustainable, the Circular Economy focuses on areas such as design thinking, systems thinking, product life extension, and recycling (Charter, 2018).

Construction is the process of constructing a building or infrastructure. It differs from manufacturing in that the latter manufacturing typically involves mass production of similar items without a designated purchaser, while construction typically takes place on location for a known client. According to Chitkara (1998), construction as an industry comprises six to nine percent of the gross domestic product of developed countries. A construction project usually starts with planning, design, and financing; it continues until a building or a non-building structure is built and ready for use (Halpin et al., 2017). However, in fact, the project continues to “live” for many years and comes to end when the structure demolished or significantly rebuilt. A construction sector is one of the world’s largest waste generators. The Circular Economy appears as a helpful solution to diminish an environmental impact of the industry. In fact, the construction industry was responsible for almost 30% of the total embodied energy consumption (Hong et al., 2016).

Decision making about the Circular Economy can performed on the operational (connected with particular parts of production process), tactical (connected with whole processes and strategic connected with whole organization) levels. It may concern both construction companies
as well as construction projects where a construction company is one of the stakeholders.

As a good case that fits the idea of Circular Economy in construction sector on the operational level, there can be pointed walnut husks, that belong to hard, light and natural abrasives used for example in cleaning brick surfaces. Abrasive grains produced from crushed, cleaned and selected walnut shells. They classified as reusable abrasives. A first attempt to create a holistic measurement for Circular Economy implementation in a construction company performed by the international research team Pedro Nuñez-Cacho, Jarosław Górecki, Valentín Molina-Moreno, and Francisco Corpas-Iglesias. The results of the study were published in 2018 in Sustainability (Nuñez-Cacho et al., 2018).

The objective of a transition toward the Circular Economy in the construction sector is to maintain, reuse, refurbish and/or recycle resources and materials used in all parts of the value chain. Most of the new policy instruments that the interviewees have suggested have focus on rules and regulation. Waste from construction and demolition activities is often used as a substitute for gravel. Thus resulting in a high percentage of recycled waste. It can be argued that waste used in this manner is down-cycled leading to a significant loss of material value. Waste from construction and demolition may contain hazardous substances that need to be identified and removed from the building materials to allow for possible recycling purposes thus ensuring that the hazardous substances are removed from the recycling loop – thus preventing health and environmental problems in new product system loops.

This paper aims is to contribute with an overview of the CE concept in construction sector as presented in literature that will assist those actors that wish to work in this field in having a more clear definition of CE.

2. The Concept of the Circular Economy

The improving economic, social and environmental indicators of sustainable development are drawing attention to the construction sector, which is a globally emerging sector, and a highly active industry in both developed and developing countries (Ortiz et al., 2009). It is confirmed that the construction activities have major impacts on the social, environmental and economic aspects of sustainability (Smol et al., 2015).

As early as 1966 Kenneth Boulding raised awareness of an "open economy" with unlimited input resources and output, in contrast with a "closed economy", in which they are tied and remain as long as possible a
part of the economy. Boulding's essay "The Economics of the Coming Spaceship Earth" (Boulding, 1966) is often cited as the first expression of the "circular economy", although Boulding does not use that phrase (Allwood, 2014). The Circular Economy is grounded in the study of feedback-rich systems, particularly living systems. The contemporary understanding of the Circular Economy and its practical applications to economic systems evolved incorporating different features and contributions from a variety of concepts sharing the idea of closed loops. Some of the relevant theoretical influences are cradle to cradle, laws of ecology, looped and performance economy, regenerative design, industrial ecology, biomimicry and blue economy (Geissdoerfer et al., 2017).

CE was further modelled by British environmental economists in 1989 (Pearce and Turner, 1990). In Economics of Natural Resources and the Environment, they pointed out that a traditional open-ended economy was developed with no built-in tendency to recycle, which was reflected by treating the environment as a waste reservoir (Su et al., 2013). In the early 1990s, Tim Jackson began to pull together the scientific basis for this new approach to industrial production in his edited collection Clean Production Strategies (Jackson, 1993). In their 1976 research report to the European Commission, "The Potential for Substituting Manpower for Energy", Stahel and Reday-Mulvey (1981) sketched the vision of an economy in loops or circular economy and its impact on job creation, economic competitiveness, resource savings, and waste prevention. Promoting CE was identified as national policy in China's 11th five-year plan starting in 2006 (Zhijun and Nailing, 2007).

