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Circular Economy Trends – Potential Role of Emerging Technologies

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Abstract. The circular economy and digital transformation are two of the major trends over the last decade. Integrative methodological advances such as life cycle assessments, material flow analysis, and input-output tables are some of the current trends in circular economy case studies and scenarios. However, more efficient processes are required, and methods need to be adapted to the unique attributes of circular economy systems. This paper presents a descriptive analysis of current technological trends and topics in the circular economy. A scoping review and an automated content analysis were conducted in over 6000 abstracts available in Springer journals. Strategies such as applying data-driven design in the field of circular economy and using innovative information and communication technologies (ICTs) offer new possibilities for optimizing existing integration methods. New circular economy approaches, and systems could emerge based on taking advantage of technologies such as: artificial intelligence (AI), Internet of Things (IoT), Advanced Data Analytics, etc. Also, emerging topics in circular economy technologies focus on energy, policy, models, and global systems. The paper concludes with an outline of emerging technologies and identifies several future research directions.

1. Introduction

Research linking circular strategies and their applications within industry to digital technologies is a new area of research and an area for further studies as very few papers offer an overview of developing circular approaches [1]. Digital technologies, such as the Internet of Things (IoT), big data and data analytics have been considered enablers of the circular economy (CE) however, CE and digital technologies are emerging fields and more systematic guidance is required on how digital technologies could be applied to capture the full potential of circular strategies to improve resource efficiency and productivity [2].

Construction consumes more than 3 billion tons of raw materials globally each year, adopting CE principles could reduce waste and save more than $100 billion per year by improving construction productivity [3]. The CE paradigm encompasses various strategies including the 9R framework: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover [4]. For circular buildings, elements from existing buildings could be retrieved and used for the whole or parts of new buildings. This upcycling of materials creates new value chains resulting in new jobs and new skills [5].

Emerging digital technologies such as machine learning, data-driven design, and parametric 3D modelling enable greater automation in early design exploration, and advance decision making in design optimization [6]. In addition, the technology of Design for Deconstruction (DfD) has been hindered by lack of effective DfD tools [7]. Influential areas of CE in the construction industry are circular product design, end-of-life consideration including the quality, economics, and modular integrated construction [8].

This study focuses on the emerging technologies in CE strategies and influences for determining core themes and indicators as they are crucial for early decision-making towards applying technology towards CE in building construction projects. The following sections include the growing importance of CE, emerging technologies, technology support for CE, technologies and circular strategies, technology support and strategies, and an automated content analysis for topics on emerging CE technologies.

2. Growing importance of circular economy

A scientific evolution analysis of 7000 documents that was published between 2005 to 2020 at Web of Science and Scopus for the application of CE detected the following trends: a) the development and use of alternate construction materials, b) the development of circular business models, c) smart cities, industry 4.0 and their relations with CE [9]. Materials and strategies in CE are presented below.

2.1. Materials

The global trend of zero waste has caused building and construction industries to gain interest in utilizing inorganic waste for building materials. This has led to the conversion of waste into value-added products. Construction and demolition waste were transformed to aggregates and cement [10-12]. Industrial waste was utilized through industrial symbiosis for panels and additives [13]. These transformations and others support the goal to achieving the 70% recovery target of the Waste Framework Directive, diverting waste from landfills to new resources in buildings [14, 15].

2.2. Strategies

A content analysis of 486 abstracts on CE in the construction industry provided critical understanding of current research trends and applications. These trends and applications reveal that circularity in the construction industry has key influential areas in circular product design, end-of-life consideration, and modular integrated construction. Although these strategies exist there is a lack of practical CE approach which could integrate a holistic performance assessment tool with the circular business model for the construction industry [8]. The research framework from the content analysis consisted of eight different research themes- a) the circular design, b) manufacture and supply, c) strategies for CE adoption, d) consideration of end-of-life principle, e) CE outcomes/consequences, f) information exchanges, g) construction process, h) waste management strategies. This study focuses on the third theme “strategies for CE adoption” and indicates technologies that have been applied towards implementing circularity in the construction industry.

