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Facilitating Circular Economy Strategies Using Digital Construction Tools: Framework Development

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Abstract: The construction sector has undergone several transformations to address adverse environmental, economic, and social impacts. The concept of the circular economy (CE) has transcended into this domain to solve the needs of construction amid resource constraints. Furthermore, advanced digital tools are being implemented across industries owing to the boost given by the fourth industrial revolution. This paper aims to develop a framework that investigates the effect of digital tools on CE implementation in the construction sector. The study is based on a three-step approach, where first, an initial framework design based on a systematic literature review was conducted. This is followed by framework optimization using semistructured interviews with experts and validation through a case study. This study resulted in the development of a new framework, which aims to investigate how advanced digital tools can be used in the construction sector to enhance CE implementation. The contribution of the present study is two-fold: (1) the integration (addressing existing research gap) of CE and digitalization concepts in the construction sector; (2) an investigation into the critical barriers, offering insights for construction practitioners.

Keywords: digitization; circular economy; industry 4.0; framework development

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1. Introduction

Despite the key role (e.g., provision of basic infrastructure, employment generation, etc.) of the construction industry in the economic development of a nation [1], it is known for being one of the most resource-intensive industries [2]. The sector is responsible for generating one-quarter of the waste produced and 39% of energy and gas emissions worldwide [3–5]. Additionally, 50% of all materials consumed in continental Europe only are used by the construction sector [6]. Those materials are sent to the landfill (after the end of life) as a result of a linear economic model, which dictates the "take, make, dispose of" approach [3,4]. Given the sector's negative impacts, it has become of strategic importance to take action to change the current paradigm and make the sector truly sustainable by effectively implementing the resources through another approach called the circular economy (CE) [7].

The CE concept has been getting wider attention due to its restorative or regenerative nature by design and intention. It eliminates the "end of life" stage in the life cycle and substitutes it with restoration, recycling, or reuse [8]. Although the basics of the CE concept have been widely implemented in various sectors, the adoption of the concept in the construction sector has yet to be sufficiently achieved [4]. With the widening scope of the "Industry 4.0" concept, advanced technologies have been reported to be the main tool to unlock new value from the CE, making strategies cost-effective [9]. Thus, digitalization, as a part of the Industry 4.0 concept, can foster the wider adoption of the CE concept in the construction sector by facilitating the interaction between products, processes, and humans in the lifecycle through cyber–physical technologies [10–12].

The digitalization-led CE has attracted a significant amount of attention from both industry and academia. For example, some authors discussed the potential of digitalization and Industry 4.0 to improve the adoption of the CE [13,14] and their combined influence to foster sustainability goals [15]. This idea of incorporating circularity and digitalization was further developed to find a practical implementation: Liu, Yang [16] developed an emerging framework correlating the digital functions of Industry 4.0 and CE strategies, while Çetin, De Wolf [17] focused on the digital tools as a whole as CE enablers. Kovacic, Honic [18], focused on a digital platform incorporating data exchange opportunities among stakeholders in a digitalization-led CE-built environment. A robust literature review suggests that the studies on digitalization-led CE focus more on how digital technologies can facilitate CE adoption. However, the topic of how different digital technologies can enhance diverse CE strategies in the construction sector is still undiscovered. Therefore, the present study addresses this gap and frames how different digitization tools can support the implementation of different CE strategies in the construction sector. It is hoped that the developed framework guides industry stakeholders and decision-makers toward the efficient digitization of each CE strategy; consequently, it drives its industry-wide adoption more efficiently and cost-effectively.

In order to achieve this aim, the paper is outlined as follows. The following section provides background information on the CE and a brief review of the construction industry's digitalization. Afterward, the methodological approach is presented, which is followed by a discussion of the framework development. The framework is then validated through a case study of the largest construction company in Kazakhstan.

2. Literature Review

2.1. Circular Economy: Background

The concept of the "Circular Economy" has seen an increasing trend since the end of the 1970s [19] and continues to expand in its application across multiple sectors, including the construction sector. Geissdoerfer et al. [20] defines it as a regenerative process whereby input resources, wastage, emission, and energy leakage are reduced by closing, slowing, or narrowing the material and energy cycles. Çetin, De Wolf [17] elaborated on these, where "Closing the loop" is the reuse of materials and components or postconsumer material recycling; "Slowing the loop" is reducing the use and consumption, increasing the product lifetime of materials and the extension of the useful life of products, and "Narrowing the loop" is efficiency improvements in production and design to minimize resource waste.

The CE represents a new approach that opposes the traditional linear consumption model and promotes a resource-based approach that dissociates from the extraction of raw materials [19]. CE has its roots in response to the proliferation of environmental catastrophes globally, including ozone depletion, biodiversity loss, climate change, and global warming [20]. In its modern sense, the practical applications of the CE within economic and industrial frameworks have advanced to include a range of concepts pertaining to closed loops. Despite being one of the top three high-potential sectors, evidence shows that the built environment lags in the implementation of CE strategies compared to other sectors, such as electrical equipment, furniture, and textiles [21]. The construction sector consumes the largest amount of material globally [22], while the level of consumption is only expected to increase further to meet future demand [23]. Although waste generation occurs throughout the building lifecycle, including the design and planning stages [11], most building materials are disposed of at the end of life [24]. Practical experiences on a country level can be presented in the case of China, which is known as an early-bird adoptee of the CE strategy. Since 2002, a series of legislative decisions have been made to enhance and promote the wider adoption of CE implementation and reach more sustainable practices in various sectors. In turn, Yuan, Bi [12], stated that the initial role model for CE application was taken from the experiences of developed countries, such as Sweden and Germany. In terms of household waste management and landfill reduction, Denmark has taken the lead among other European countries [25]. Therefore, the obvious gap in CE development in developed and developing countries can be seen, urging developing countries to concentrate on that area.

