Supplemental Materials

Table S1. Descriptions and sample applications of Construction 4.0 technologies.

Technologies	Descriptions	Sample applications in construction
Laser scanner/3D Scanner	It is a type of scanner that can contain both color and depth information of the scanned image.	The scanner can implement 3D recording of construction sites with the scanner [1].
	It can automatically identify and track tags attached to objects, such as tracking transportation during construction.	Bluetooth, Wi-Fi, Ultra-Wideband (UWB), and Near Field Communication (NFC) are applied for communication on construction sites [2].
Sensors and actuators	They are devices for data collection using the reflection of the waves with different wavelengths.	Different sensors record different types of data during construction. For instance, thermography sensors are applied to improve building envelope thermal performance [3].
Unmanned aerial vehicles (UAV/drone)	It is an aircraft without a human pilot on board and is usually known as a drone.	It can capture images to provide construction information, such as 3D point clouds or RGB images, without on-site inspection for construction progress monitoring [4].
New materials	They refer to advanced materials, such as nanotechnology, which are innovatively applied in industry.	Advanced materials for a circular economy can be applied in product life cycle management [5].
Building Information Modeling (BIM)	It is defined as "a digital representation of physical and functional characteristics of a facility" by the National Building Information Model Standard Project Committee of the United States [6].	BIM 3D models can be applied to visualize building components, optimize buildings' performance, and help improve the project delivery process [7].
Additive manufacturing (3D printing)	It is defined as "the process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" by the American Society for Testing and Materials [8].	It can provide 3D-printed buildings with unlimited shapes to be constructed using innovative materials to replace human labor [5].
light detection and ranging (LiDAR)	It is a method for determining ranges by measuring the time for the reflected laser beam to return to the receiver.	LiDAR can provide 3D spatial relationships of objects, such as buildings and roads, surveying before and during construction [9].
Artificial intelligence (AI)	It is an area of computer science that enables machines to generate intelligence that helps them to work and react like humans.	It can be applied for automation in construction, such as modular or temporary construction object detection for risk management [10,11].
Virtual Reality (VR)/ Augmented Reality (AR)/ Mixed Reality (MR)	VR works to generate entirely computer-generated environments that allow users to sensate of being complemented immersed in the virtual environment. AR is a technology that enables the overlay of digital information onto the real environment to enhance the real environment. Finally, MR refers to a virtual continuum or the spectrum whereby different technologies exist with the mix of VR and AR.	In the UK's AEC industry, AR and VR are considered as crucial new technologies to facilitate infrastructure delivery and maintenance productivity and support decision-making [12].
Robotics	It contains several intelligent robots which perform tasks by themselves with high autonomy or without explicit human control.	Some repetitive and dangerous construction tasks can be executed by robotic systems and their applications, such as progress

Technologies	Descriptions	Sample applications in construction
		monitoring and building inspection [13].
Big data	It refers to storing a large volume of data that is hard to process by traditional methods.	Big data technology can help other technologies, such as the cyber-physical system, store huge amounts of data [14].
Blockchain or distributed ledger technologies (DLT)	It is a database or system of recording information which is difficult or impossible to change.	With the integration of IoT and BIM, DLT can help to track building components and information sharing [15].
Cloud computing	It delivers computing services such as servers, databases, and software over the Internet with remote control.	Cloud computing can provide digitization and visualization in the cloud for storing data and making decisions [16].
Cyber security	It protects systems, devices, and data from cyber-attacks.	Sensitive cyber information and construction processes can be protected with cyber security systems [17].
Cyber-physical system (CPS)	It is a system integrating computation and networking into physical processes. Embedded computers and networks monitor and control the physical processes.	It provides bi-directional information to monitor construction projects and alert possible problems in the physical environment [18].
Global navigation satellite system (GNSS)/Global positioning system (GPS)	GNSS is a general terminology describing any satellite-based radio navigation system that provides positioning, navigation, and timing services. One of the famous GNSS is GPS. GPS can calculate and display accurate locations, time, and speed information in real time.	It can provide real-time locations of assets for planning and surveying before and during construction projects [19].
Geographic information system (GIS)	GIS was coined by Tomlinson [20] and was defined as “a computer-based system, whereby map and related data can be stored in a form suitable for rapid measurement and comparison.”	GIS can be integrated with BIM, GPS, or VR/AR for localization and visualization of products to assist analysis during the whole project lifecycle phase. It can map the location and transportation network of resources for a project, so the distribution of resources can be analyzed based on a 3D map [21,22].
Remote sensing (RS)	It is defined as “the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance” by the United States Geological Survey [23].	Data in construction can be recorded automatically with RS technologies [24]. Furthermore, over the years, surface subsidence and land deformation can be detected by RS for surveying and planning before construction [25].
Industrial Internet of Things (IoTs)	It refers to the various sets of hardware equipment in the construction project that are connected to the Internet for collecting and sharing data.	IoT can be used to secure construction and better process control and optimization through real-time data sharing and monitoring [26].