3. Emerging technologies

Emerging technologies such as big data, cloud computing, cyber-physical systems, blockchain, virtual and augmented reality, could play an integral role in embracing CE concepts and programs by governments, organizations, and the society [16, 17]. Various other technology enablers such as IoT, artificial intelligence (AI) and robotics could reshape and optimize aspects of manufacturing with respect to CE from production through sales and operations planning, logistics and end to end supply chain management of construction materials [18]. In addition, an analysis across the five Fourth Industrial Revolution technologies focused on: AI; mobility (including autonomous vehicles); blockchain; drones; and IoT. Common challenges analyzed include a lack of regulation, misuse of technology and challenges in addressing cross-border differences [19].

These emerging technologies provide optimization in manufacturing and could optimize circularity in many aspects of building construction stages. However, a standardized approach is required for technologies in CE. Life cycle impacts differ widely and few of the databases used for quantifying impacts are open source and accessible. Circular building life cycle is applicable during stages such as the product stage, construction process stage, use stage, end of life stage shown in Figure 1 [20].

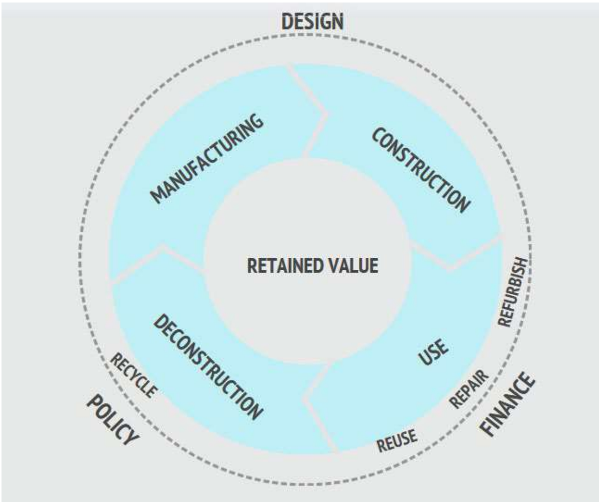


Figure 1. A circular building-life-cycle stages, adapted from [20]

In studies on green buildings, different kinds of computational optimization exist in various contexts, but a critical review identifying and comparing the optimization approaches is still lacking and needed to demonstrate their strengths/weaknesses and to highlight the future research challenges [6].

4. Technology support for circular economy

Circular economy (CE) offers an opportunity to close the loop on materials and processes [21]. Currently, some studies have utilized strategies to implement CE in buildings such as BIM and Materials Passports [22]. Assessment tools used to investigate CE impacts from 96 relevant papers include life cycle analysis (LCA), life cycle costing (LCC), cost-benefit analysis (CBA) tools [23]. LCA was by far the most used assessment method and waste management was the most common aspect of CE in the construction industry. Outcomes of CE could also be analyzed through material flow analysis (MFA). [24] highlight key opportunities in integrative methodological advances such as an expanded use of consequential LCA, development of physical Input-Output tables, and integrating MFA with dynamical models. This aligns with [25] where a concrete integrative framework could achieve CE at a systemic level. CE and Industry 4.0 (I4.0) were two key concepts to envisage a new framework focused on circularity among supply chains. Six R strategies (Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture), were considered the most affected by I4.0.

In another study, CE was studied in relation to virtual reality using advanced BIM-based prefabricated construction in a novel case study approach [26]. A game design and BIM digital twin of a purposed CE prototype building; virtual reality (VR) environments were designed to provide visual representation of materials and components that could be reintroduced into the supply chain at the end of life, their removal procedures and material provenance. BIM model was combined with Unify game software to allow building designers to view and implement their strategies to advance CE design. In addition, the research also proposed a VR tool to visualize the bill of quantities (BOQ) and material stock embedded in the studied building. The workflow is shown in Figure 2.

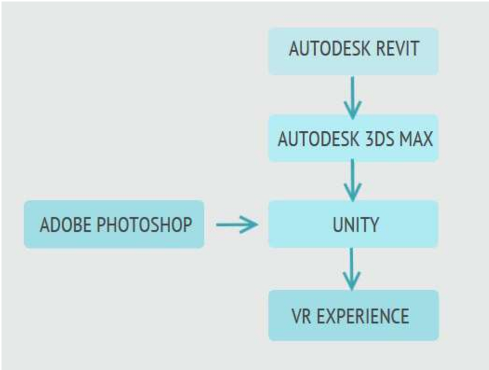


Figure 2. Workflow and experience of virtual reality (VR) programs

5. Technologies and circular strategies

Technologies applied with the goal of CE included low waste technologies (LWT) for design and construction comprising designing for thinner inner walls, floor slabs, reduced foundation size, reusing excavated spoils, recycled materials, and hanging cradles [27]. Other LWT include waste sorting technologies, modular building designs and prefabricated components, reuse technology, deconstruction, and use of large panel formwork. Technologies for the earlier mentioned six Rs are explored further.