2.2. Digitization in the Construction Industry

The construction industry has been facing cost, time, and quality challenges while meeting the increasing demand for population growth in urbanized areas [26]. Additionally, complicated work processes and tiresome managerial activities result in the inefficient administration of construction management processes [27,28]. The digital transformation of the management of the construction process has been offered as a solution to overcome these challenges [29,30]. The prevalence of big data and digital platforms has increased significantly over the last decade and is disrupting every industry. A study carried out by the Association of German Chambers of Commerce and Industry [31] showed that 93% of the participants agreed that digitization would affect their construction processes. Digitalization requires businesses to utilize connected systems at every link of their value chain. It requires the development and transformation of its business model through the adoption of digital technology, allowing it to generate more revenue and provide higher value to all players involved in the supply chain. Through the digitalization of a business model, the benefits included increased communication, higher management efficiency over the construction process, higher levels of sustainability, better communication between plants and increased safety, enhanced customer satisfaction, the simulation and digital modeling of various scenarios, accurate forecasting, and enhanced document management systems [30,32,33]. Digitalization also offers new opportunities, such as new partnership models, high-level performance tracking, and enhanced project deliverables [34]. Thus, the construction context is reviewed (refer to Table 1) to identify the digital technology utilized by the construction industry.

Despite its potential benefits, digitization presents a complex cyberspace network making companies susceptible to cyber attacks [35]. This complexity has led to an increase in the level of cyber threats. As a result, the infrastructure for cyber security has become a necessity across companies. The lack of attention to security issues has created considerable cybersecurity threats at the system and system-of-system levels [36]. Different models have been proposed based on the nature of the supply chain and industry. According to Boyes [37], a model utilizing the Parkerian hexad is particularly relevant to supply chains in the construction industry, which are cyber-physical, complex, and time-sensitive [37]. The Parkerian hexad consists of confidentiality, integrity, possession, authenticity, availability, and utility [38].

Digitization also faces other challenges in its adoption in the construction industry. Aside from merely technical limitations, such as applicability, usability, interoperability, cost, and time, digital tools often receive a negative response from potential end-users [39]. Technology acceptance and ease of use are factors that influence people's perception of digital technologies early in their adoption. Furthermore, the digitization process is characterized by high levels of initial investments, mainly for hardware, software, licensing costs, training, and running operational costs [39].

Table 1. Review of digital tools in the construction sector.

Industry 4.0 Tools	Definition	Examples
Internet of Things (IoT)	The network of connected devices interacting and exchanging information with each other through wireless means [40]	IoT sensors, controllers, and actuators: NFC/RFID tags, Auto-ID tags, barcodes, and satellite nodes. Electronic devices & machinery: computers, smartphones, drones, robots, and laser scanners
Big Data	It includes data mining, classification, and storage [41]	On-cloud database, embedded machine learning algorithms, and artificial technology
Additive Manufacturing(or 3D printing)	The process of extracting the CAD model and building a complex physical entity, usually a 3D object [42]	3D printers and 3D scanners
Digital Twin	It is the digital footprint of the products. It creates the virtual model of a physical entity to predict its behavior in the real world [43]	Building Information Modeling (BIM): e.g., Revit, Naviswork, SAP, and Vertex.
Cloud Computing	Technology provides a pool of shared devices with on-demand network access to information and services stored on powerful internet servers, and they can be easily retrieved remotely through wireless communication [44]	Computer software and mobile applications. Web interface: e.g., application programming interface (API) and human-machine interface (HMI).
Augmented & Virtual Reality (AR/VR)	AR is an interactive environment that allows users to (1) view the info in the offline mode; (2) actively interact with the material; (3) actively interact with people remotely but in real-time. VR is a step ahead of the virtuality aspect. It allows users to completely dive into 3D experiences [42]	Augmented Reality (AR) and Virtual Reality (VR) platforms

3. Methodology

A three-step approach was adopted to achieve the aim of the present study, which is also illustrated in Figure 1: (i) the initial framework design based on a systematic literature review (SLR); (ii) framework optimization through semistructured interviews with experts; (iii) validation of the framework by conducting a case study.

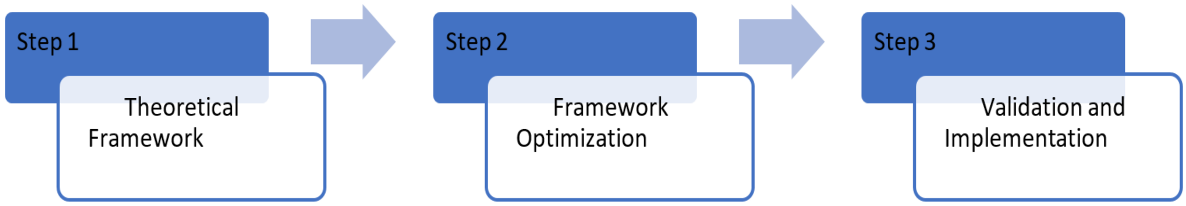

Figure 1. An overview of the methodology steps.