2.1. Industrial Ecology theory

Roots of CE are also found in General Systems Theory (Von Bertalanffy, 1950) and Industrial Ecology (IE) (By et al., 1995). The latter is the study of material and energy flows through industrial systems. The global industrial economy can be modelled as a network of industrial processes that extract resources from the Earth and transform those resources into commodities which can be bought and sold to meet the needs of humanity. IE seeks to quantify the material flows and document the industrial processes that make modern society function. Industrial ecologists are often concerned with the impacts that industrial activities have on the environment, with use of the planet's supply of natural resources, and with problems of waste disposal. Industrial Ecology is a
young but growing multidisciplinary field of research which combines aspects of engineering, economics, sociology, toxicology and the natural sciences.

IE has been defined as a systems-based, multidisciplinary discourse that seeks to understand emergent behaviour of complex integrated human/natural systems (Allenby, 2006). The field approaches issues of sustainability by examining problems from multiple perspectives, usually involving aspects of sociology, the environment, economy and technology. The name comes from the idea that the analogy of natural systems should be used as an aid in understanding how to design sustainable industrial systems. Industrial Ecology is concerned with the shifting of industrial process from linear (open loop) systems, in which resource and capital investments move through the system to become waste, to a closed loop system where wastes can become inputs for new processes (Torres and Parini, 2019).

IE seeks to understand the way in which industrial systems for example a construction project interact with the biosphere. Natural ecosystems provide a metaphor for understanding how different parts of industrial systems interact with one another, in an ecosystem based on resources and infrastructural capital rather than on natural capital. It seeks to exploit the idea that natural systems do not have waste in them to inspire sustainable design. Along with more general energy conservation and material conservation goals, and redefining commodity markets and product stewardship relations strictly as a service economy, Industrial Ecology is one of the four objectives of so called ”Natural Capitalism” (Hawken et al., 2013). This strategy discourages forms of amoral purchasing arising from ignorance of what goes on at a distance and implies a political economy that values natural capital highly and relies on more instructional capital to design and maintain each unique industrial ecology (Kay, 2003). This scientific field has grown quickly in recent years. The Journal of Industrial Ecology (since 1997), the International Society for Industrial Ecology (since 2001), and the journal Progress in Industrial Ecology (since 2004) give Industrial Ecology a strong and dynamic position in the international scientific community. Industrial Ecology principles are also emerging in various policy realms such as the concept of the Circular Economy that is being promoted in China. Although the definition of the Circular Economy has yet to be formalized, generally the focus is on strategies such as creating a circular flow of
materials, and cascading energy flows. An example of this would be using waste heat from one process to run another process that requires a lower temperature. The hope is that such a strategy will create a more efficient economy with fewer pollutants and other unwanted by-products (Yuan et al., 2006).

2.2. Life Cycle Assessment

Lowering the ecological impact of buildings is receiving increased attention by researchers, policy-makers, and companies. Mostly the focus is on reducing energy consumption and the use of eco-friendly materials, but the concept of life-cycle thinking is growing in importance. After 2000, there have been also some developments specifically targeting the construction sector, in addition to the ISO 14040 standards. In 2003, SETAC published a state-of-the-art report on Life-Cycle Assessment in Building and Construction, an outcome of the Life Cycle Initiative (Kotaji et al., 2003). This study highlights the differences between the general approach of LCA and LCAs of buildings.

This section tries to give an overview of the current situation of Life Cycle Assessment (LCA) in the construction sector, both of regulatory developments and academic case studies. In the beginning of the 1980s, life cycle thinking appears in the construction sector with a study of Bekker, with focus on the use of renewable resources (Bekker, 1982). Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Designers use this process to help critique their products (Buyle et al., 2013). The goal of LCA is to compare the full range of environmental effects assignable to products and services by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. This information is used to improve processes, support policy and provide a sound basis for informed decisions (Treloar et al., 2000).

Buildings play an important role in consumption of energy all over the world. The building sector has a significant influence over the total natural resource consumption and on the emissions released. A building uses energy throughout its life i.e. from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, renovation, and
demolition in a building; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations (Sartori and Hestnes, 2007). Life cycle assessment (LCA) methods have been used for environmental evaluation of product development processes in other industries for a long time, although application to the building construction sector is stated of the art for the last 15 years (Singh et al., 2011).