5.1. Reduce

Reduce focuses on pre-manufacturing, reduced used of energy, materials and other resources during manufacturing, and the reduction of emissions and waste during use stage [28]. There are insufficient techniques and tools towards reducing construction waste during design and procurement stages and BIM has the potential for building design waste minimization [29, 30]. In addition, techniques such as Global Position System (GPS) and Geographical Information System (GIS) have been integrated to reduce construction waste in a prototype study developed from automatic data capture system to demonstrate its deployment and minimize the amount of onsite material wastage [31]. The use of prefabrication in buildings also reduces construction waste at average of 52% [32].

5.2. Reuse

Reuse involves the reuse of products as a whole or their components after their first life cycle to reduce the usage of virgin materials in newer products and components. Reuse technologies usually acquire spoil material and process or transform them into building materials. Reuse is the most preferred choice for waste reduction due to minimal requirement for processing and energy [33]. Embodied energy (EE) comparison is used to measure environmental impact of construction and the efficacy of building material choices, specifically for CO_2 emissions [34]. EE comparison measures the impacts of reuse.

5.3. Recycle

Recycling converts industrial waste to products and building materials. The impacts and benefits from recycling are explored through techno-economic analyses and LCAs [35], construction waste investigations based on material viability [36] and designing for closed-loop recycling to eliminate end-of-life waste [37].

5.4. Recover
Recovery involves the incineration of waste materials for energy recovery [38]. The energy recovered is generated in the form of electricity, heat, or fuel. Recovery is usually considered after reuse, and recycling. Three types of energy recovery technologies are thermo-chemical, chemical, and bio-chemical [39]. In the thermo-chemical conversion process waste is extracted through high temperatures; in the chemical, energy is extracted through esterification which is the creation of ester due to the reaction between alcohol and an acid; and bio-chemical process extracts energy using bio-decomposition of waste.

5.5. Redesign
The redesign process comprises four stages – understand, define, make, and release; design is constantly tested and refined as the understanding on user interaction and systems increase [40]. The scale of redesigning has shifted from products to companies, and to economic systems and ambitions are limited only by the imagination with the presence of new tools such as AI, IoT, and biomimicry [41]. Redesign involves practically iterated steps which has grown in scales, and biomimicry is also proffered as a process for circular redesign.

5.6. Remanufacture
Remanufacturing processes were pioneered over 80 years ago in the United States (U.S.). Between 2009 and 2011, the value of U.S remanufactured production grew by 15%, reaching $43B and supporting 180,000 full-time U.S. jobs. However, technologies in manufacturing and product markets across industry continue to advance at an unprecedented rate [42]. New approaches and technologies must be developed and deployed to the unique needs of remanufacturers and transform their role within the broader industrial economy and the technology research must be supported by advanced models of industry collaboration so that its fruits may be broadly accessible. Robotics and digital technologies have great potential to accelerate the spread of remanufacturing activities [43].

6. Technology support and strategies
Emerging technologies in the six R strategies showing CE concept and technologies include – reduce: BIM, GPS, and GIS; reuse: EE comparison, recycle: techno-economic analyses and LCAs; recover: thermo-chemical, chemical, and bio-chemical; redesign: AI, IoT, and biomimicry; and remanufacture: robotics and digital technologies. Figure 3 shows the strategies and emerging technologies in the six Rs. All Rs share input-output analysis, life cycle costing, cost benefit analysis, and material flow analysis. Approaches in each strategy could be tried in other strategies, for example the use of Geographical Position System could also be applied in other Rs.

7. Automated content analysis
Automated content analyses were used to gain insights on the literature of CE technologies and emerging technologies using *pyResearchInsights* - an analysis package. The package uses a scraper to collect abstracts from Springer journal repositories, cleans the texts, after which an analyzer performs automated content analysis. A natural language processor engine performs topic modelling, and a visualizer presents a visualization of research topics. Searches were conducted in over 6,000 abstracts and returned visuals of topics, their word count and weight. The weight of a keyword is calculated by its: i) frequency of occurrence in the corpus and, ii) its frequency of co-occurence with other keywords in the same topic.