Step 1: Theoretical framework design. The theoretical framework (FW) design step aimed to map the construction-specific CE strategies and construction digital tools. The FW was designed based on the systematic literature review recommended by [45,46]. The search strings were composed of dual combinations: 'Circular Economy', and 'sustainability', AND 'construction industry', 'strategies', 'digital technologies' and 'assessment model'. The search procedure was performed within the Google Scholar and Web of Science databases, including the journals, conference articles, and industrial reports of all related stakeholders. The initial search resulted in 249 documents. During the screening process, 115 papers were excluded due to the following exclusion criteria: articles in languages other than English, nonindexed journals, and published before the year 2000. Thus, 134 articles were screened to identify the CE strategies and the construction digital tools that have been reported to in the industry.

The construction lifecycle stages (LCSs) were considered following the practices in the current construction sector: design, planning/scheduling, construction, operation/maintenance, and end-of-life. Various CE strategies and their significance to the market were elaborated. This resulted in the mapping of the following strategies (with meaning) against LCS (Figure 2): (1) material flow–an assessment of the value of the construction products and materials and its impact on the development of the circular practices; (2) resource utilization—the state of reuse and the reintroduction of different resources back into the value chain of the construction project, and (3) reversibility—the concept of transforming or dismantling the parts of the building for future use. Additionally, the current state of advancement of digital tools in the construction industry was evaluated, and the following technologies were located in the framework formation: building information modeling (BIM), big data, internet of things (IoT), cloud applications, and others.

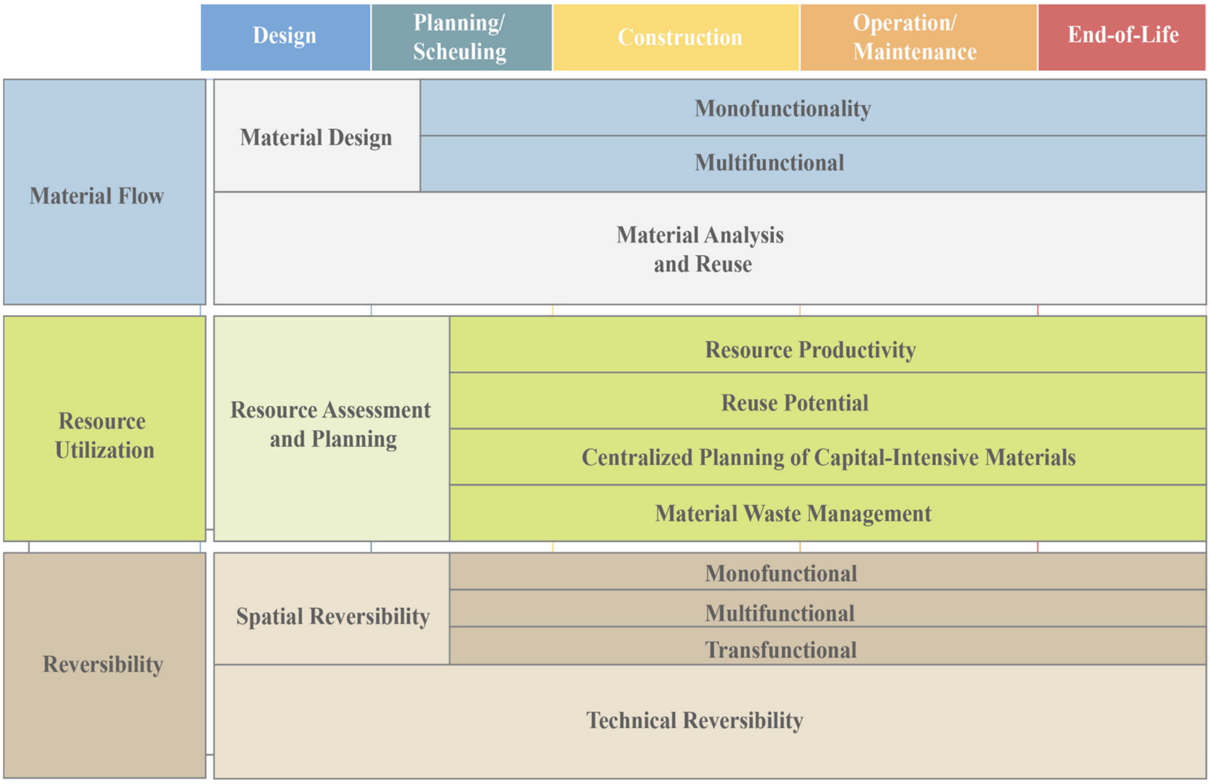

Figure 2. Theoretical framework design.

Step 2: Framework optimization. Once the initial FW was developed, it was then optimized through semistructured interviews with industry experts, as recommended by [22]. The purpose of the interview sessions is threefold: (1) to evaluate the awareness and practices of CE principles in the construction industry; (2) to understand the application of different digital tools during the construction value chain, and (3) to determine whether the initial framework model fully reflects the current market situation in the construction sector. The list of possible interviewees, which consisted of 14 experts from academia and 10 from industry, all with the relevant area of expertise (e.g., CE, digital construction, lean, etc.), was created, and the experts were invited to interview sessions. After receiving the replies (15 out of 24 or 63% response rate), the list of experts was narrowed down to 6 experts in total, eliminating the others based on their availability. Detailed information about the participants and their demographic background can be found in Table 2. The common characteristics of people interviewed are (a) at least 7 years of experience in the construction sector, (b) relevant academic degrees within civil and environmental engineering, construction management, and architecture, and (c) confidence in using the

English language. Prior to the interviews, the respondents were provided with information regarding the brief project description, goals, and the initial framework. The sessions were organized via online video conferencing platforms, taking from 60 to 90 min each, and were recorded by the research team.