Norris and Yost (2001) discuss Life-Cycle Explorer (LCE) software, designed in part to address two specific challenges for construction LCAs—that aspects of the use phase of building materials may be context-specific; and that the outcome of the LCA may rest on the building materials' service life. The authors propose the prototypical LCE model through a case study application. Strengths of the LCE software include the ability to make product comparisons and incorporate parameter and model uncertainty into the analysis. Erlandsson and Borg (2003) recognized the above challenges and concluded that building systems offer the highest complexity in LCA. They recommended not using a simple linear, static approach, beginning with construction, then operation (including maintenance), and ending with demolition and waste treatment phases. Instead, they advocated using services provided as the functional units, treating buildings as dynamic service providers that might change with modifications and rebuilding and over time, using a sequential approach in LCA, and developing a flexible LCA modeling structure that allows user choices. Osman and Ries (2004) used the process-based LCA framework to evaluate environmental impacts of construction and operations of a cogeneration facility for meeting the energy requirements of a commercial building. They conducted energy simulations to determine the building's energy needs throughout the year. The authors concluded that certain cogeneration facilities might be environmentally preferable over conventional energy production facilities. Guggemos Angela and Horvath (2005) compared environmental effects of steel and concrete framed buildings using LCA. Two five-storey buildings with floor area of 4400 m2 were considered which were located in the Midwestern US and were expected to be used for 50 years. In this study two methods, process based LCA and EIO-LCA, were used to evaluate life-cycle environmental effects of each building through different phases: material manufacturing, construction, use, maintenance and demolition phase. The results showed that concrete structural-frame had more associate energy use and emissions due to
longer installation process. Guggemos and Horvath (2006) proposed an augmented process-based hybrid LCA model – the Construction Environmental Decision Support Tool (CEDST) – to analyze the environmental effects from the construction phase of commercial buildings as applied to a California building. The authors argued that significantly larger use-phase effects often overshadow the construction phase in building LCA. However, such construction-phase effects, when aggregated at the national level, may prove to be significant. CEDST evaluates environmental effects from the manufacture of temporary materials used in the construction process (e.g., formwork), transportation of materials and equipment, equipment use, and waste generation during construction. In the case study, equipment use accounted for about 50% of environmental effects, while temporary construction materials had the second largest impact on the environment. Citherlet and Defaux (2007) presented a process-based life cycle assessment of three home designs in Switzerland. They classified life-cycle environmental impacts into direct and indirect categories; direct impacts included all use-related energy consumption impacts; and indirect impacts included other upstream and downstream impacts from material extraction, production, construction, demolition, etc. Their results show that direct environmental impacts can be significantly reduced by better insulation and by the use of renewable energy sources. Bilec et al. (2006) also applied an augmented process-based hybrid LCA model to evaluate construction-phase environmental impacts of a precast parking garage in Pittsburgh, Pennsylvania. Environmental impacts caused by transportation, equipment use, construction service sectors, production and maintenance of construction equipment, as well as on-site electricity usage and water consumption were assessed. Transportation had the largest impact in most categories. The authors recommended including environmental costs as social externals in bid evaluations when awarding construction contracts. Koroneos and Dompros (2007) studied the brick production process in Greece, using data from a local brick production plant and from published literature, to identify possible areas for improvement from the environmental perspective. The authors included recycling of bricks within the analysis but excluded the construction, use, and disposal phases. Using the Eco-indicator 95 aggregation method, analysis showed that acidification contributed more than half of the total environmental impact. The authors recommended use of lowsulfur fuels to reduce such impact. Dodoo et al. (2009) showed that even with the inclusion of end of life carbonation of concrete, timber frame buildings were still better
performing in terms of environmental profile. Salazar and Meil (2009) conducted an Life cycle assessment (LCA) of two Canadian residential buildings, one using a conventional construction and a wood frame house that maximised the use of timber. Zhao et al. (2009) used the transfer coefficients from Swiss inventories to estimate the landfill gas emissions in Tianjin, China for 100 years. Transfer coefficients are the percentages of total amount of pollutants emitted through a specific pathway (Doka and Hischier, 2005). De Gracia et al. (2010) evaluated the environmental impact of including phase change materials (PCM) in a typical Mediterranean building—with traditional brick and an air chamber as envelope construction system, using measured operational energy savings in an experimental set-up. Results showed that the addition of PCM (paraffin and salt hydrate) in the building envelope, although decreasing the energy consumption during operation, did not reduce significantly the global impact throughout the lifetime of the building. For the hypothetical scenario considering summer conditions all year around and a lifetime of the building of 100 years, the use of PCM reduced the overall impact by more than 10%. Moreover, salt hydrates are more environmentally friendly than paraffins as PCM. Optis and Wild (2010) studied 20 journal articles describing LCA energy studies of buildings finding that documentation was omitted and that calculation procedures were not stated in the majority of articles, although data sources were generally well-referenced. The embodied energy varied between 2-51% of the total life cycle energy associated with the building. It was concluded that the articles were of limited use for comparing the life cycle energy efficiency of buildings. They commented that the high level of detail required in order to ensure that an LCA is transparent, is not compatible with the length of a paper required for publication in a scientific journal. Optis and Wild (2010) studied 20 journal articles describing LCA energy studies of buildings finding that documentation was omitted and that calculation procedures were not stated in the majority of articles, although data sources were generally well-referenced. The embodied energy varied between 2-51% of the total life cycle energy associated with the building. It was concluded that the articles were of limited use for comparing the life cycle energy efficiency of buildings. They commented that the high level of detail required in order to ensure that an LCA is transparent, is not compatible with the length of a paper required for publication in a scientific journal. Gong et al. (2012) show on three types of residential buildings with framework structures in Beijing—concrete framework construction (CFC), light-gauge steel framework construction (SFC), and
wood framework construction (WFC)—that over the life cycle, the energy consumption of CFC is almost the same as that of SFC, and each of them is approximately 30% higher than that of WFC. The net CO2 emission of CFC is 44% higher than that of SFC and 49% higher than that of WFC. The net CO2 emissions in the transport category cannot be ignored, with proportions amounting to 8%, 12%, and 11% for WFC, SFC, and CFC, respectively. Life cycle carbon efficiency, which is determined by dividing the product of life span and building area or volume by life cycle carbon emission of building, was proposed by Li et al. (2013) to evaluate the environmental impacts of buildings. The idea of per capita annual efficiency of life cycle eco-footprint and space efficiency of life cycle eco-footprint was introduced by Teng and Wu (2014) to evaluate the eco-efficiency of building projects. Energy Payback Time and Net Energy Ratio were also used to evaluate the life cycle efficiency of buildings by Berggren et al. (2013). Rincón et al. (2013) extended the study use not only LCA but also mass flow analysis (MFA) to assess the sustainability of the new construction system. MFA results showed the significant quantity of natural resource extraction required for building which leads to a considerable ecological rucksack; while LCA results showed the importance of the operational phase of the building in the overall building energy consumption, and therefore in the environmental impact. Zhang et al. (2014), estimated the impacts of land footprint by computing the net effects of carbon sources and sinks within a city. The carbon sinks include livestock while carbon sources include forests and transportation. Chau et al. (2015) studied the environmental impact of buildings using LCA, life cycle energy assessment and life cycle carbon emissions and reviewed previous findings using these methods. They found that discrepancies arose between the three methods and they identified limitations in the use of these methods as decision tools for building design. Hong et al. (2018) developed an integrated framework for embodied energy quantification of China’s buildings from a multi-regional perspective. Their article builds on previous work on embodied energy quantification and develops an optimized algorithm that illustrated how the technological difference and the regional features are calculated as indices of embodied energy quantification at the project level, using multi-regional inputoutput (MRIO) analysis, structural path analysis (SPA), and process-based LCA model as the underlying methods.
3. Construction waste management

