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A New Perspective for Construction Supply Chains in Digital Era

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Abstract

The construction industry is a highly labor-intensive industry with a low degree of automation and digitization. However, as in the manufacturing industry, a 'new order' is emerging for the way the construction industry works today. This study aims to present the transformation of construction supply chains (CSCs) in Industry 4.0 by considering each supply chain stage separately, where the main purpose is to determine the criteria for the integration of the CSC with the Industry 4.0 perspective. A literature review and a Delphi study were conducted, and thirteen criteria are proposed to show the integration of Industry 4.0 aspects and CSC stages. Furthermore, one of the multi-criteria decision-making (MCDM) methods, the Best-Worst method, is used to prioritize the criteria for guiding future implications during the transformation of construction supply chains. Among the six CSC stages, the design stage is the most important from the Industry 4.0 perspective. In addition, client collaboration by ICT (BIM) during the design phase is the most important sub-factors' overall rank. Although there is a limited number of studies on the CSC, there are no empirical studies addressing the current digital age approach. As a result, there is a significant gap in the construction literature, and a thorough assessment of the building supply chain in an Industry 4.0 setting is lacking. To the best of the authors' knowledge, this is the first study to illustrate the transformation of CSCs in Construction 4.0 by looking at each supply chain stage separately.

1. Introduction

The world has changed at an incredible pace as a result of the rapid adoption of various digital technologies. The third industrial revolution, i.e., computerization, has already become redundant. The newcomer, also known as Industry 4.0, combines and integrates numerous technologies to help industries create a digital working environment. Sebastian et al. (2018) [1] note that the fourth industrial revolution is essentially different from its ancestors by combining the physical, digital, and biological worlds. The new digital revolution emerges not only for firms but also for all stakeholders at all tiers of the supply chain, as well as the final customer.

The construction industry is a leading industry for almost every country's economy with its volume of business [2][3]. Construction, which comprises real estate, infrastructure, and industrial structures, is the world's largest industry, and the importance of the construction sector can be defined as the "engine of the economy" [4]. The industry and its ecosystem are worth 13% of the world's total GDP [5]. The industry's outputs, including as buildings and infrastructure, have a positive impact on our daily life and well-being. In spite of the construction industry's economic magnitude and the created benefit for humankind, the industry is being judged for several issues such as low efficiency, low labor productivity and resistance to change [6]. Besides, while construction projects' complexity is rising, quality expectations, cost and time pressures are forcing the industry to change [7]. One of the most significant improvements in the construction industry is implementing supply chain management methods with its associated benefits such as 'improving visibility', 'reducing waste arising from incompetent materials management', and 'eliminating waste caused by poor logistics' [8][9][10], to name a few. The implementation of construction supply chain management (CSCM) is relatively new, compared to several industries. Implementing CSCM solves various problems caused by the construction industry's peculiar nature and promotes improved market competitiveness, profitability, and reductions in costs[11][12].

Construction is known as a highly labor-intensive industry with a low degree of automation and digitalization. However, nowadays, as in the manufacturing industry, a "new order" is emerging for the construction industry's way of working. Infusing digital technologies into the built environment is the new challenge facing the industry. This new paradigm is called Construction 4.0 without consensus about its whole scope yet. Although the transition pace is relatively slow compared to other industries [13][14][15][16], the construction industry has become more automatized and digitalized since the introduction of Information Communication Technologies (ICT), Building Information Modeling (BIM), and Cyber Physical Systems (CPS), which can be named as game-changers for the industry. Consequently, it is expected that newly introduced technologies to the construction industry will reduce costs, improve productivity, and safety while enhancing sustainability [17] and market competitiveness.

There are some initial attempts for providing background information for the transition of construction supply chain (CSC) in Industry 4.0, for instance [18], conducted a pioneering systematic literature review. [19], propose a map of Construction 4.0 research using a systematic literature review approach. [3] offer a conceptual framework of Construction 4.0. They listed emerging technologies for Construction 4.0 by estimating these technologies' potential effects to the life cycle of a construction project. It has been observed that there have been some other studies on this subject. However, after an in depth analysis of the Construction 4.0 literature, these studies that have been conducted could not go beyond the discussion and very rear empirical work has been conducted in this area.

Construction supply chains perform successive stages and all the stages are not equally digitalization friendly. KPMG's Global Construction Survey 2019 presented a future-ready index. The survey claims that construction supply chain would be the weakness of the industry throughout the digitalization process [20]. How can construction firms prioritize supply chain stages as they transition to the fourth digital revolution? Prioritizing stages based on future-readiness in terms of digitalization could be a valuable contribution to the literature and the policy-makers in the industry. This study aims to contribute to the existing literature by introducing the digitalized construction supply chain by presenting the main and sub-criteria for digital transformations in the construction industry. In addition, another important difference of this study is to reveal which elements of the construction supply chain are prominent in the fourth industrial revolution by conducting empirical research with the established criteria.

Thus, this study considers the following research questions to contribute to the literature:
How shall we prioritize the CSC stages in the transition of Construction 4.0?
What is the rank of sub-criteria of CSC stages for the integration of Industry 4.0 aspects?