Table 2. Information on expert session participants.

No.	Background	Years of Experience	Field of Expertise
1	Academia	11	Construction Management & Sustainability
2	Industry	9	Technology Management in Construction
3	Industry	8	Kaizen and Lean Practices in Construction
4	Industry	5	Optimization of Construction Processes
5	Industry	7	Project Design and Architecture
6	Industry	7	Production of Construction Materials

The format of the questions asked in the interview was open-ended, giving the interviewees space to elaborate on their answers while still framing them by the definitions and goals of the project outlined at the beginning of the sessions. The sample question devoted to identifying one of the circular economy strategies is stated as follows:

Resource Utilization—Does your company consider resource utilization in its processes? If yes

1. In which stage of the construction process is resource planning introduced?
    a. How and when is the building's potential for being reused considered?
    b. Is it optimal to carry out planning for high-cost materials? In which level should this be carried out? What are the tools used for it?
2. What tools have been used in your company in order to measure and improve the utilization of resources?
    a. At what stages can lean operations be introduced in the construction process?
    b. What measures of efficiency are used in your domain? When are they used?

The interview and meeting minutes were recorded as per the consent given by the interviewees, and the information was reflected on top of the theoretical framework. In places where synthesis was impossible, the strategies were adapted/optimized to the current market situation in terms of circularity and digitalization. The optimized framework includes (i) resource management, (ii) building management, and (iii) social involvement with related digital technologies that were determined and validated via semistructured interviews.

Step 3: Framework Validation: A case study. The final step of the methodology section is the validation of the optimized framework. The procedure was performed with an initial aim to validate the optimized framework in the scope of a company and assess the enterprise in terms of circularity progress. The analyzed company is a well-known construction developer with an operational history of more than 25 years, a USD 2 billion market capitalization, and around 5000 employees. It operates in different regions and has more than 80 ongoing administrative, residential, and industrial construction projects. An executive-level expert (15+ years of experience in the field) and middle managers (5+ years of experience in the field) from the case study company were involved in the model validation and the assessment of the enterprise's construction projects through an initial online survey followed by an in-person interview to discuss the results. The same questions (as in workshops) were used to reduce the gap and bias between the circularity and digitalization performances of those companies (in which the previous interviewees had worked).

4. Results and Discussions

4.1. Theoretical Framework

Figure 2 shows a simplified schematic of the initial framework design, and it maps the identified CE strategies in three main areas (with 14 substrategies in total) against LCS. The entire building lifecycle is considered when categorizing the stages of implementation for the identified substrategies. The presence and absence of digital tools are planned to be filled in each cell of the substrategy or strategy at a certain LCS. The corresponding cells in the building lifecycle were intended to be marked to gain an insight into which stages of construction are digitally intensive.

As for the technologies, the primary goal of the theoretical framework was to differentiate those technologies from each other by understanding their interactions and purpose for the construction sector. The route typically starts with embedding IoT devices into physical assets in the building to collect information. Those IoT devices could consist of operational infrastructures, like HVAC, signaling systems, auto ID sensors, scanning devices, robotics, and drones. After the data are collected, they are optimized through artificial intelligence (AI) and stored in the cloud, while the dynamic data are directly embedded into the BIM Model. The BIM Model and big data act as input data to the digital twin, where the digital twin reflects the information to update the BIM. The interaction of those technologies in the environment is presented in Figure 3, as recommended by [42,47–49].

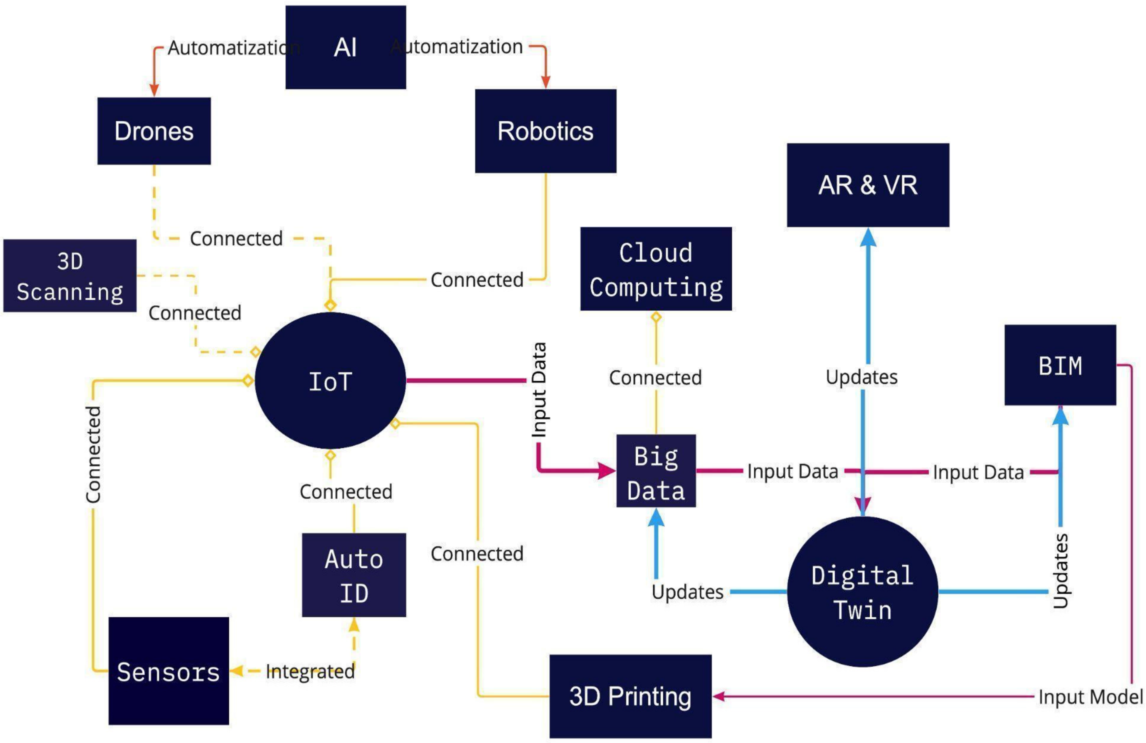

Figure 3. The interaction map of Construction 4.0 tools.