Table S2. Distribution of included journals.

No.	Journal	Number of articles
1	Automation in Construction	7
2	Buildings	6
3	Construction Innovation-England	5
4	International Journal of Construction Management	5
5	Journal of Information Technology in Construction	5
6	Journal of Management in Engineering	5
7	Engineering Construction and Architectural Management	4
8	Journal of Civil Engineering and Management	4
9	Journal of Construction Engineering and Management	4
10	Computers in Industry	3
11	Sustainability	3
12	Applied Sciences-Basel	2
13	Journal of Cleaner Production	2
14	Academic Journal of Interdisciplinary Studies	1
15	Advanced Engineering Informatics	1
16	Ain Shams Engineering Journal	1
17	Archives of Computational Methods in Engineering	1
18	Benchmarking: An International Journal	1
19	Built Environment Project and Asset Management	1
20	Business Process Management Journal	1
21	Construction Economics and Building	1
22	Economies	1
23	IEEE Access	1
24	IEEE Transactions on Industrial Informatics	1
25	Intelligent Buildings International	1
26	International Journal of Civil Engineering	1
27	International Journal of Scientific and Technology Research	1
28	Journal of Civil Engineering	1
29	Journal of Engineering, Design and Technology	1
30	Journal of leadership studies	1
31	Malaysian Construction Research Journal	1
32	Materials & Design	1
33	Polymers	1
34	Smart and Sustainable Built Environment	1
35	Sustainable Development	1
	Total	**77**

Table S3. Distribution of countries or regions.

No.	Country or region	Number of selected articles
1	Unspecified	28
2	Multi-country	11
3	United States	7
4	Nigeria	6
5	South African	4
6	UK	3
7	Turkey	2
8	Switzerland	2
9	New Zealand	2
10	China (HK)	2
11	China	2
12	Vietnam	1
13	Spain	1
14	Singapore	1
15	Qatar	1
16	Norway	1
17	Malaysia	1
18	France	1
19	Australia	1
	Total	**77**

Table S4. Details of multi-country studies.

No.	Relevant countries
1	US, UK, and South Korea
2	Association of Southeast Asian Nations, China, Korea, China (Taiwan), the Middle East, Finland
3	UK, Canada, Qatar, US, Spain, Bahrain, Australia, Kuwait, Germany, China, and Egypt
4	UK, China, US
5	UK, US
6	Korea, US
7	UK, US, Germany
8	UK, Hong Kong, US, South Korea, Sweden, Mainland China, Germany, Australia
9	US, Canada
10	China, US
11	UK, China, South Korea

Table S5. Identified influencing factors related to Construction 4.0 Technology Implementation.