From this point of view, this study aims to present the transformation of CSCs in Industry 4.0 by considering each supply chain stage separately. In order to do that, an in-depth analysis of literature review and a Delphi study are conducted to determine the main and sub-criteria for transformations of the CSC in Industry 4.0. Later, we analyze and figure out the relationship among the criteria of the CSC in Industry 4.0. To achieve these aims, one of the multi-criteria decision-making (MCDM) methods, the Best-Worst method, is used to prioritize the criteria for guiding future implications during the transformation of CSCs.

The article starts with an introduction part. In Section 2, a brief overview of the theoretical background related to CSC and the stages of CSC are given. Then, in Section 3, CSC in Industry 4.0 is presented by including proposed criteria. In the next section, details of the methodology used in this article are highlighted. In Section 5, implementations of the study are presented. Section 6 gives the results of the study. An finally the last section includes the conclusions.

2. Theoretical Background

Theoretical background of this study consists of two sub-sections. Firstly, details of CSCs are given, secondly stages of CSC are explained.

2.1 Construction Supply Chain

Construction is one of the main industries for economic growth [21], financial growth and development of the countries [22]. Not only the socio-economic situation but also civilization and livability of countries are improved through the instruments of the construction industry. However, construction industry is widely criticized for following issues: low performance [11], adversarial relationship between stakeholders [23], fragmentation [24], complexity [25], harsh working environment [26], high inefficiency [27], instability [28], lack of mutual trust [29], lack of process standardization [26] , lack of mutual information exchange [3], low labor productivity [13], low level of profitability and price-based selection [23] low level of automation [30], , resistance to change [31], rigid culture and uncertainty [25], short-term thinking [32]

Traditional project delivery practices in construction generate numerous challenges, and supply chain management methods are seen as a remedy by several construction professionals. [28] claimed that CSCM is a useful approach to achieve integration among the stakeholders of the chain. Ensuring the appropriate communication infrastructure among project partners results in better performance [33]. [34] defined CSCM as: "the integration of key construction business processes, from the demands of the client, design to construction, and key members of the CSC, including client/owner, designer, contractor, subcontractor and supplier". [9] identified CSC as 'from supply points to the construction site'. According to [35], "CSCM is a specialized variant of SCM which is designed for the unique characteristics of the construction industry". Some of the benefits of implementing CSCM are: improving construction performance, adding more customer value, reducing overall costs, reducing inefficient materials management [34] and reducing sources of uncertainty [32].

CSC literature is becoming more sophisticated progressively. [36] applied a case study approach to show the effects of strategic partnership in CSCM. They found that an integrative supply chain management approach is needed in the construction industry. [31] reviewed twenty popular studies on CSCM and also conducted qualitative research by using a triangulation approach. [37] presented a systematic literature review (SLR) to comprehensively define green supply chain management in construction. [38] conducted a critical literature review to create a taxonomy for the precast supply chain, which is a subset of CSCM. [39] proposed a methodology that combines AHP (Analytic Hierarchy Process) and GRA (Grey Relational Analysis) to ensure a supplier selection framework for resilient construction. [18] studied an ETO (Engineer-to-order) construction supply chain to ensure real-time master production schedules via implementing a discrete event simulation method. [40] applied the DEMATEL (Decision-Making Trial and Evaluation Laboratory) technique to promote customer-supplier relationships within construction supply chains via understanding barriers that prevent collaboration within supply chains.

2.2 Stages of Construction Supply Chain

Although several scholars have made different classifications (e.g., Mohamed et al. 2010; Lu and Yuan 2011), the main stages of a CSC are considered in this study to be (1) Design, (2) Tendering, (3) Procurement, (4) Construction, (5) Maintenance, and (6) Recycle/Demolition. In the following, each stage of the CSC is explained briefly.

The design stage is described as the stage where the appearance and dimensions of the building are determined (Chaudhary, 2018). Tailored solutions for the client are realized at this stage. Information sharing has occurred in a circular form during the design stage among project stakeholders [41]. The most important criticism of the design phase is its separation from the construction phase. Because of fragmentation and lack of communication, design professionals may complete the design regardless of its constructability. Delays and disputes have occurred during the construction process due to the separation of design and construction phases [42]. When design errors are discovered after finishing the design phase, rework is inevitable most of the time. Conflicts and disputes among project stakeholders result in poor planning and incorrect design documents afterwards [33]. In spite of this, the early involvement of the project stakeholders in the design phase has resulted in better functioning regarding constructability, cost, quality, and end-user satisfaction [41].

[43] defined tendering as the preparing, publishing, and executing of tender documents by the awarding party. It is commonly believed that one of the major effects of the inefficiency of the construction industry is caused by tendering [44]. Transparency and integrity are important issues for the tender process [45]. It is reported that there is a need for accountability and transparency, especially in public procurement [46].

Procurement means conveying materials, equipment, workforce, knowledge, and supervision to the construction site [8], [47] Procurement connects the supply and demand sides of the construction supply chain [47]. The need for effective materials management has been widely recognized throughout the construction industry community. Procurement generally is done under the material flow defined in the project time table and quantity report. In this way, the material storage period on a construction site can be shortened. It leads to decreasing stocking costs, internal logistic activities, and security risks at the site.