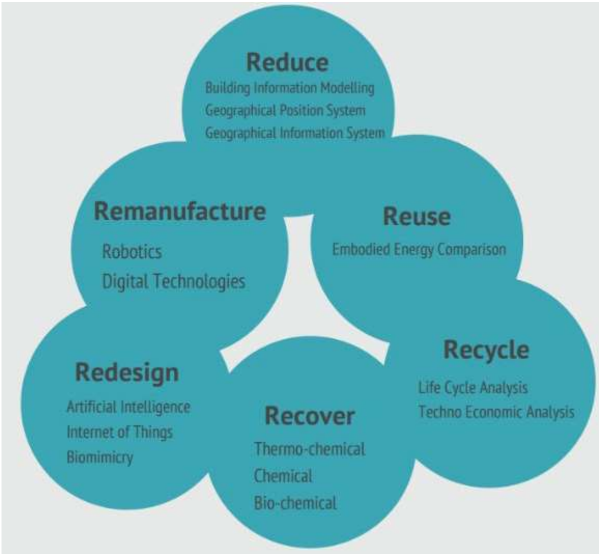
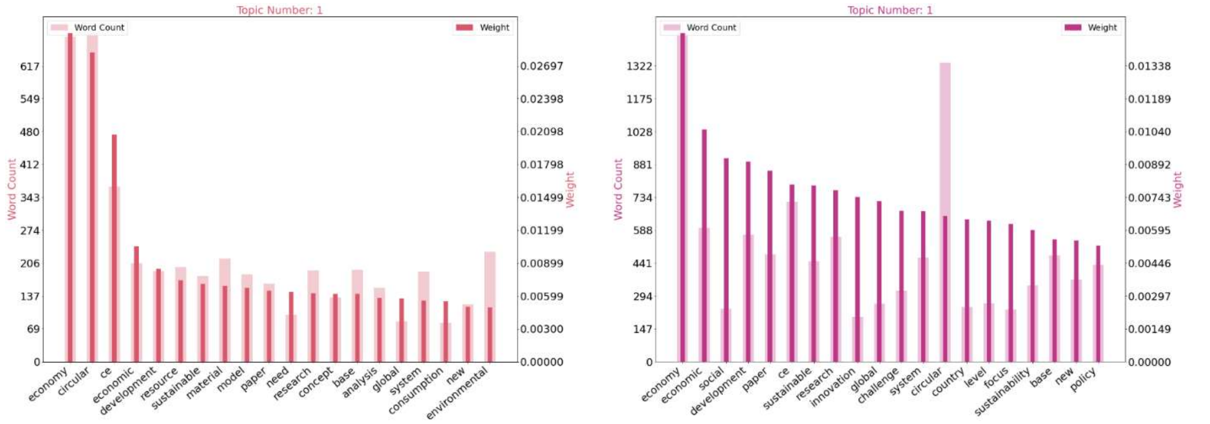


Figure 3. Circular economy strategies and their emerging technologies

Two searches were carried out using the following keywords: a) circular economy technology, and b) circular economy emerging technology. The first list of topics from the analyses are shown in Figure 4a and 4b.



a) b)

Figure 4. Visualization of research topics with keywords a) "circular economy technology" and b) "circular economy emerging technology".

Each search returned 200 topics in 10 charts generated by the natural language processor engine. 400 topics from the two searches, were displayed in word clouds after removing keywords such as circular, economy, emerging and technology.

In the word clouds presented at Figure 5 topics in "circular economy technology" include analysis of waste materials, industry, development, recycling, system, environment, development, plastic, process, strategy, etc. While topics in "circular economy emerging technology" comprise policy, model, production, waste, research, energy, sustainable, global, market etc. Hence, emerging technologies are global, involve policy, production, models, markets, and waste. Similar topics in both analyses comprise sustainable systems, research, models, etc. Emerging topics have less focus on materials such as food and plastic while both groups showed the importance of waste for technologies in CE.

Figure 5. Word clouds from topics in “circular economy technologies” and “circular economy emerging technologies” keywords.

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