Construction waste generation has been identified as one of the major issues in the construction industry due to its direct impacts on the environment as well as the efficiency of the construction industry. As the industry cannot continue to practice if the environmental resources on which it depends are depleted, the significance of waste management (WM) needs to be understood in order to encourage stakeholders to achieve related goals (Udawatta et al., 2015). There is lack of comprehensive research to explore solutions for construction waste generation. By implementing proper WM practices, the construction industry can gain economic, quality and sustainability benefits (Kulatunga et al., 2006).

3.1. BIM for construction waste minimization

There is an agreement in the literature on the potential use of Building information modelling (BIM) for construction waste minimization during design stages, including BIM-aided coordination by reducing conflicts between disciplines (Krygiel and Nies, 2008); reducing re-work (Hardin and McCool, 2015, Nisbet and Dinesen, 2010, Eastman et al., 2011); clash detection for error reduction (Love et al., 2013); enhancing communication and integration (Hardin and McCool, 2015); increasing the ability to quantify and test numerous design options of varying waste reduction performance (Eastman et al., 2011); and improving the quality of knowledge for construction waste minimization decision making (Nisbet and Dinesen, 2010). Construction waste minimisation is a process which helps to prevent, eliminate, or reduce waste at its source during design (Osmani, 2013a). Prevention includes all activities that can reduce the amount of construction waste, which involves minimising waste generation at source and reducing waste before it enters the waste stream (Osmani et al., 2008). A significant proportion of construction waste occurs during the early design stages. Around 33% of waste may be directly influenced by design decisions (Innes, 2004). There is agreement in the literature that construction waste during design is mainly related to design changes (Alwi et al., 2002), ineffective coordination and communication (Keys et al., 2000), material specification (Ofori and Ekanayake, 2000), design and detailing complexity (Poon et al., 2003), and design and construction detail errors (Osmani et al., 2008). A number of studies indicated that design changes during the construction stage, known as rework, are major waste generation causes. It has been reported
that causes of re-work are mainly due to client changes during site operations and poor communication among project stakeholders. Al-Hajj et al. (2011) argued that poor design-related material off-cut waste is clearly outside the control of the contractors but is within the control of the designers. They believed that construction waste causes should be taken into consideration through better management of the design process. A study conducted by Liu et al. (2015) suggested that designers have a great deal of influence over construction waste generation during various project stages.

