Creative Construction Conference 2019, CCC 2019, 29 June - 2 July 2019, Budapest, Hungary

Digital construction and its role in driving the circular economy

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Abstract

Digital technologies can be used at any stage of the life cycle of a construction project, from the concept of the facility to the final of its operation. Construction companies use more and more available technological solutions, increasing mobility and safety at the construction site and facilitating the construction process. Digitization is increasingly affecting the modernization of the building management and operation process, saving time, making decision-making easier, causing saving financial resources and reducing the costs of energy and materials consumption. Not only investment of construction entrepreneurs in internal start-ups has been observed, but also the reverse phenomenon, involving the interest of technology companies in the construction investment market.

The closed-circle economy allows economic growth while reducing and optimizing resource consumption - it deeply transforms patterns of production and consumption chains and designs business models anew. The aim of the article is to present the results of the literature review, from the angle of discussion of issues related to the digital technologies used in various stages of the life cycle of construction projects with the assumptions of a closed-cycle economy. three successive steps were carried out: (1) a search strategy was developed to systematically review the literature and collect a representative set of publications on the relation of circular economy to building and digital technologies applicable to the life cycle of a building facility using Google Scholar; (2) a list of publications in the ad-doc database was prepared in order to synthesize the literature review; (3) a subset of the literature reviews was organized, which enabled the acquisition of quantitative and qualitative data as well as information on the phenomenon of digital construction and the impact of this innovative change on the development of the concept of closed circuit economics.

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Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: digitization; BIM; construction sector; circular economy

1. Introduction

The traditional linear production model (linear economy) assumes a schematic course of the production process in which the following stages are successively followed: obtaining raw materials, processing and then disposing of the product (take, make, dispose).

According to the circular economy paradigm, the materials and articles used in production are designed to be re-usable or safely introduced into the biosphere, and the technologies used in production cycles are environmentally safe [1,2,3,4]. This is an extension of the "cradle to cradle" production idea, which was defined for the first time by Stahel [5]. In this manner, the production model is changed and now includes stages: "take-make-consume-reuse and recycle" [6,7]. In the macroeconomic context, in relation to the functioning of regions, especially urban areas, the

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concept of circular economy refers to other complementary economic solutions, e.g., to the concept of sharing economy, according to which, unlimited consumption or accumulation of property gives way to their common use, exchange or borrowing of possessed goods [8]. One of the key issues in business models based on the economics of closed-loop (CE) is that instead of selling and buying products, they are manufactured with sustainability and then, where possible, they are leased, rented or shared [9]. An important feature of the concept of closed-loop economy is the fact that it allows for the elimination of conflict between the issues of economic profitability and ecological effectiveness of the business activity.

2. Method

The results presented in the article were obtained using the method of systematic literature review defined as the 5-stage review approach. This method is appropriate in the case of explanatory research concerning complex phenomena, which, in the authors' opinion, include the integration of CE assumptions with the digitalisation trend in the construction industry. Fig. 1 illustrates the course of the test in a schematic manner.

Figure 1. The 5-stage review

As a first step, a study area was identified and its aim was to establish, as a result of a literature review, the current state of knowledge related to the potential of digital tools used in construction in relation to the implementation of Circular Economy in this sector and Digitalisation in the AEC sector: State-of-the-art. The second step included Literature Collection, followed by Literature Filtration and Synthesis. Publications were searched for using the Google Scholar database and the Web of Science. A timeframe was adopted from 2000 to 2019. The search was carried out using these keywords: 1. digital construction + circular economy 2. BIM + circular economy, 3. Digital tools + LCA in construction projects. From among 95 articles, and as a result of a preliminary analysis of their content 65 were chosen, which, in the author's opinion, presented the most adequate relationship with the subject of the study. The next steps concerned a detailed and critical analysis of selected articles, which resulted in the identification of the main thematic areas of the links between digitisation and CE in construction, the determination of the current state of knowledge on the subject and the identification of areas that require further knowledge and research.