Construction is on site realization of the design [1]. The construction phase should be completed in accordance with construction documents, namely drawings and specifications, which are agreed upon [48].

Critical activities for construction are scheduling, site coordination and management of resources, materials and logistics [32]

Maintenance for CSCM can be defined as preserving the building to optimally operate during its useful life. The role of maintenance is ensuring a safe and healthy environment, optimizing the performance of the building and preventing degradation, to name a few. When maintenance fails, the facility starts to deform. This deformation could cause several problems, such as safety problems and unhealthy settings. The maintenance phase causes the largest costs throughout the construction project management lifecycle. However, the maintenance phase is neglected mostly during the design phase. Broadly speaking, operation and maintenance professionals' preferences are excluded.

The construction industry has a positive impact on the liveability of the cities and helps increase the prosperity and comfort of society. Despite this, the sector is a large waste producer in terms of land depletion and deterioration at the same time. The construction sector improves city liveability and contributes to society's prosperity and comfort. Construction demolition activities cause environmental degradation. Due to increasing urban renewal projects all over the world, the need for demolition has soared. After finishing the useful economic life of a building, demolition of the building takes place. While helping the economic and social development of countries, the construction industry needs to recycle demolition waste due to today's sustainability sensitivity. Demolition waste is one of the main polluters in the world [49] and needs to be not only disposed of in the landfill but also recycled where possible to reduce its environmental footprint.

3. Construction Supply Chain Transformation in Digital Era

When compared to other industries, the construction industry is relatively slow and has been resistant to the adaptation of new technologies. Furthermore, it is usually seen as more risk-averse and fragmented [50]. Due to the bespoke demands of clients, construction projects are one-off in nature, and standardization of the construction processes is always an issue. [51] stated in his review "Modernise or Die" that the construction industry has not yet finished its evolution to reach Industry 3.0 transition. Indeed, for the past 50 years, the industry has relied on manual labor and mechanical technologies [52]. However, in order to keep pace with new industrial trends, the construction industry should also adopt technologies derived from the new industrial revolution. With the rise of construction projects' complexity and project data volume [20], execution of the projects efficiently without exploiting cutting-edge digital technologies is almost impossible.

From a broader perspective, the impact of Industry 4.0, or in other words, digitalization, does not only alter the industry by itself, but will reshape the entire CSC structure. Construction 4.0 is the reflection and industry-specific version of Industry 4.0. [26] defines "Construction 4.0" as a combination of CPS and a digital ecosystem. With the Industry 4.0 point of view, automation in the construction industry has started to be integrated with the regular construction processes, and especially advanced sensor technologies and BIM would help the evolution of the processes [53]. A fundamental change in the construction industry can be achieved by using automation technologies, which have the potential to reduce costs, decrease durations, improve quality, and reduce the need for manpower [54]. As a response to implementing Industry 4.0 at the building site, Construction 4.0 offers optimization of time, cost reduction, and safety by collecting real-time data and the usage of on-site sensors [13]. Due to the complex structure of CSCs, a great effort is needed for the coordination, which reveals the potential benefits of Industry 4.0, such as digital data, automation, connectivity, and digital access [7][18]. Digital technologies are gradually changing how built assets are designed, constructed, operated, and maintained [52]. Moreover, according to the pioneering systematic literature review by [25], BIM has appeared as the main digital technology as a facilitator for several technologies, and it is followed by concepts like CPS, modularization and robotics, mobile computing, RFID (Radio Frequency Identification), and Product Life Cycle Management in CSCs [55]. Furthermore, Industry 4.0 technologies for smarter construction as robotics, automation, augmented reality (AR), virtual reality (VR), and mixed reality, discrete event simulation, and digital twins.

During the third industrial revolution, CAD was one of the main technologies for the construction industry. However, nowadays it is understood that BIM conquers CAD's importance. BIM provides 3D (dimension), 4D, 5D, and even 6D digital representations of building structures and simulation features [26] to ensure and facilitate a more efficient and collaborative CSCM by reorganizing information flow among all project stakeholders. BIM also leads to transparent and productive CSC [56]and provides digital representations for the whole life cycle of a construction project. To clarify, BIM appears across the whole construction management stages, from the concept phase of designing, then engineering, planning, construction, and finally handing over the building to the client [57] Using BIM is becoming compulsory for public infrastructure projects in Germany (as of 2020), the UK, the Netherlands, Denmark, Finland, and Norway [7]. Despite this, implementation of BIM has been slower than expected [58].