According to Liu et al., (2015), O’Reilly (2012) argued that construction waste minimisation could be supported and enhanced through the use of BIM, particularly during the design stages. An increasing body of literature suggested the importance of investigating the impact of adopting information communication-related techniques and tools, such as BIM, to assist in minimising construction waste during building design and construction (Sacks et al., 2010, Whyte, 2012). Few studies have attempted to investigate the use of BIM to address construction waste generation. These include BIM-enhanced coordination (Ahankoob et al., 2012); structural reinforcement of rebar waste reduction (Porwal et al., 2011); material resource efficiency; demolition waste management (Cheng and Ma, 2013); and on-site waste management improvement (Hewage and Porwal, 2011).

Lingard et al. (2000) inferred that even though managers think training programmes are effective to use, construction workers believe it is irrelevant. Thus, it is necessary to encourage the industry to promote suitable WM practices and take environmental aspects into consideration in the design and tendering stages. Poon et al. (2001) introduced a waste index of materials to calculate the total construction waste. Shen et al. (2004) defined construction waste as building debris, rubble, earth, concrete, steel, timber, and mixed site clearance materials, arising from various construction activities including land excavation or formation, civil and building construction, site clearance, demolition activities, roadwork, and building renovation. Poon et al. (2004b) highlighted that in order to reduce the level of waste in building projects it is necessary to pay more attention to WM at the planning stage of building development. Cochran et al. (2007) defined equations which incorporated the level of activities and the average waste generation per unit area for construction projects in the U.S. Tam et al. (2007) also suggested that construction
waste generation can be fully avoided by using prefabrication technologies. However, Osmani et al. (2008) found that architects are less engaged in waste minimisation due to lack of knowledge about what causes design waste generation and the perception that contractors are liable for waste minimisation. While promoting onsite WM systems helps to minimise construction waste generation. They demonstrated that legislation is one of the key incentives for the implementation of WM in the design process and asserted that WM policies encourage architects to design out waste in construction projects. In order to promote zero waste culture, the construction industry and authorities have to improve legislation with a solid enforcement plan and methods of systematic tracking of proposed measures. Tam (2008) analyzed the wastage levels of four types of construction waste in residential and non-residential buildings in Hong Kong through interviews with practitioners in the construction sector. However, Jaillon et al. (2009) revealed that the average waste reduction rate from the use of prefabricated material is 52%. They further stressed that even though prefabrication construction methods help to create a tidier and safer working environment as well as reducing the time and onsite labour requirements, these methods cannot fully avoid the production of construction waste. There are also other disadvantages associated with prefabrication including less flexibility with manufacturing, and restrictions on site and transportation. Katz and Baum (2011) quantified construction waste generated in residential buildings in Israel by monitoring actual construction sites. McKenzie-Mohr (2011) has argued that improving knowledge and changing attitudes has little to no effect on behaviour change. Yuan (2013) also highlighted the critical role of enhancing major project stakeholders’ awareness about saving resources and environmental protection in order to improve WM performance in construction projects. However, construction practitioners have conflicting views on the benefits of training programmes. He also emphasised the importance of developing a mature recycling market for construction products in order to promote recycling in construction projects. In the European Union (EU) as part of the Circular Economy (CE) system in the construction sector there is a desire to keep the added value in products as long as possible to eliminate waste. Smol et al. (2015) advocate a transition to a CE which requires changes throughout the value chains. Liu et al. (2015) proposed a design decision making framework for improving construction waste minimization performance, which can be used in the design phase of construction projects. Cheng et al. (2015) proposed potential opportunities of BIM for efficient
construction waste management in the various phases of construction projects. Won et al. (2016) reported that the BIM-based design validation process, which involves design review and 3D coordination using BIM, prevented 4.3% to 15.2% of construction waste that might have been generated without using BIM. In addition, standardization and optimization of construction materials and elements can be conducted through reviewing constructability and material specifications based on BIM-based design review.

3.2. Circular Economy in construction sector

In recent years, environmental policy has become increasingly important for more efficient use of resources. This has led to increased focus on the development of a more circular economy. From an environmental-economic perspective, a circular economy means that the greatest possible prosperity is created at the lowest possible resource use and costs. The objective of a transition toward the Circular Economy in the construction sector is to maintain, reuse, refurbish and/or recycle resources and materials used in all parts of the value chain. (Høibye and Sand, 2018). Kirchherr et al. (2017) reviewed 114 definitions of CE which were coded on 17 dimensions.

Chen (2009) promoted the key role of Material flow analysis (MFA) to enhance the understanding of the economic dimension of a CE.

Allwood and Cullen (2012) used MFA to map global flows of key materials, energy, and emissions, which allow greater confidence in exploring opportunities for efficiency and recovery.