4.2. Optimized Framework

Based on practical application, the theoretical framework was optimized to consider the relevant areas of CE application in the building sector. While the theoretical framework considers the "ideal case" scenario, it should be noted that the implementation level of the CE concept and its strategies in Kazakhstan is at the infancy stage of development and utilization [24]. This has been attributed to various technological and social barriers. The technological barriers include a lack of proper infrastructure for recycling and the lack of a reuse and resale market for durable, certified materials [50]. Additionally, digitization tools are either scarce or unavailable on the initially designed framework based on the current state of the CE in the research domain [51].

Meanwhile, social issues account for two main factors [52]. The first one is the lack of stakeholders' awareness of the impact of a sustainable design, and the second one is the shortage of green financing and regulations both at the country level (imposed by the government) and at the company level. Cost is identified as the primary factor in purchasing construction materials. Virgin materials are preferred due to the high cost associated with recovering and maintaining the residual value of the materials at their end of life. Since such barriers exist, the initial framework was inapplicable to the responder's experience. Moreover, the transition to the CE is impossible without different parties involved in the construction sector, such as the government, manufacturers, building owners, project managers, material engineers, and in situ labor [53].

The optimized framework, which was developed based on the expert's opinions on the theoretical framework and local construction industry facts and needs, is summarized in Figure 4. The new framework adopts three main strategies: resource management, construction management, and social involvement. They are further subdivided into planning and utilization stages.

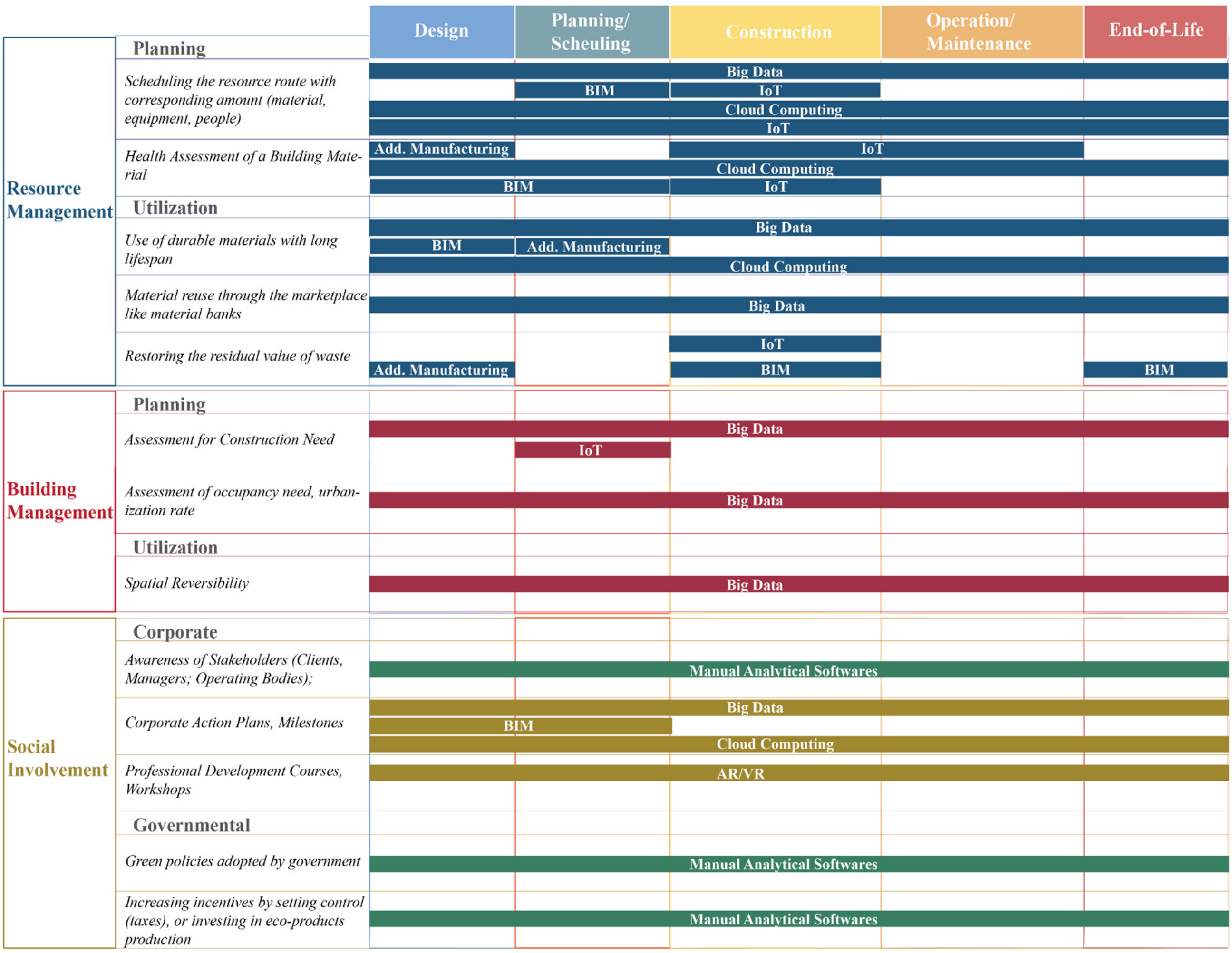

Figure 4. Optimized Framework Diagram.