Adoption of CPS makes possible the combination of old and new industrial and communication technologies. A CPS combines computation, communication, and storage capabilities to construct a cyber space while containing sensors and actuators as part of its physical system to ensure real-time data [59], and to create a networked world with intelligent objects [26]

Potential benefits or applications of Industry 4.0 are not well known in CSCs, and there is a need to define potential benefits of Industry 4.0 in CSCs by considering all the supply chain stages, i.e. design, tendering, procurement, construction, maintenance, and recycle/demolition. Digital technologies are expected to change all processes fundamentally, and new business models are essential to transform traditional CSCs into digitally integrated ones [60]

As the starting point for CSC, the design phase provides important insight into the rest of the supply chain. 3D printing (also known as additive manufacturing-AM) is a technology that could be beneficial for CSCs, especially in the design phase, where individualized products can be produced with nearly zero marginal cost, and virtualization can be used in construction engineering [61]. Compared to traditional manufacturing processes, AM makes it easier to create customized, complicated geometries. AM techniques also give architects more flexibility in developing complex shapes, making it much easier and less expensive than subtractive and formative processes). Land surveying is one of the preparation phases before starting the construction phase to understand land conditions and boundaries. Differences between land survey estimates and actual ground conditions could lead to time delays and overruns for construction projects. Surveys are used during the design phase to establish the foundation for a precise design and to identify any potential bottlenecks. Several digital technologies are in use for high-definition land surveying, such as Light Detection and Ranging (LiDAR) systems, drone-mounted LiDAR systems, and 3D laser scanners. These methods could improve both data accuracy and speed [62]. When clashes (the detection of any undesired intersection between building elements) are discovered during the construction phase, cost overruns and time delays are inevitable. BIM provides clash detection during the design phase to overcome difficulties caused by clashes such as excess material purchases, delays, and remakes, and enhances constructability [63]. Redesign and modification need that arise when the client is not included in the design process as required cause inefficiency and losses. Collaboration is one of the building blocks of the CSC and needs to be supported with seamless information exchange among stakeholders of the projects [64]. BIM can foster client participation in the design phase to achieve collaboration among CSC parties via an open communication atmosphere [56] [65]. Incorporating the client into not only the initial briefing of the project but also the design phase is possible through BIM, which supports collaborative design technology [66].

With the aid of digital technologies, e-tendering practices have been increasing in the construction industry [67]. Moreover, e-tendering practices can be used in order to achieve integrity and transparency through digital technologies [68]. Blockchain technology can also be integrated with the tendering activities to increase the security and reliability of the CSCs [69] [70] offered a tender price evaluation based on big data.

The procurement stage has a critical role in the CSC. [68] made a comprehensive literature review to identify digital technologies for construction procurement. They divided the procurement stage into six sections and suggested several technologies for each section to use to digitalize and facilitate procurement activities. Smart contracts by using blockchain technology could improve payment systems in construction procurement [71]. Blockchain technology provides transparent and accurate transaction records on a shared ledger which improves trust (Mason and Escott, 2018). In brief, BIM, blockchain, big data, e-market places, cloud-based platforms are some of the technologies being used for procurement activities during the Construction 4.0 transformation [72]

In a nutshell, the construction stage is the actual execution of the architectural design. There are several tasks to be accomplished, and digitalization may facilitate the overwhelming workload of the construction stage. Many construction projects are affected by cost overruns and schedule delays [73]. As a result, site monitoring is critical for identifying construction progress in accordance with the project timeline. Monitoring of a construction project is traditionally possible with the daily reports of site surveyors. These reports are used as data to obtain tracking reports from the project time table/schedule. Tracking reports mainly give results for time, resources, manpower and machine usage, and cost. Despite that, traditional monitoring methods of building activities at construction sites are claimed as being ineffective [74]. In recent years, lots of mobile devices and applications for BIM have been developed for real-time site monitoring to improve accuracy and speed. [75] presented a drone-aided augmented reality system for construction site monitoring and documentation. Nowadays, mobile augmented reality and mixed reality technologies have been used for construction project tracking [76] [77]. [78] offered the usage of CPS for gathering data to prepare construction progression reports. Support of ICT is important, where improvements in processes by reducing waste [79], enhancing predictability, reducing defects, and eliminating accidents are possible through these technologies. In line with this, challenges related to data collection and sharing can be overcome by computing technologies, where the location of materials, labor, and equipment can be known in a real-time manner. Today's enabling technologies, such as robotic construction, are more developed and capable of facilitating the anticipated disruption. However, in the near future, the high complexity and dynamic conditions of building sites and the high cost of sensors will limit their adoption across the construction industry [14]

Multiple stakeholders would be involved in the maintenance stage, and comprehensive information would need to be documented such as historical operations and maintenance records, facility performance, and exact locations [80]. IoT-based predictive maintenance solutions [81]; and augmented reality applications in maintenance activities by process visualization could be beneficial to provide safety and security-based site visualization for safe and secure maintenance [81]. Because they are linked to the physical structure, digital twins of buildings are the most advanced level of digitization for preventive and predictive maintenance [3].

Industry 4.0 technologies are not only used for production activities, but also have benefits for the end of life (EoL) activities. For the CSCs, the recycle/demolition stage could be improved by the support of Big Data in terms of planning the EoL activities. In addition, the increased traceability through Industry 4.0 technologies could be used for tracking and managing construction waste statistics by data acquisition for environmental goals [82]. [83] developed a robot for automatically sorting construction and demolition waste. [84] benefited from 4D BIM, which ensures visual planning of construction waste.