Cole and Kernan (1996) showed that the operating energy of a building was a much more important factor than the embodied energy of the materials contained therein and that it was a better strategy to concentrate on the energy efficiency of the building before turning to embodied energy considerations. However, as the operating energy of the building sector decreases, it is necessary to pay more attention to the energy and carbon emissions associated with the constituent building materials.

Hendrickson et al. (2000) estimated the major commodity and service inputs, resource requirements, and environmental emissions and wastes for four major U.S. construction sectors as defined by the Department of Commerce. They found that in general, the four major U.S. construction sectors appear to use fewer resources and have lower rates of environmental emissions and wastes than their share of the GDP might suggest.
Thormark (2001) computed feedstock energy equivalent to as high as 40% of the embodied energy of material waste released from the construction site. Pingoud et al. (2001) investigated the wood substitution potential in new building construction in Finland. They determined the total amount of materials used in the construction of different buildings, as well as the commercial potential for increased wood use.

Morel et al. (2001) reported that the amount of energy used to manufacture and transport building materials represented nearly 8% of primary energy consumption in the UK. They showed that by using local materials, it was possible to reduce the embodied energy associated with a building by up to 215% and the impact of transportation by 435%.

Lawton et al. (2002) estimated a reduction of 70% in in-situ concreting by using volumetric prefabrication, as well as a reduction of 70% in construction finishing works on-site.

Scharai-Rad et al. (2002) analysed central European single-family houses constructed in wood or brick. In their analysis they considered the utilisation of processing and demolition residues to replace fossil fuels, and found that net greenhouse gas emission decreased as the volume of recovered wood increased.

Poon et al. (2004a) demonstrated that timber formwork was the major contributor to construction waste in Hong Kong accounting for 30% of all identified waste. Also, wet trades of finishing work, such as screeding, plastering and tile laying represented about 20% of all identified waste.

Tam et al. (2005) revealed that the use of prefabrication reduced waste arising from timber formwork and concrete works by 74–87% and 51–60%, respectively.

Poon et al. (2004b) highlighted that in order to reduce the level of waste in building projects it is necessary to pay more attention to waste management at the planning stage of construction development.

Werner et al. (2005) analysed the consequences of the increased use of timber in construction on the carbon storage and emissions associated with substitution for more energy-intensive building materials. The study showed that the effects due to carbon storage were of minor importance compared with those due to substitution for more energy-intensive materials and the use of timber residues and post-consumer waste wood as an alternative energy source compared to fossil fuels.

Gustavsson et al. (2006a) compared the net carbon dioxide emissions associated with a timber-frame and concrete-framed building in Finland and Sweden. The results showed that the production of materials for the timber framed building required less energy and produced lower CO₂
emissions compared with the materials used for the concrete construction. According to Trusty (2006), feedstock component is the largest contributor to the total energy embodied in some construction materials such as asphalt and asphalt concrete, which are commonly used in constructing site components such as roads, parking areas, and sidewalks around buildings. Feedstock energy is significant and hence, must be included in an embodied energy calculation.

In an extension of this work, Gustavsson and Gustavsson et al. (2006b) explored a large number of possible scenarios when comparing two buildings constructed using a timber frame or a concrete frame. They found that the timber frame construction method exhibited superior environmental credentials in all explored scenarios except for one.

Gerilla et al. (2007) studied a house in Japan with a reinforced concrete or wooden frame, concluding that the timber framed building had a lower environmental impact. Sathre et al. (2007) showed that only timber has a negative energy of production, compared to the manufacture of particleboard, steel, concrete, or plasterboard. This was because of the high-energy value obtained from the timber processing residues compared to the energy of production. Nässén et al. (2007) compared the results of 20 (mainly Scandinavian) studies published before 2001. They found that there was almost a 90% higher energy use when a top down analysis was compared with previous bottom-up analyses. Of this, only 20% of the discrepancy was due to the embodied energy of the materials, the rest being due to differences in energy in construction, transport, etc. This discrepancy was considered to be of less importance where materials choices were concerned.

Bergsdal et al. (2007) presented a study on flow dynamics of the Norwegian building stock, comparing the demand for floor area to the demolition activity in an input output analysis. The scenarios show that starting in 2030, increasing demolition activities due to renewal of the old building stock will increase the demand for new dwellings drastically. This trend is similar for all population scenarios and shows the challenges and opportunities for the building market in the decades to come.

Asif et al. (2007) compared the environmental impact of building construction in Scotland, concluding that the embodied energy of concrete was responsible for 65% of the embodied energy of the building, but 99% of the house building sector because of its high impact and the large quantities used.

Sartori and Hestnes (2007) found that the proportion of embodied energy in the materials compared with the overall energy (embodied plus
operating energy) over the lifetime of the building varied between 9-46% in well-insulated buildings and 2-38% in conventional buildings. The building lifetime for many studies was considered to be 50 years.