Category	Code	Influencing factors	Descriptions
External environment	F1	Level of awareness, acceptance, and applications in the industry	It refers to the level of awareness, acceptance, and market knowledge; willingness or reluctance to adopt digital technologies in the industry.
	F2	Level of standardization	It refers to the level of standardization in the construction industry.
	F3	Market demand	It refers to the continuous owners', customers', clients', or subcontractors' requirements, interests, demands, or leadership of digital technologies.
	F4	Fragmentation of the construction industry	It refers to the fragmented nature of construction projects and the supply chain due to the many stakeholders and subcontracting.
	F5	Appropriate legislation	It refers to the development of the appropriate legal framework and government regulations.
	F6	Shared knowledge and training schemes in the industry	It refers to knowledge-sharing, training schemes, or platforms (e.g., seminars, workshops, conferences) in the industry.
	F7	Governmental initiatives or incentives	It refers to government guidance, initiatives, or incentives.
	F8	Persuasion and inspiration	It refers to the adoption of BIM by other stakeholders in the industry, the subjective norm in the industry, social trends, and inclusion.
	F9	Advanced technology development in the industry	It refers to the advanced technology development in the implementation of C4.0 digital technologies.
	F10	Pressure to innovate	It refers to the market pressure to innovate and adapt to technological change.
Project-related factors	F11	Project size, complexity, site nature, scope, delivery method	It refers to the effects of project attributes such as project size, complexity, site nature, scope, and delivery method on the implementation of C4.0 digital technologies.
	F12	Lack of legal framework and contract uncertainties	It refers to the lack of legal framework and contractual uncertainties concerning the use of C4.0 digital technologies.
	F13	Effective communication among project stakeholders	It refers to effective communication among project stakeholders.
	F14	Clear contractual provisions	It refers to the robust and precise contractual provisions such as data integrity and reliability, the duties and power of information management, and procedures on formation sharing and appointment.
	F15	Level of stakeholder collaboration and coordination	It refers to the level of the project stakeholder to work together in design, construction, engineering, and facility management processes to achieve a shared desired outcome.
	F16	Lack of commitment from clients	It refers to the lack of commitment from project clients.
	F17	Health and safety risks in the workplace	It refers to the potential health and safety risks regarding any hazards resulting from the use of C4.0 digital technologies (e.g., robotics and automation technologies)

Category	Code	Influencing factors	Descriptions
			that could lead to harm or injury to the user in the workplace.
Organizational factors	F18	Availability of capabilities	It refers to the availability of skilled workers' capabilities, expert knowledge, training, and technical competency.
	F19	Availability of resources	It refers to the availability of resources such as technical support from software vendors, equipment specification, time & effort, trainers and training materials, hardware infrastructure, financial resources, information and technology infrastructure, and power supply.
	F20	Awareness and willingness within organizations	It refers to the awareness and willingness of staff to learn new technologies and of top management to implement C4.0 digital technologies within organizations.
	F21	Organizational culture	It refers to the organizational culture for adopting digital technologies and sustainable development.
	F22	Corporate strategy and management policy	It refers to the strategic decision from top management, top organizational management support, and strategic plan using C4.0 digital technologies.
	F23	Organizational business modal adaptation	It refers to the organizational business model adaptation (e.g., organizational structure) to support C4.0 technology implementation.
	F24	Unclear benefits, gains, and business value	It refers to the uncertainty about the potential benefits, gains, and business value of implementing C4.0 digital technologies.
	F25	Consulting	It refers to receiving consultancy services from other firms and universities.
Technology competence	F26	Integration and interoperability	It refers to the integration and interoperability of diverse documentation/software/platforms
	F27	Quality, safety, health, and risk management	It refers to quality control, monitoring the structural health, damage identification of buckled or yielded steel, improved site layout, planning, and safety; improved construction project quality; and risk management when applying C4.0 digital technologies.
	F28	Cost-saving	It refers to the potential cost savings when applying C4.0 digital technologies.
	F29	Time-saving	It refers to the potential time saving when applying C4.0 digital technologies.
	F30	Improved project efficiency and productivity	It refers to the potentially improved project efficiency and productivity when applying C4.0 digital technologies.
	F31	Simulation and visualization for better decision-making	It refers to the simulation and visualization estimation for better decision-making when applying C4.0 digital technologies.
	F32	Design flexibility	It refers to assisting in optimizing the design of a building and improving design flexibility.
	F33	Resource and waste optimization	It refers to waste reduction and reusing components strategies, life cycle management of elements, and waste optimization.
	F34	Improved automation and	It refers to the improved automation and information