3.1 Proposed Criteria for Construction Supply Chain 4.0

One of the main challenges of the study is determining which technology should be included in which CSC stages. This is because several technologies overlapped among stages and applied more than one stage of CSC. From this point of view, a wide list of Industry 4.0 and Construction 4.0 technologies and areas of usage in accordance with CSC stages are selected both from literature and the construction industry related reports [5][7][20] By scrutinizing both academic and industrial resources we expect to present the real need and near future perspective of the global construction industry to transform Construction 4.0.

After selecting the preliminary list, we decided to choose the expert panel for Delphi study among international contractors' employees to prove the reliability of the expert panel's opinion. Thus, we prefer to choose our panel from among Engineering News-Record (ENR) international Top 250 contractor list. This annual list ranked companies according to their construction related revenue generated outside of each company's home country in previous year in U.S. $ millions. Because of their international project execution experience and their insights about the industry's future developments.

Because the study was carried out in Turkey, we refined the list to filter out Turkish contactors who are included in ENR 2020's top 250 international contractors. 44 Turkish contractors are listed between the ages of 23-236. Among these 44 companies, ten middle/top-level managers are reached by the judgmental sampling method to conduct the Delphi study. The data collection was conducted between May and July 2021. The Delphi study has finished after two rounds when no further insights were gained at the second round. We sent the list via e-mail to the respondents. The list consists of the criteria associated with CSC stages.

The respondents are being asked to limit their final criteria list by choosing up to twenty criteria, in order to present a prioritized lean list for both academia and practitioners at the end of the BWM implementation. The experts are given three rules to eliminate the proposed criteria: (1) if the criteria are not applicable for their company in the near future (at most two years; the reason could be various such as high implementation cost, non-existent of skilled work-force etc.); (2) Although one of the proposed criteria is currently in use at their company, if the experts do not believe it is a game-changer for their company's global competitiveness. (3) If the criteria are not evaluated as a good option for the industry's future prospects. Finally, if one of the experts eliminates a criterion, this criterion is deleted from the preliminary list. Table 1 shows the CSC stages, areas of usage and related technologies.

Table 1 *Preliminary List of Criteria*

Design	Tendering	Procurement	Construction	Maintenance	Recycle/Demolition
Land surveying with drones & Lidar & 3D lasers [7][62])	E-tendering to achieve integrity and transparency [67][68]	BIM based e-procurement to strengthen collaboration throughout the supply chain [72]	Real time monitoring of site progression [20][77]	IoT based predictive maintenance [81]	Waste management by using 4D BIM [84][100]
BIM based Clash detection for enhancing constructability [63]	Integration of Blockchain in tendering][69][87]	Cloud base platforms for stakeholder data integration [88][89]	Human machine interaction during the construction (Robotic Automation) [92]	Augmented reality based site visualization for safe and secure maintenance [77]	Planning EoL activities through the support of Big Data [18]
Client collaboration by ICT (BIM) during the design phase [56][65]	Tender price evaluation of construction project based on big data [70]	Smart Contracts enabled by Blockchain [71][90]	Real Time locating systems (RTLS) for worker safety and productivity [93][94][95]	Location based asset tracking by creating a digital twin [80][96]	Tracking and managing construction waste statistics by data acquisition for environmental goals [82]
BIM aided Generative design to optimize design process [85][86]		Real time communication with subcontractors [91]	3D printing to fabricate the formwork and parts [7]	Edge computing for quick alert reaction to emergencies [98][99]	Robots for sorting construction and demolotion waste [39][83][101]
		Forecasting of the quantity needed materials [24]	Extended reality (XR) for remote collaboration and coordination among offsite and onsite teams [7][97]		
		E-market places [7][68]			

After the elimination process via Delphi study, we identify a total of thirteen sub-factors by consensus those are grouped into six CSC stages. In Table 2, these final criteria are presented with academic studies and industry reports that are supported by.

Table 2 *Main and Sub-Criteria of the Study*

CSC Stage Factors	Sub-factors
Design	(C1) Land surveying with cutting edge technologies (drones & Lidar & 3D lasers)
	(C2) Client collaboration by ICT (BIM) during the design phase
Tendering	(C3) E-tendering to achieve integrity and transparency

		(C4) Integration of Blockchain in tendering
	Procurement	(C5) Real-time communication with subcontractors through mobile devices
		(C6) Cloud base platforms for stakeholder data integration
		(C7) Forecasting of the quantity of the needed materials by using intelligent systems
	Construction	(C8) Real time monitoring of construction progression on site.
		(C9) Real Time locating systems (RTLS) for worker safety and productivity.
	Maintenance	(C10) IoT based predictive maintenance
		(C11) Augmented reality based site visualization for safe and secure maintenance
Main Factors	Recycle/Demolition	(C12) Planning EoL activities through the support of Big Data
		(C13) Tracking and managing construction waste statistics by data acquisition for environmental goals

In the following section, before moving to implementation of the study, details of the methodology are presented.