3. Circular economy in construction – main assumptions

The implementation of circular economy in the AEC sector is particularly justified due to the very intensive and degrading impact of this sector on the natural environment and on a single building scale, as well as on a regional and global scale [10]. Architecture and construction in line with the circular economy aim to reduce the use of natural resources, reduce the amount of waste and reduce the impact of buildings on the environment. In terms of architectural practice, methods have been developed in recent decades to accurately predict the reuse of recovered materials outside the "end-of-pipe" design solutions that only delay the waste phase [11]. In buildings designed in accordance with the principles of closed-loop management, secondary materials are used, but above all, facilities are designed in such a way that their elements can be recovered in the future. Life cycle analysis of a building's structure allows for the identification of key aspects of circular economy in subsequent stages of this cycle (Fig. 2) [12].

Figure 2. Key aspects of circular economy in subsequent stages of the building life cycle. Based on [12].

The general principles of circular buildings can be summarised as follows:

- it has been proposed to minimise the total energy expenditure on the maintenance of the building and to move towards net zero energy buildings, i.e. those in which the used energy comes entirely from renewable sources,
- circular buildings, apart from energy conditions, are materially conditioned. Construction products should have well-defined technical characteristics, well-defined usefulness and be well suited to the application in question. Technical features not used in a given application or representing excess values constitute an unreasonable cost (energy input) which is paid for by the user.

The 3R - Reduce-Reuse-Recycle concept, according to which unused structural elements or other construction waste is used, adapting projects to limit construction activities to the minimum necessary, is well known in construction

activities [13,14]. Circular economy extends this approach by prioritising the deconstruction of facilities before demolition and recycling of demolition materials [15].

Analysing the circular buildings framework model, two issues important for further consideration are identified. The first concerns the specificity of construction production, which is much more complex than in the case of the industrial products with short life cycles. This means that the solutions proposed under the CE concept for industrial production are not fully adequate for the AEC sector. At the same time, construction facilities are constructed from elements, materials and products which separately constitute products with characteristics similar to industrial products (manufactured products), while being integrated into the structure, they acquire common features of uniqueness, durability and long life cycle, far removed in time from the creation of the transformation possibility [16].

The impact of the implementation of circular economy principles on ecological efficiency and, at the same time, the profitability of production, can be observed on the example of the results of research conducted from the perspective of the supply chain, comparing the results of LCA analysis for two insulation materials, one of which is produced in the traditional linear method, the other with the use of the closed-loop method. According to the obtained results, a smaller impact can be observed with regard to the second material, produced according to the assumptions of circular economy [17].

Publications indicate that technology is a key aspect in construction, enabling the creation of circular loops, combining supply and demand, as well as the handling, storage and management of the vast amount of data required by CE.

In the case of construction facilities, the range of data over the whole life cycle of such a facility is very large and varied. Relevant data in addition to facility information resulting from the construction project include schedules, cost information, energy analysis details, lighting information, waste management plan, etc. This additional data is used at different stages of the facility's life cycle for various analytical, simulation and evaluation purposes.

Due to the need to manage resources and information wisely throughout the life cycle of a building, the possibility of using digital technologies that can support the implementation of CE in the AEC sector has become increasingly important in recent decades [16].

3.1. Digitisation of the life cycle of a building - enabler of CE in the AEC sector

The effectiveness of a business model implemented according to circular economy assumptions can be supported by digital technologies, which facilitate and help to close or slow down material flows, with increased resource efficiency [17,18,19,20,21].

Literature, which discusses the opportunities and challenges of the impact of digitisation on the results of the implementation of CE in construction processes is relatively limited. As a result of the analysis of selected publications, thematic mainstreams combining the issue of CE and digital technologies in the AEC sector, in terms of the life cycle of the building, have been identified (Fig. 3).

Figure 3. Thematic mainstreams combining the issue of CE and digital technologies in the AEC sector

The results concerning the issue of BIM and circular construction are presented in tabular form (tab.1).