Sathre et al. (2007) found that during the construction phase, more energy could be derived from the biomass residues obtained from processing the timber for the structure than was used to produce the building. Additional energy could also be obtained when wood-based demolition residues were recovered and used as a substitute for fossil fuel.

Langston and Langston (2008) investigated 30 case studies of building construction in Melbourne and found that there was a very strong correlation between capital cost and embodied energy, at a building level, but this correlation was very weak when examined at a materials level.

Tam (2008) has researched the effectiveness of the implementation of the existing waste management plan method in Hong Kong construction sector. In this study, the main benefits gained in waste reduction and waste separation are the proposed methods for on-site reuse of materials. To that end, the use of prefabricated components is considered as the major measure to encourage waste reduction.

Osmani et al. (2008) revealed architects assume that waste is mainly produced during site operations and rarely generated during the design stages. However, about one-third of construction waste essentially arises from design decisions, as this study stated. Osmani et al. (2008) found that architects are less engaged in waste minimisation due to lack of knowledge about what causes design waste generation and the perception that contractors are liable for waste minimisation.

Jaillon et al. (2009) revealed that the average waste reduction rate from the use of prefabricated material is 52%. They further stressed that even though prefabrication construction methods help to create a tidier and safer working environment as well as reducing the time and onsite labour requirements, these methods cannot fully avoid the production of construction waste.

Begum et al. (2009) stated that the majority of contractors do not practice source separation, source reduction, reuse or recycling, at Malaysian construction sites. The results of the study showed as key factors: construction-related education among employees, contractor experience in construction works, source reduction measures, etc. are the most significant factors affecting the contractor’s performance.

Acquaye et al. (2010) estimated the energy-related carbon emission of Irish construction sector, which is highly correlated with total primary
energy consumption (TPEC). The results showed that the energy-related carbon emission of construction sector accounted for 11% of the total domestically arising CO$_2$ emissions of Ireland in 2005.

Chong and Hermreck (2010), point out that saturation of local markets for recycled construction materials can become a critical factor, given that an increase in the distance between project sites and recycling facilities might counteract the benefits of recycling. The study concludes that further increases in recycling activities depend on the existence of a market for recycled materials, regional recycling capacities, total energy used to recycle, and the knowledge of the workers and designers of options for using recycled materials in construction projects.

Huang and Bohne (2012) conducted an input and output analysis of embodied atmospheric emissions in the Norwegian construction sector and showed that their contribution to total national emissions increased between 2003 and 2007.

Gustavsson and Sathre (2011) note that much of the methodology developed for determining the global warming potential (GWP) impacts associated with the production and use of biofuels is also useful for the comparison of harvested wood products (HWPs) with alternative construction materials.

Monahan and Powell (2011) reported that in the UK construction sector, contingency related over-ordering amounted to about 10% of materials transported to site and that 10-15% of materials transported to site were subsequently exported as waste. This unplanned waste can be substantially reduced by increasing the use of modular off-site construction, a technology for which timber is well suited.

Bribián et al. (2011) note that mineral extractions for the building sector per capita in Europe amount to 4.8 tonnes per person per year. In Spain, every square metre of a habitable building requires a total of 2.3 tonnes of more than 100 different materials. If the material intensity per unit service (total resources necessary to produce the materials) is examined, then this amounts to 6 tonnes per square metre. The sector is also responsible for the generation of large amounts of waste, with Europe producing 850 million tonnes of construction-related waste every year.

Nässén et al. (2012) considered that the case for favouring timber over concrete as a construction material was more ambiguous. The methodology that they chose involved the evaluation of net present costs and carbon balances over the whole life of building structures with different material compositions. Lauk et al. (2012) noted that a better
understanding of the global carbon cycle as well as considering potential mitigation options requires an understanding of both natural and socio-economic flows of carbon. They point out that an under-researched part of the global carbon budget is the storage of carbon in long life products, such as buildings or furniture.

Danatzko et al. (2013) concluded that there is at present not any design tool that is sophisticated enough to be used at the whole building level to assist in making decisions regarding design alternatives to ensure the most sustainable form of construction.

Fu et al. (2014) estimated the energy embodied in construction services (EECS) of China and concluded that EECS accounted for one-third of the TPEC of China in 2007.

Udawatta et al. (2015) stressed out the importance of avoiding the construction waste generation as early as possible. For instance, instead of disposing the waste into the landfills, an early planning of selecting the most suitable materials would help in promoting the recycling mechanism.