Category	Code	Influencing factors	Descriptions
		information-sharing level	sharing level when applying C4.0 digital technologies.
	F35	Energy efficiency	It refers to improved energy efficiency and emissions reduction.
	F36	Increased accuracy and reduced errors	It refers to higher accuracy and reduced human errors in model-based documentation.
	F37	Improved facility management and service	It refers to the improved facility management and service when applying C4.0 digital technologies.
	F38	Mass customization	It refers to the degree of requirements for mass customization of design and parameters for functional and aesthetic purposes.
	F39	Perceived overall organizational performance improvement	It refers to the perceived overall organizational performance improvement, e.g., organization's work culture, new and better services, organization efficiency, and productivity when applying C4.0 digital technologies. Factors in this category present the desire of firms to strive for firm success as a whole.
	F40	Project planning optimization	It refers to the optimized project planning when applying C4.0 digital technologies.
	F41	Improved information retrieval process	It refers to the improved information retrieval process when applying C4.0 digital technologies.
	F42	Increased competitive advantage	It refers to the improved competitive advantage when applying C4.0 digital technologies.
	F43	Synchronization of procurement and improved supply chain management	It refers to the synchronization of procurement with design and construction (e.g., e-procurement) and improved supply chain management using intelligent contracts resulting in automated payments, provenance tracking, contract administration, disintermediation, ownership, and data control, and redefining trust.
	F44	Reduced labor	It refers to potentially reduced labor when applying C4.0 digital technologies.
	F45	Shared value or value chain	It refers to greater added value for the customer and shared value for stakeholders.
	F46	Improved estimation method	It refers to an improved estimation method of the project when applying C4.0 digital technologies.
	F47	Better project delivery	It refers to better project delivery when applying C4.0 digital technologies.
	F48	Easy to use	It refers to C4.0 digital technologies that are easy for data input and output and can be used easily.
	F49	Reduced claims or litigation (risks)	It refers to reduced potential claims or litigation (risks) when applying C4.0 digital technologies.
	F50	Optimum performance of manufacturing	It refers to optimum performance manufacturing of design-based configuration and assembly.
	F51	Supporting education and training	It refers to the implementation of C4.0 digital technologies that could support education and training.
Technology challenges	F52	Immaturity of the technologies	It refers to the immaturity of the technologies.
	F53	Data-related issues	It refers to data-related issues such as lack of data

Category	Code	Influencing factors	Descriptions
			accuracy tests, lack of information loss, poor understanding among different stakeholders,
	F54	Uncertainty about the cost-efficiency	It refers to the uncertainty about the costs associated with adopting new technologies.
	F55	Security of intellectual property and rights	It refers to the property rights through patents and copyrights of the model and participants' contributions.
	F56	Uncertainty about the time efficiency	It refers to the time efficiency associated with adopting new technologies.
	F57	Lack of practical validation	It refers to the lack of consideration of projects, the context conditions, and real practice validation.
	F58	Energy consumption	It refers to the potential energy consumption for technology operations.
	F59	Lack of better-performing devices	It refers to the lack of better-performing devices such as better signal range and strength, reduction of damage, faster reaction speed, such as active RFIC, and improved working capacity in the concrete environment of prefabricating components.
	F60	Difficulty in explaining the output of the new technology to the client	It refers to the difficulty in explaining the output of the new technology to the client.

Table S6. Types of the reviewed articles and the corresponding reference matrices.