Tab.1. Articles concerning the linkage between the issue of BIM and circular construction

Thematic trend linking CE and BIM	Publications
Building Information Modelling (BIM)	
and Energy	[32], [40], [41], [42], [44], [55]
and Material consumption (waste utilization)	[27], [29], [34], [39], [47]
LCA	[23], [24], [25], [26], [28], [30], [31], [33], [35], [36], [38], [43], [45], [46], [48], [49], [50], [51], [52], [53], [54], [56], [57], [58], [59], [60]
LCCA	[61], [62], [63], [64]

The results of the literature review related to the possibilities of implementing the BIM method in the context of achieving sustainable development goals in the construction industry show that there is a significant amount of research and development in this use of BIM at different stages of the project. One of the key features of BIM, which makes it a suitable method for use in the life cycle of a building in accordance with CE assumptions, is the ability BIM offers three basic functions that make it both an economically and environmentally efficient way to manage the life cycle of buildings. These basic features include: (i) parametric modelling of objects, (ii) bidirectional association and (iii) intelligent modelling [26].

Publications of solutions integrating BIM tools with sustainability analysis applications indicate two main approaches. The first one concerns the combination of environmental analysis instruments already developed and functioning in practice with BIM tools. The second approach proposes the development of new analytical tools with the ability to communicate with BIM software. The choice between these solutions determines the costs of modification of already used programs and implementation of new tools [34].

The thematic scope of a significant part of publications related to BIM synergy and sustainable construction principles, concerns material analysis of building structural elements. This is based on the premise that, in order to ensure the efficiency of circular economy in construction, it is important that a significant proportion of the construction materials and used products should be reusable and recyclable [33,35]. Tools related to this area include Materials Passports and Reversible Building Design Protocols (RBDP). The first instrument contains digital sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery and reuse. RBDP contains a set of instruments to inform designers and decision makers about the technical and spatial reversibility of building design(s) and the impacts of design solutions during the conceptual design phase.[36].

However, only a few works can be identified concerning the possibilities offered by the BIM method for increasing the ecological efficiency of the renovation and demolition of the building. [37, 38].

The use of BIM has also been analysed in the context of the zero-carbon buildings concept. [39,40,41,42]. Achieving zero carbon emissions in buildings requires monitoring and sharing information and knowledge about building performance during operation, from the moment the building is handed over to the occupants. One of the main assumptions of the BIM method is the discipline of cooperation between all participants of the investment process, which significantly facilitates the exchange of information and knowledge between the interested parties. The concept of BEM - Building Energy Modelling is related to the issue of energy efficiency. In the Building Energy Model, it is possible to study the impact on the energy efficiency of different design variants (e.g., different thicknesses of thermal insulation in a building), to test different variants of installation and automation. The building model is located in a specific geographical location for which a set of meteorological data is used. As a standard, calculations for simulations are performed with a frequency for each hour of the year (8760 hours), which gives great accuracy of results, incomparable with, for example, the results obtained from the preparation of the energy performance certificate of the building [43].

The integration of BIM with analytical tools related to sustainable construction concerns analyses in the area of ecological footprint and LCA. LCA analysis makes it possible to assess the environmental impact of a building facility by estimating the raw materials and energy consumed at different stages of its life cycle, as well as the amount of pollutants emitted.

It is a tool used to quantify environmental loads generated during the manufacture of construction products and the erection of buildings. LCA has great potential to support sustainable construction. However, in a traditional construction process, due to the limited data availability and time-consuming process of compiling this data, LCA analysis is not widely used. The BIM method, which uses a model that provides a comprehensive repository of knowledge about the object, creates perspectives for improving the LCA procedure. Restrictions are pointed out and are mainly related to the interoperability of BIM and LCA tools, but the authors describe significant opportunities to increase the speed of LCA calculations using a repository that collects building data in one place, which covers a very wide range [44]. Researchers also propose an automatic LCA calculation model at an early stage when developing the first data level in the BIM model (LOD100), and then expanding and updating the calculations as the object model develops. This method requires checking the application possibilities with the use of available IT tools [45]. In reference to the assumptions of circular economy, the area which requires deeper knowledge and research work towards the development of new tools is the integration of BIM and LCCA [46 – 60]. At the design stage, it is possible to determine about 80-90% of the costs incurred subsequently over the course of construction, use and operation of the facility, hence it is an adequate stage of the life cycle of the facility in terms of optimising these costs. [61, 62]. The integration of the BIM model and analytical tools used in LCCA is a direction of development of instruments that can significantly improve cost optimisation due to the possibility of faster and more accurate examination of operating scenarios of the facility and determination of costs in accordance with the assumptions of circular economy, especially in terms of its operation and demolition [63,64,65]. This is one of the most important trends in the development of construction on a global scale [66]. One of the concepts concerning tool solutions is Computer Aided Life Cycle Cost Analysis (CA-LCCA) of a building both for new projects and renovation jobs. This