4. Methodology: Best Worst Method

The Best Worst Method is one of the novel comparison-based MCDM methods. BWM was developed by [102] to derive the weight of each criterion. Some of the important studies are as follows: [103] applied BWM to find the best suppliers from among the qualified suppliers based on the environmental criteria. BWM is also used to rank the airports based on the relative performance criteria [104].[105] chose the BWM to define relative importance of technology dominance factors. BWM has some important benefits comparing to other models. The most important one is that BWM needs fewer data points to comprise the criteria [106], and it has a simple procedure. Because of these features, in this study, BWM is adopted to compute the weights of each criteria in the CSC stages based on the Industry 4.0 aspects.

The application steps of the BWM are as follows;

Step 1. Decision makers determine the most appropriate decision criteria for the problem. In addition, a set of criteria is created.

Step 2. The decision makers determine the best and worst criteria from the set of criteria. The best criterion means the most desirable or the most important criterion. The worst criterion is the least desirable or least important criterion.

Step 3. A pairwise comparison best to others matrix is created by the decision makers. Decision-makers compare the best criterion with other criteria using a number from one to nine (one is equally important and nine is much more important).

$C_{\mathrm{b}} = (c_{\mathrm{b}1}, c_{\mathrm{b}2}, \dots\dots, c_{\mathrm{b}_n})$ where c_{bj} is the preference of the best criteria b over the criteria j.

Step 4. A pairwise comparison *worst to others* matrix is created by the decision makers. Decision-makers compare the worst criterion with other criteria using a number from one to nine (one is equally important and nine is much more important).

The pairwise comparison vector is;

$C_{\mathrm{w}} = (c_{\mathrm{w}1}, c_{\mathrm{w}2}, \dots\dots, c_{\mathrm{w}_n})$ where c_{wj} is the preference of the worst criteria w over the criteria j.

Step 5. Determine the optimal weights of the each criteria

$$(w_1^*, w_2^*, w_3^*, \dots\dots, w_n^*)$$

To find the optimal weights of the each criteria, the maximum absolute differences for all *j* should be minimized.

$$\text{minmax}\{|\, w_b - c_{bj}\, w_b|, |\, w_j - c_{jw}\, w_w|$$
$$\sum_j W_j = 1$$
$$w_j \geq 0, \quad \text{for all } j$$

To solve this model, the minmax model should be transferred to the linear programming problem:

minmax $\mathcal{E}_j$	(1)

Subject to

$\lvert w_B - c_{Bj} w_j \rvert \leq \mathcal{E}$	(2)
$\lvert w_j - c_{jw} w_w \rvert \leq \mathcal{E}$	(3)
$\sum_j W_j = 1$	(4)
$w_j \geq 0, \quad \text{for all } j$	(5)

5. Implementation and Results

The main purpose of this study is to determine the criteria for the integration of the CSC with the industry 4.0 perspective. In addition, the weights of these criteria and their importance will be determined.

Firstly, the evaluation criteria are extracted from a detailed literature review. 26 criteria in total have been identified from the literature for CSC and industry 4.0 integration. Then, these 26 criteria were reviewed with the Delphi study formed by experts in the field. As a result of expert opinions, a total of thirteen criteria consisting of six main headings (design, tendering, procurement, construction, operation and recycling/demolition) were determined and the criteria table in Table 1 was finalized. Lastly, in order to evaluate the criteria stated in Table 1, ten employees from the construction industry were consulted.

The nature of the multi-criteria decision-making models implies that the consistency of a homogeneous group is not different from the inconsistency of the most inconsistent individuals in the group. Therefore, in these models, the number of experts involved in a decision should not be more than seven [107]. The experts in the Delphi study were selected based on their experiences in the industry, who have at least ten years of experience in the field. The experts were selected from the management positions of companies operating at an international level. Table 3 shows the demographic information about the experts.

Table 3 *Information about the Experts*

Experts	Area of Expertise	Fields of Activity	Experience	Position
1	Civil Eng.	Infrastructure	11	Project Manager
2	Structural Eng.	Prefabricated Buildings	13	Construction Manager
3	Civil Eng.	Industrial Buildings	19	Project Director
4	Civil Eng.	Construction and Installation	10	Deputy Project Manager
5	Structural Eng.	Real Estate Development	14	Business Development Manager
6	Civil Eng.	General Contracting	11	Project Manager
7	Civil Eng.	Engineering And Contracting	18	Regional Manager
8	Architect	Engineering and Construction	25	Project Consultant

9	Structural Eng	Construction and Commitment	17	Director of Strategy
10	Structural Eng	Infrastructure	15	Operations Director

Table 4. *Local Weights and Ranks of the Analysis*

CSC Stage Factors	Local Weights	Rank	Sub-factors	Global weights	Global Rank
Design	0,379	1	- Land surveying with cutting edge technologies (drones & Lidar & 3D lasers) - Client collaboration by ICT (BIM) during the design phase	0,031 0,158	6 1
Tendering	0,221	2	- E-tendering to achieve integrity and transparency -Integration of Blockchain in tendering	0,030 0,012	7 11
Procurement	0,112	4	-Real time communication with subcontractors through mobile devices - Cloud base platforms for stakeholder data integration - Forecasting of the quantity of the needed materials by using intelligent systems	0,070 0,026 0,016	2 8 9
Construction	0,147	3	- Real time monitoring of construction progression on site - Real Time locating systems (RTLS) for worker safety and productivity	0,055 0,038	3 4
Maintenance	0,088	5	- IoT based predictive maintenance -Augmented reality based site visualization for safe and secure maintenance	0,038 0,012	5 12
Recycle/ Demolition	0,052	6	- Planning EoL activities through the support of Big Data - Tracking and managing construction waste statistics by data acquisition for environmental goals	0,016 0,004	10 13