Nepal et al. (2016) studied the implications of increased wood use in low-rise non-residential construction in the US. Mitterpach and Štefko (2016) calculated the environmental impacts associated with the construction of a timber and a brick house. The analysis showed that the timber house had a lower environmental impact compare with the brick equivalent. The two houses were identical apart from the materials used in construction.

Hong et al. (2016) provided insight into the energy consumption status of Chinese construction industry from both regional and sectoral perspectives, which can be a basis for energy policy making and implementation. Li et al. (2016) estimated the energy embodied in construction services (EECS) of Beijing and confirmed that EECS was the largest type of embodied energy of Beijing in 2010.

Nuñez-Cacho et al. (2018) created a first comprehensive evaluation system, useful for entities involved in construction projects executed under Circular Economy requirements. A design of the dimensions that comprise the scale was their valuable contribution. The most important dimensions in measuring the implementation of the Circular Economy in the construction industry are Energy management, Water management, Waste management, and application of 3Rs principles (Reduce-Reuse-Recycle). Finally yet importantly, according to the authors, are Emissions, Material, and Transition of CE.
Zhang et al. (2019) developed a combination static and dynamic hybrid input-output model to forecast the total primary energy consumption (TPEC) and estimate the energy consumed by construction services (EECS), which is the energy cost of economic development, based on the gross domestic product (GDP) prediction. They used China as a case study.

4. Discussion on future development

1. The perspectives of CE are huge and appealing. An overall increase of knowledge of theoretical and practical framework of circular economy, CE, as well as the monitoring of the presently existing construction projects at the different levels are fundamental for advancing CE progresses in Europe, China and worldwide. The most important aspect, i.e. the one that still seems to need improvement, is the knowledge and awareness of European producers and consumers, because of the important role devoted to producers and consumers responsibility in European policies. The same aspect is certainly important in other countries and China, but CE awareness seems to be more analysed only in China, at least based on literature.

2. Considering the life cycle in the energy certification process of the buildings allows the promotion of sustainable buildings with low energy consumption and high efficiency and favours innovation in the construction sector. Therefore, in addition to promoting the use of renewable energy and equipment with high energy efficiency, priority must be given to bioclimatic ecodesign and bioconstruction, the use of low impact, natural, recyclable materials available in the local area, the minimisation of water consumption by designing rainwater collection systems and grey water networks in buildings, the design of green roofs, etc.

3. The application of the concept of the Circular Economy thinking in construction, which is in its infancy, has been largely limited to construction waste minimization and recycling. Little research on CE from a systems perspective including how new business models might enable materials to retain high residual values has been undertaken.

4. System theory can be used for future research on integrating the Circular Economy concept as an approach to reduce the generation
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of construction waste during the construction cycle using the system dynamics modelling (Esa et al., 2017). The development of a Causal-Loop Diagram is imperative in portraying the structure of the system dynamics modelling itself; in this case the key principles and strategies of construction waste minimization.

5. There is a lack of decision making tools for construction waste minimisation during design in the literature (Osmani, 2013b). Moreover, the literature revealed that there are no BIM related tools to support waste minimisation throughout building design stages. This emphasises the need for a comprehensive investigation to explore the potential of BIM to reduce construction waste in building design. Additionally, no research attempts were made to relate the use of BIM to construction waste causes.

6. The designers should think about future courses of actions, and decide which project variant is the most sustainable, and suitable for the Circular Economy application. Therefore, one can find more and more fashionable expressions for such functions in literature or in the Internet. Architects should use BIM to simulate the most effective mode of construction, and the most sustainable and “circular able” project configuration. These approaches can be described as Design for Deconstruction (DfD), but also Design for Recovery (DfR), Design for Reuse (DfR), or Design for Recycling (DfR) may become a popular standard for construction projects in the near future.

5. Conclusion

A growing body of literature has emerged during the last two decades on various theoretical, methodological and empirical aspects of CE and its implementation. China has made serious efforts to intensively and on a large scale implement CE with the objective of providing long term and sustainable solutions to its severe resource scarcity and environmental degradation problems. The circular economy has becoming more and more important at the global level in many economic sectors. The construction sector, which is one of the major sectors responsible for the production of global wastes, has a great potential to ensure a more ecological and circular approach, although, compared to other sectors, it is very far removed from a circular approach. Yet, significant efforts in improving the environmental awareness and sustainability of the construction sector are arising through the introduction of the numerous
regulations, directives, and initiatives. The findings suggest that while some of the major construction companies are currently looking to integrate circular economy thinking into their strategic planning and a number of them have reported on innovative and experimental initiatives, the widespread and comprehensive translation of such thinking into construction practice is still at an early stage. At the same time the authors suggest that the widespread adoption of the concept of the circular economy within the construction industry will face a number of challenges. More contentiously, there must be concerns that the major construction companies might effectively capture the concept of the circular economy to justify continuing economic growth.

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