tool allows for the combination of technical parameters and financial data to help make investment decisions [67]. Another proposed solution analysed within the case study is the integration of data collected in the BIM, BEM and BIM-FM into LCCA tools. The results indicate a significant increase in the accuracy of calculations and an acceleration of the cost data analysis process [68].

Sensoring enables the collection and generation of data in real time. Current, detailed information on the exact location of waste production, its exact material composition, etc. can be recorded ("fast data") and forwarded to other companies, who then use it as secondary material to plan their production processes. Big Data applications can then provide and design information for further use as practical logistics solutions.

Such solutions are increasingly used in office buildings and large service buildings like shopping malls. Systems using sensors and the Internet of Things (IoT) record, monitor and constantly report data from the current use of the building, which allows for the creation of a profile of historical and real-time behaviour, which is useful in FM. When complex data from several assets are aggregated, emerging patterns of usage, energy consumption, preferred lightening and temperature, and collections of interior assets can lead to reconfigured workforce patterns and reduced energy consumption [69].

The idea of "smart contracts" is related to the issue of sensoring – digital contracts functioning in the form of self-service applications. A sensor-equipped intelligent building component can send information about its performance to a distributed data base. Components can be programmed via "smart contract" to initiate the necessary maintenance or repair work, which prevents deterioration of the building and optimises maintenance costs, providing predictive just-in-time maintenance versus just-in-case costly maintenance. The results of the life cycle analysis of individual objects can be compared, on the basis of which it is possible to work out a data set on standard user habits, energy and water consumption, maintenance mode, for the purpose of Facility Management improvement [70].

Adapting supply and demand to the availability of waste or secondary raw materials can be revolutionised through the use of online solutions, as is already the case for product distribution. A potential automated market and logistics platform have the capability to reduce search and transaction costs. This could also facilitate economy of scale, as the question of the amount of materials needed would be more transparent [71-74].

4. Conclusions

The idea of circular economy is derived from concepts that have been in development since the 1970s, especially since the great energy crisis in 1973. These included concepts such as Cradle to Cradle, Regenerative design, Biomimic and Blue economy, initiated by Belgian businessman Gunter Pauli. The effectiveness of the implementation of circular economy in the AEC sector can be increased by combining the digitisation trend with the use of tools related to environmental and economic analyses at every stage of the life cycle of a building.

An area which, according to the findings of the literature review, requires in-depth research is the integration of economic aspects with environmental analyses with the use of digital tools. The issue of inclusion of costs related to life cycle analysis results is the subject of a very limited number of publications. Meanwhile, it is an issue that fills the scope of implementation of the circular economy in the construction industry, due to the inclusion of the financial aspect in the analyses. Until now, the calculation procedure for LCCA analysis required time-consuming data collection for the purpose of determining the costs of procurement of raw materials, transport to the production site, costs of production of construction materials and products, transport to the construction plan, cost of impact at the construction stage, then environmental costs of loads associated with the operation of the building and, finally, its decomposition, including the costs of recycling demolition waste. The calculation process itself, depending on the chosen method, can also be complex, especially if the calculation method assumes an analysis of the discounted cash flows over the period from the construction work up to decommissioning, taking into account different cost elements over the life cycle (e.g., maintenance, use, repairs, overhauls, dismantling). The use of digital tools such as the BIM model in combination with LCCA principles can help optimise investment decisions. In order to broaden knowledge

in this area, it is justifiable to check the application possibilities of the proposed model LCCA and BIM solutions, using the case study method. This may be an interesting direction of research, useful both for private investors and institutions implementing public investments, which should be planned in a way that ensures rational use of public money and in a manner consistent with the assumptions of sustainable development and circular economy.

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