First of all, experts were sent an e-mail and asked to choose the best and worst criteria from the industry 4.0 perspective within thirteen criteria. Later, they were asked to compare the best and worst criteria, from one (equally important) to nine (extremely more important) with other criteria. The information obtained from the feedback of ten experts, who were given a period of one week, was also used in equations to be used in the BWM. To use BWM equations, a unique integer mathematical model has been developed and run by CPLEX 9.1 on a computer with a Pentium 42.8 GHz processor and 1 GB of RAM.

According to results, Table 3 shows the local weights of the analysis. As demonstrated in Table 4, design has been selected the most important main factor among the CSC factors. Then tendering, construction, procurement, operation/maintenance and recycle/demolition are respectively.

To test the reliability of the analysis results, the mean and consistency values should be checked. The consistency value of ε should be close to zero which shows the reliability of results. Almost all values are very close zero in Table 5, so high reliability is revealed.

Table 5 *Mean and Consistency Values of the CSC's Criteria*

	Design	Tendering	Procurement	Construction	Operation	Recycle
Mean	0,083	0,095	0,333	0,312	0,258	0,195

ε	0,416	0,271	0,069	0,375	0,428	0,608

In the next section, the results extracted from the BWM will be presented, and the findings will be discussed. Suggestions and recommendations are also given for construction industry professionals based on these results.

6. Discussions and Implications

In this study, multi-criteria decision-making analysis has been employed to prioritize the CSC through six stages and to rank the sub-factors for the integration of Industry 4.0 aspects. The results of the study are intended to provide some insights to facilitate CSC's transition to Industry 4.0. As it is seen, this is not an industry-wide study. However, we tried to encapsulate an overarching panel from a wide range of professional backgrounds with international expertise to represent the industry's overall position.

According to the results of the study, the highest weight among the CSC stage factors is design, and the lowest is recycle/demolition (Fig. 1).

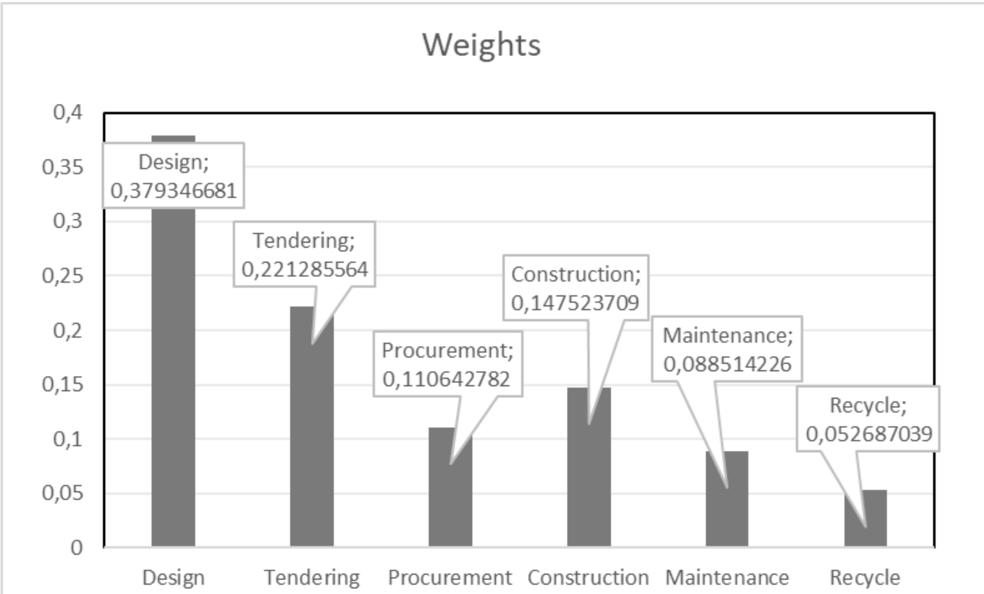

Fig 1 *Weights of main dimensions*

Improvements to be made at the design stage are a critical component of Industry 4.0 applications. Design has been selected as the most important criterion, which means that construction firms could prefer to attempt the digital transformation of the design phase in the first place. Actually, design is the most suitable phase to implement the Industry 4.0 transformation because it is where smart technologies can effectively demonstrate themselves. [108] state that the construction industry exists with bespoke projects led by one-off designs. When the design phase is digitalized, more quality, speed, and accuracy will be achieved.