Resource Management includes the evaluation of construction industry performance in the advancement of economic transformation towards circular approaches through a reduction in resource demands, which increases the security of the resource and lowers the environmental impact [54]. This strategy allows for avoiding the depletion of material sources resulting in the further application of resources such that they could provide benefits for future needs, increasing sustainability and circularity [55]. The effect could be measured by examining the initial design of the material, i.e., whether its characteristics provide opportunities for future reuse and reapplication in building structures. Moreover, other measurement metrics could include the availability and awareness of sustainable resource management practices in the existing market.

Planning requires scheduling the resource route with the corresponding amount of material, equipment, and people. Material flow analysis can help to avoid waste ending up in landfills. It optimizes the utilization of the material, equipment, and workers by reducing downtime, unnecessary logistics, and, consequently, the material or everything considered waste and increasing job site safety [56]. For scheduling purposes, the real-time location sensing (RTLS) system could be used to (a) track the location (or coordinates) of construction resources (i.e., concrete mixer track to reduce CO_2) and to (b) track the potential hazards and near misses through the RTLS coordinates. Meanwhile, Autodesk Navisworks's plug-in, called CPSPlugin, extracts the coordinate of each tagged part and updates the status property of the model of the tagged part. It updates the 3D model and stores the change in a database when the design is changed [18]. Alternatively, the i-Share software uses coordinate information to compute the relative proximity of the tags. These are subsequently communicated to a web interface from which the database is regularly updated [48]. The data on inventory, logistics, modular digital solutions for document-based cooperation, and documentation across the construction value chain are collected and procured using web or cloud-based team management resources. AR is used throughout the lifecycle to optimize production planning and enable the remote expert system to deal with faults directly [42].

Planning is also linked to a better health assessment of a building by providing efficient material performance monitoring throughout the building lifecycle, creating opportunities for circularity [57]. The health assessment starts at the construction site. Smart bins and smart vehicles collect and detect waste streams, sort them, and provide quality assurance and human-machine interaction (HMI). Scanning sensors or sensors embedded or attached to bridges, dams, and buildings are used for the health assessment of structural components by detecting corrosion and identifying cracks. Some of the contemporary solutions for this purpose are piezoelectric ceramic (PZT) sensors and optical fiber sensors. Another digital solution is a standardized BIM-based material passport. It allows for the assessment of ecoindicators, such as primary energy intensity (PEI), global warming potential (GWP), and acidification potential (AP), and their use [58]. Moreover, it displays recycling potential, environmental impact, and temporary structure monitoring (TSM) through Autodesk Navisworks [58]. Smart metering devices could also be applied for energy assessment and its effective utilization.

The utilization of durable materials with a long lifespan is key to achieving circularity in resource management. For example, designing for longevity and reuse opportunities could be seen as costly, but in the long-term, they have several potentials for the industry, such as reducing the cost of maintenance and prolonging the economic value of the material. Moreover, durable materials reduce waste [19]. The digital material marketplace (Airfaas), the open-source flow data from the value chain, and the internal data from sourcing could be used to design durable materials or buy them from manufacturers with the appropriate certifications. In order to design a durable material, several additive manufacturing techniques could be used. For example, fused-filament fabrication can be used to customize building facades or construct a zero environmental impact house module [47]. A standardized BIM-based material passport can help to monitor the durability of those materials or products, while the field personnel can read and update the contents of the RTLS tag using a client application running on a mobile device (e.g., BIM 360) to have up-to-date information on hand [48].

Material reuse through the marketplace, such as with material banks (BAMB), and creating a digital platform for users to reuse and resale the products are vital for circularity.

For example, several car manufacturing companies are selling parts for cars [59]. Likewise, a building could be used as a material bank for second-hand stores, where durable materials are sold for the optimal price. Along with the digital marketplaces discussed above, waste-based printed materials could be used for various fields of application in construction, i.e., thermoplastics, for both existing and new projects [47].

Restoring the residual value of waste plays a key role in circularity by regenerating resources and returning them to the biosphere. Additionally, saving energy, recovering biochemicals from the product, and using byproducts to keep the revenue stream and the nutrients in the cycle [60] are all desirable. The Reuse Potential tool (RP) embedded in BIM could be used as an evaluation tool through the decision-making cycles of the definitive design phase and can be further used for the preparation of the construction phase to verify the final reuse potential index, while the BIM-based Whole-life Performance Estimator (BWPE) could be used for material value recovery [24]. Some examples of resources with restored value are concrete with recycled plastic fibers, which are mixed and set to be cast in 3D-printed molds to create marine habitat walls, the facades and roofs made from 3D-printed tiles using ceramic waste, and houses that are 3D printed from industrial rice scraps [47].