Reviewed articles	Type	Corresponding reference matrix	
		X	**Y**
Bock [27]	A	√	
Merschbrock and Munkvold [28]	A	√	
Bilal, *et al.* [29]	A	√	
Oesterreich and Teuteberg [30]	A	√	
Wu, *et al.* [31]	A	√	
Ozorhon and Karahan [32]	A	√	
Amuda-Yusuf [33]	A	√	
Antwi-Afari, *et al.* [34]	A	√	
Chen, *et al.* [35]	A	√	
Dallasega, *et al.* [36]	A	√	
Jin, *et al.* [37]	A	√	
Chan, *et al.* [38]	A	√	
Chowdhury, *et al.* [39]	A	√	
Craveiro, Duarte, Bartolo and Bartolo [9]	A	√	
García de Soto, *et al.* [40]	A	√	
Ibrahim, *et al.* [41]	A	√	
Koseoglu, *et al.* [42]	A	√	
Li, Greenwood and Kassem [15]	A	√	
Maskuriy, *et al.* [43]	A	√	
Maskuriy, *et al.* [44]	A	√	
Olawumi and Chan [45]	A	√	
Tetik, *et al.* [46]	A	√	
Abdul Nabi and El-adaway [47]	A	√	
Adepoju and Aigbavboa [4]	A	√	
Alaloul, Liew, Zawawi and Kennedy [16]	A	√	
Dao, *et al.* [48]	A	√	
Davila Delgado, Oyedele, Beach and Demian [12]	A	√	
Evans and Farrell [49]	A	√	
Evans, *et al.* [50]	A	√	
Forcael, Ferrari, Opazo-Vega and Pulido-Arcas [5]	A	√	
Khoshfetrat, *et al.* [51]	A	√	
Lekan, *et al.* [52]	A	√	
Lekan, *et al.* [53]	A	√	
Maali, *et al.* [54]	A	√	
Newman, *et al.* [55]	A	√	
Okakpu, *et al.* [56]	A	√	
Olanrewaju, *et al.* [57]	A	√	
Osunsanmi, *et al.* [58]	A	√	
Patrucco, *et al.* [59]	A	√	
Perrier, *et al.* [60]	A	√	
Qi, *et al.* [61]	A	√	
Wang, Wang, Sepasgozar and Zlatanova [1]	A	√	
Wen and Gheisari [62]	A	√	
Zabidin, Belayutham and Ibrahim [18]	A	√	
Abdul Nabi and El-adaway [63]	A	√	
Alade, *et al.* [64]	A	√	
Boton, *et al.* [65]	A	√	
Demirkesen and Tezel [66]	A	√	
Ghosh, Edwards and Hosseini [26]	A	√	
Karmakar and Delhi [67]	A	√	
Kedir and Hall [68]	A	√	
Kozlovska, *et al.* [69]	A	√	
Lekan, *et al.* [70]	A	√	

Reviewed articles	Type	Corresponding reference matrix	
		X	Y
Li, *et al.* [71]	A	√	
Mannino, *et al.* [72]	A	√	
Mansour, *et al.* [73]	A	√	
Turner, *et al.* [74]	A	√	
Gosselin, *et al.* [75]	B		√
Boke, *et al.* [76]	B		√
Lee, *et al.* [77]	B		√
Chen, *et al.* [78]	B		√
Diaz-Perete, *et al.* [79]	B		√
Tahmasebinia, *et al.* [80]	B		√
Aghimien, *et al.* [81]	B		√
Bademosi and Issa [13]	B		√
Danel, *et al.* [82]	B		√
Tezel, *et al.* [83]	B		√
Lee and Yu [84]	C	√	√
Liao and Teo [85]	C	√	√
de Soto, *et al.* [86]	C	√	√
Yang, *et al.* [87]	C	√	√
Hasan, *et al.* [88]	C	√	√
Phang, *et al.* [89]	C	√	√
Qin, *et al.* [90]	C	√	√
Saka and Chan [91]	C	√	√
You and Feng [17]	C	√	√
Aghimien, *et al.* [92]	C	√	√

Table S7. Differences between the results from social network analysis and simplified analysis.

Code	Factor	Differences in normalized scores (X-Y)	
		SNA	Simplified analysis
F39	Perceived overall organizational performance improvement	0.346	0.325
F22	Corporate strategy and management policy	0.339	0.275
F19	Availability of resources	0.325	0.400
F26	Integration and interoperability	0.298	0.325
F52	Immaturity of the technologies	0.298	0.050
F53	Data-related issues	0.275	0.375
F43	Synchronization of procurement and improved supply chain management	0.266	0.225
F35	Energy efficiency	0.255	0.125
F54	Uncertainty about the cost efficiency	0.253	0.300
F27	Quality, safety, health, and risk management	0.216	0.400
F44	Reduced labor	0.177	0.050
F28	Cost-saving	0.174	-0.100
F29	Time-saving	0.169	0.050
F12	Lack of legal framework and contract uncertainties	0.152	0.150
F1	Level of awareness, acceptance, and applications in the industry	0.150	0.225
F11	Project size, complexity, site nature, scope, delivery method	0.144	0.200
F15	Level of stakeholder collaboration and coordination	0.141	0.150
F47	Better project delivery	0.140	0.100
F46	Improved estimation method	0.125	0.100