Surprisingly, tendering is selected as the second important criteria among all CSC stages. According to [109] tendering is led by arm's length relationships with limited information sharing. [44] point out that the primary reason for ineffective applications in construction is improper tendering practices. This limited information sharing could be overcome by a transparent tendering process. Paper-based tender methods are still alive in some countries, which are time-consuming [45].For an average-scale construction project, hundreds of goods should be procured in accordance with the schedule and the project budget. E-tendering allows effective purchasing conditions, creates an ultimate competitive supply, and leads to just-in-time (JIT) delivery on site. These advantages are some of the reasons for being in second place. Consequently, tendering needs to be more digitalized for better performance of the whole industry.

Construction is ranked in third place based on the analysis. The construction stage is known as the most labor-intensive and least digitalized stage of the CSC. From the so-called "brick and mortar" industry to become a digitalized one needs too much effort, especially for the construction phase. With the aid of digital technologies, construction processes are projected to become more standardized, consolidated, and integrated. According to [27], automation could improve productivity in the construction phase, but adoption of these technologies incorporates high commercial and technical risks.

Maintenance is ranked in fifth place. It may appear to be a contradiction, yet buildings cost more to maintain than they do to build. Typically, operations and maintenance consume 75% of a building's total cost. Therefore, the maintenance phase deserves more attention and effort to be digitalized.

It's hardly unexpected that the recycling/demolition stage is ranked last. This is due to the fact that this phase has received the least attention from both academics and practitioners.

When the results related to each sub-criterion is analyzed, client collaboration by ICT (BIM) during the design phase (C2) occupies the first rank after the implementation of the BWM. The success of a construction project is dependent on the communication and interaction of project partners. BIM is a revolutionary breakthrough that changes the way construction projects are delivered. BIM ensures better design and visualization, improved communication and more effective collaboration. Because it leads designers to more accuracy and ease of decision making on a multidisciplinary platform.

One of the basic requirements for construction is project progression tracking. Due to this necessity, real-time monitoring of construction progression on site has the third level global rank. This is understandable, as monitoring is required for effective and efficient labor, plant and equipment, and material cost management [110]. Monitoring is typically accomplished through the use of project management software and its mobile applications. It was able to adapt to the construction industry early compared to other criteria because it was an easily accessible and cost-effective tool that met a requirement.

In the region where the study was carried out, "Planning EoL activities through the support of Big Data" criterion came in 10th place rank, because there is no legal regulation in accordance with the recycling principle of construction waste management yet.

Among all the thirteen sub-factors, "Tracking and managing construction waste statistics by data acquisition for environmental goals" (C13) takes the last place. Although its importance was understood by the panel, it remained in the last place due to the fact that the rate of recycling was not yet at the desired level all over the world. Although promising, tracking and managing construction waste statistics was seen as the least important. Construction 4.0 and seven of its most often mentioned technologies, according to [111], include integrated BIM, AR, VR, robots, 3D printing, AI, and drones. Our analytical results are remarkably comparable to those of El Jazzar et al.'s study. BIM, augmented reality, and drones are among the technologies chosen as sub-factors.

7. Conclusion

Despite the importance of the construction industry in the economies of countries, the industry is recognized for its reliance on old business methods and inefficient use of technology. Alongside hospitality, agriculture and hunting, construction is one of the least digitalized industries (Agarwal et al., 2016). Market conditions and industry dynamics shaped the construction industry's slow digitalization as an outcome (McKinsey, 2020). Digital disruption has been slowly affecting the construction industry and its ecosystem. Fundamental digital changes are needed to take place in the construction industry. For this reason, the construction industry has started to push new boundaries in order to attain Construction 4.0.

Many of the latest reports and scholarly articles prove that the construction industry has lagged behind in terms of digital transformation. The industry needs to embrace new technologies to boost productivity in order to avoid losses in both time and money. The digital transformation is dependent on the incorporation of cutting-edge industry 4.0 technologies into building project procedures.

We believe that scientific research on Construction 4.0 requires both detailed analysis and the prediction of possible future technological trends. So, we conducted an extensive Delphi study with 10 panel experts, including industry professionals. We identified 13 sub-factors that must be addressed to enable Construction 4.0 under six categories.

This study is the first attempt to examine the supply chain stages separately and try to offer the most beneficial technologies to the industry's professionals. We believe that our findings have significant implications. Although the unique nature of projects, the adversarial relationships between stakeholders, and technical difficulties of standardization of construction decelerate the pace of the transition to Industry 4.0, the current research on digitalization of construction is an emerging issue with full potential for both researchers and practitioners. The construction industry should apply Industry 4.0 technologies in accordance with its unique nature. All technologies do not fit into the industry that fits into other industries.

Finally, the industry has been struggling to fully embrace technological advancements (KPMG, 2016). However, the future in the construction industry is promising. Implementing digital technologies throughout all the CSC stages can unlock the full potential of the industry. One of the most important thing is that all CSC phases should not work in isolation but rather as part of a larger cyber-physical system.

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Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** Ozlem Koctas-Cotur*; Yesim Deniz Ozkan-Ozen* ***data collection:*** Ozlem Koctas-Cotur*;* ***analysis and interpretation of results:*** *Yucel Ozturkoglu,;* ***draft manuscript preparation:*** Ozlem Koctas-Cotur*; Yesim Deniz Ozkan-Ozen, Yucel Ozturkoglu. All authors reviewed the results and approved the final version of the manuscript.*

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