Construction Management includes activities toward the changes and optimizations of existing building models following CE principles by focusing on the whole lifecycle of the construction value chain, including business aspects starting from the initiation of the need for construction [61]. The effect could be measured by evaluating existing construction needs in terms of the preliminary designs for buildings. These include the technical and environmental characteristics of the applied resources. Construction needs should be assessed in the planning stage based on any deviation in tenant requirements and urbanization rate. For example, building facilities and occupations may change dramatically after new tenant types, where the urbanization rate grows every year, and commercial buildings are required to provide spaces for multiple users [62]. Thus, the need for construction changes. Understanding and adapting to such new realities when considering the differences in work conditions, digitalization, and other external factors help to reduce the demand for the construction of high-rise, multistory buildings. The needs assessment will be required to incorporate advanced analytics because the occupational pattern will differ, i.e., hot-desking, utilizing the full capacity of a space, and renting workspace and not floorspace, where drones can deal with collecting the data and scanning the site.

Comparatively small-sized facilities using the modular construction principle would facilitate space management [63]. Spatial reversibility (renting, leasing, and renovating) could be a challenging but highly circular strategy in construction management utilization. Renovating a whole building for a similar purpose or reutilizing the building area through a shared, flexible workspace, coliving, or renting the space are identified as widely implementable circular practices due to the growing demand for land [63]. Image recognition and purity/quantity analysis, Blockchain, and 3D scanning technologies can be used for effective space allocation at the design and planning stage, while travel/property renting apps like Airbnb will be helpful after the building starts being used.

Social involvement includes evaluating employers, employees, and general shareholders' engagement, participation, and general awareness of the development of CE principles in the construction sector. The strategy reflects the importance of shareholder behavior changes and the established social norms for circular economy transition [64]. The effect could be measured by the industry's attitude towards existing substrategies, i.e., whether there is an awareness of product consumption, material reuse (different attitudes towards repair and refurbishment), and resource disposal (waste remanufacturing and recycling rates). The substrategies for social involvement include corporate and governmental perspectives. Clients, managers, and other operating bodies are fundamental actors in any transformation. Their awareness can be achieved by organizing professional development courses and workshops. Those actors involved in ordering and managing resources (e.g., owners, project managers, and field labor) should have priority in acquiring awareness and participating in a “circular movement” by changing their cost-driven mindset and position towards disposal [65]. For instance, VR can be operated to provide workers with a platform to train in a safe environment, where they can sense, analyze, and prevent potential hazards [42].

Setting corporate action plans and measurable goals would navigate the progress better while changing the business models to adapt to circular economy strategies [66]. The government’s green policies increase incentives by setting controls (taxes) or investing in ecoproduct production. For the transition to occur, they could change the taxation policies around consumption, set the rules for industrial strategies, consider environmental issues, and alter the building codes [66]. In order to track the changes and all the analytics of the Kemira Smart Process Management Transformation Capacity tool (TC), the evaluation tool is used when starting the preliminary design right through to the final design stage for the purpose of verifying the transformation capacity index [49]. Alternatively, deep learning tools, such as factor analysis algorithms and self-optimized recycling algorithms, are needed for the impact measuring and analysis of recycling activities.

4.3. Framework Validation: Preliminary Case Study

After the development of the final framework, it was tested on a construction company that operates in six different cities with more than 80 ongoing construction projects. Due to the COVID-19 restrictions, the validation of the final framework was carried out through an online survey among the project management decision-makers of the case study company. Next, the survey results were analyzed to form the existing observations and any possible recommendations. Further, an online workshop (1.5 h) was conducted where the results and the case study format and recommendations were discussed. A summary of the actual advancement in CE strategies and the existing limitations within the company is presented in Table 3.

The case study selection process is reflective of the nature of the construction industry in this particular context. The chosen company is the largest construction developer in Central Asia, with operations spanning the whole region at a high level of BIM integration (LOD-450). As one of the major regional players, this selection provides a comprehensive overview of the nexus of the digitization of the Circular Economy in Central Asia. The chosen company was also considered due to the availability of data pertaining to digitization, which is missing among other construction developers.

Since the materials and resources are one of the major expenditures in construction costs, three different digital instruments are being applied within the company in order to plan, monitor, route, and use different resources, which are summarized as (i) Building Information Modeling (BIM), (ii) web platforms for the planning and procurement of materials, and (iii) BIM instruments—the web platform for benchmarking and internal analysis.

Use of BIM. In 2018, the government of the Republic of Kazakhstan issued a governmental program named ‘Digital Kazakhstan’, which aimed to focus on three strategic directions: the digitization of different industries in the economy, the transition to a digital state, and the creation of an innovation ecosystem. This initiative created an opportunity to develop further digital instruments and motivated key construction market stakeholders to adapt their current strategies. As a result, the BIM department of the company was established with key responsibilities to (i) introduce the software to the line managers and project teams by conducting training and educational programs, (ii) analyze the existing project documentation and evaluate the project organizations work, and (iii) provide technical support for BIM models of the construction projects of the company. Recently, the company introduced BIM Cost, which mainly focuses on material planning, scheduling, routing, and organizing on the construction site. The tool helps to keep track of the construction materials, including technical specifications within one project documentation, through a centralized database during the design stage. Additionally, BIM Cost estimates the project’s construction cost, calculating the key metrics and boundaries of material usage, which are further established as a threshold. As a result, the company reduced its overconsumption.

This tool significantly improves resource management and planning as it allows users to control the material contribution and apply the respective measurement if needed. Moreover, there is also a sustainability advantage as the company tends to minimize its resource usage and produce the buildings in the most effective ways.

Table 3. Circular Economy readiness of the company.