Code	Factor	Differences in normalized scores (X-Y)	
		SNA	Simplified analysis
F55	Security of intellectual property and rights	0.123	0.150
F56	Uncertainty about the time efficiency	0.112	0.125
F49	Reduced claims or litigation (risks)	0.104	0.075
F50	Optimum performance of manufacturing	0.096	0.075
F41	Improved information retrieval process	0.090	0.000
F32	Design flexibility	0.087	0.100
F25	Consulting	0.080	0.075
F37	Improved facility management and service	0.057	0.100
F18	Availability of capabilities	0.052	0.200
F6	Shared knowledge and training schemes in the industry	0.045	0.075
F51	Supporting education and training	0.041	0.025
F60	Difficulty in explaining the output of the new technology to the client	0.018	0.025
F4	Fragmentation of the construction industry	0.007	-0.175
F7	Governmental initiatives or incentives	-0.001	0.100
F16	Lack of commitment from clients	-0.005	0.050
F13	Effective communication among project stakeholders	-0.015	-0.100
F45	Shared value or value chain	-0.025	0.025
F38	Mass customization	-0.028	-0.175
F24	Unclear benefits, gains, and business value	-0.034	-0.075
F42	Increased competitive advantage	-0.038	0.100
F31	Simulation and visualization for better decision-making	-0.042	-0.100
F59	Lack of better-performing devices	-0.042	-0.050
F9	Advanced technology development in the industry	-0.049	0.000
F5	Appropriate legislation	-0.054	0.000
F2	Level of standardization	-0.060	0.100
F30	Improved project efficiency and productivity	-0.063	0.175
F33	Resource and waste optimization	-0.068	-0.200
F10	Pressure to innovate	-0.088	-0.025
F57	Lack of practical validation	-0.094	-0.050
F58	Energy consumption	-0.094	-0.050
F21	Organizational culture	-0.128	-0.100
F17	Health and safety risks in the workplace	-0.137	-0.075
F3	Market demand	-0.137	-0.075
F23	Organizational business modal adaptation	-0.170	-0.075
F40	Project planning optimization	-0.181	-0.200
F34	Improved automation and information-sharing level	-0.191	-0.175
F48	Easy to use	-0.192	-0.125
F20	Awareness and willingness within organizations	-0.193	-0.025
F14	Clear contractual provisions	-0.215	-0.150
F36	Increased accuracy and reduced errors	-0.275	-0.250
F8	Persuasion and inspiration	-0.352	-0.225

Factors/ Articles	Article *j*	Article *j+1*	…	…	Article *J*
F*i*	1	1	0	0	1
F*i+1*	0	1	0	1	1
F*i+2*	1	1	1	0	0
…	0	1	1	1	0
F*n*	1	1	0	1	0

Figure S1. Example of a reference matrix.

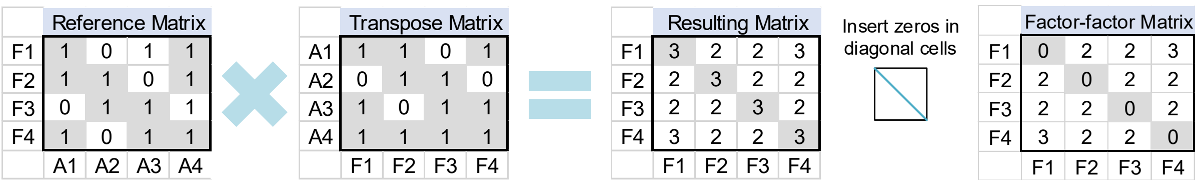

Figure S2. Example of the development of a factor-factor matrix.
Notes: Letter *F* denotes factors and letter *A* denotes articles

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