CE Strategy	Digital Technologies Utilized
Resource Management	The company utilizes the Opera Built software, which connects the project team with the procurement service such that all the materials and resources can be planned and routed during the construction planning stage. The material or resource could be tracked, modified, and updated during the lock-up period time. This digital tool allows the user to effectively schedule the resource route and plan the use of durable materials with a long lifespan.
Building Management	The company utilizes Building Information Modeling (BIM) technologies for the project design. The tool is connected to a planning system such that all the construction value chain stages can be modeled in the software. The materials assessment (i.e., passports, technical characteristics, and features) is presented in BIM under each unique resource. The tool allows for the assessment of the current construction needs during the design stage by correlating the project with other demographic metrics.
Social Involvement	Currently, no significant digital technologies are utilized during the social involvement stage for both corporate and governmental entities. The regulations and actions regarding circularity are not digitized, but some initiatives stimulate future progress in the area.
Digitization	Overall, the company is actively utilizing digital tools during its operation in terms of the following stages: (i) project design (both structural and architectural); (ii) material management; (iii) project planning; (iv) internal communications; (v) corporate database on standards; (vi) operation of the building, and (vii) customer service.
Existing limitations and strengths of the company	
Limitations	Lack of a general understanding of CE principles and the implementation strategy.
	Relatively low and no measurable support from the executive staff.
Strengths	Strong and distinctive organizational culture.
	High technological progress compared to existing competitors.
	Distinctive strategic long-term goals that include technological advancement.

Web platforms for planning and procurement. The company has a unique platform that operates as a guide and helpful tool, connecting the project managers and the specialists from headquarters. The digital instrument operates as a centralized database that allows for the planning, ordering, and tracking of the site's construction materials and resources (resource management strategy). It allows users to track weekly reports on the initialization and construction stages of the project (building management strategy), evaluating the key indicators, such as the number of people on the site, the real-time costs of the project, and a rating of the subcontractors. According to the interviewees, this digital platform creates strong communication between operations and headquarters, significantly reducing losses in construction processes.

A web platform for benchmarking and internal analysis—BIM Instruments. Another significant tool mentioned during the case study session is the company's benchmarking platform, which allows for the evaluation of building management and material consumption during the project's construction stage. Typically, all the ongoing construction projects are regularly uploaded to the database, and the algorithm estimates the critical indicators for construction, following project documentation parameters. For example, the filter allows one to examine the current ratio of structural reinforcement to concrete ratio [kg/m^3], structural reinforcement to the total area ratio [kg/m^2], the variables on each project of the company (finished and ongoing), etc. Moreover, there is a specific matrix of the maximum consumption rates for each capital-intensive material during the different stages of the construction lifecycle, which allows for determining which projects make losses in terms of the materials. Once this happens, the headquarters organizes the project committee to create a plan for solving the current issues. The same approach is applied to construction time and the number of people on the construction site.

In terms of the social involvement of the related stakeholders, there is no particular digital instrument utilized within the company. Currently, the local government does not provide a reliable infrastructure to involve all market participants through digital platforms.

5. Conclusions

The construction sector is a capital-intensive sector responsible for a high amount of CO_2 emissions due to different activities in the building lifecycle, including, but not limited to, cement-associated activities and logistics. Considering the amount of waste generated by the construction sector alone, which poses risks to human health and contributes to climate change and the rising competition in the market, construction companies have started to reconsider their approaches. The new business models oriented around sustainability were developed to satisfy this demand. The CE promotes resource longevity and durability by keeping them in the loop for as long as possible. Materials with a long lifespan are selected for further implementation and potential reuse for another purpose or another project, while building spaces are served for multiple purposes.

This study develops a framework to facilitate the need for the transition to the CE and identifies the most appropriate strategies. During the development, several interviews were conducted to shape and validate the framework with academic and industry experts, while emerging technologies and Industry 4.0 tools, as enablers, were discussed. After the framework was developed and validated, a case study analysis on large-scale construction companies in Kazakhstan was conducted. The study revealed many potentials for implementing Industry 4.0 tools to enable circular practices. Particularly, the use of BIM instruments at the design and planning/scheduling stages for resource management, the use of big data with web platforms during the whole building life cycle, and the use of IoT devices at the construction and operation/maintenance stages for resource management were prominent. Meanwhile, manual analytical software was prominent in creating social awareness.

The framework offers practical insights for construction industry practitioners and helps to investigate several critical barriers. The first one is the lack of awareness among stakeholders, customers, and the public. The strategies to improve this issue involve managing media in creating awareness regarding environmental issues and the importance of the circularity model in construction, conducting local seminars and workshops to raise awareness of the CE, and increasing the level of public education among the population. The second issue identified is the lack of government involvement in terms of laws, regulations, and initiatives. Possible mitigation methods would include increasing the participation of governmental structures in the development of circular economy awareness through digital technologies, amending and revising the existing building rules and codes, and introducing new regulations in compliance with circular economy regulations. The third one is insufficient financial resources. The improvement strategies include activating proper and adequate budget distribution at the governmental level, introducing subsidies for sustainable/environmentally friendly projects, creating circular economy investment platforms, and stimulating the participation of international organizations. The last issue identified is the poor digital progress of existing companies. It would be possible to improve this by supporting digital infrastructure within existing companies, stimulating digitization among different organizational levels, and increasing communication within the organizations.

This study examined the framework using six industry and academia experts and validated it with a case study in a large-scale construction company. Increasing the sample and validating the framework using other variables, such as developed countries and medium- and small-sized enterprises, is recommended. The developed framework can be validated further by considering other stakeholders in the construction process. However, with construction companies being the major participants in this process, they will make a significant contribution to the development and application of a digital framework.

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