



Adopting distributed ledger technology for the sustainable construction industry: evaluating the barriers using Ordinal Priority Approach

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Abstract

Construction 4.0 has become a buzzword since the penetration of building information modeling (BIM), cyber-physical systems, and digital and computing technologies into the construction industry. Among emerging technologies, distributed ledger technology (DLT), or blockchain, is a powerful business enhancer whose potential can disrupt projects, AEC (architecture, engineering, and construction) firms, and construction supply chain, and in a broader sense, the whole construction industry. This technology has not reached the plateau of productivity due to several barriers and challenges. Previous studies have started to investigate the barriers to implementing DLT in various sectors and segmentations. However, we still need further surveys in the construction industry. This study evaluates the applicability of identified challenges and barriers based on a sustainability perspective. Precisely, we will answer which challenges need to be addressed for the sustainability of the construction industry. To meet the research objective, the ordinal priority approach (OPA) in multiple attributes decision-making (MADM) was utilized. This novel method determines the weight of sustainability attributes and barriers simultaneously. The results show that DLT implementation needs (i) infrastructure for data management, (ii) advanced applications and archetypes, and (iii) customers' demand, interest, and tendency, and (iv) taxation and reporting. Solving high-ranked challenges is the key to social sustainability from the aspects of “supply chain management and procurement”; “transparency, anti-corruption, and anti-counterfeiting”; and “fair operation and honest competition.”

Keywords Construction 4.0 · Building information modeling (BIM) · Distributed ledger technology (DLT) · Blockchain · Sustainability · Ordinal Priority Approach (OPA) · Multiple attributes decision-making (MADM)

Introduction

The construction industry is one of the driving forces of economic growth due to various market players, construction

projects, complex supply chains, and extensive value networks (WEF 2016). Despite its crucial role, it has long been dealing with low productivity, delayed payments, squeezed profit margins, poor regulatory compliance, lack of trust, and poor communication among stakeholders (Li et al. 2019; Hunhevicz and Hall 2020). The problems above prevent the construction industry from being prepared for digital transformation and the benefits offered by emerging technologies. According to McNamara and Sepasgozar (2021), the industry 4.0 concept helps the construction industry keep up with other sectors in terms of performance improvement. Distributed ledger technology (DLT), or blockchain (BCT), is one of the industry 4.0 constituents that has received increasing interest in the last decade. It provides businesses and industries with novel solutions based on trust, transparency, connectivity, security, traceability, and automation (Ozdemir et al. 2020).

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A review of the existing literature shows that academia and practitioners have intensively stressed DLT/BCT and its prospect use cases, mainly 2018 afterwards (Wamba and Queiroz 2020). Saberi et al. (2019) and Lohmer and Lasch (2020) used a similar framework for categorizing barriers based on intra-/inter-organizational, system-related, technological, and external aspects. Biswas and Gupta (2019) developed a framework for identifying barriers to successfully implementing blockchains in various industries and services using the decision-making trial and evaluation laboratory (DEMATEL) technique. According to the findings, the most influencing obstacles are market-based risks and scalability issues. And, the most influenced barriers are high sustainability costs and poor economic behavior. Helliari et al. (2020) conducted a comprehensive literature review and explored 28 barriers of blockchains diffusion for permissionless and permissioned types. Bag et al. (2020) explored barriers to blockchain adoption in green supply chain management (GSCM). The findings show that the most influencing barriers are “cultural differences among partners” and “lack of management vision.” The most influential barriers are “workforce obsolescence and hesitation” and “collaboration challenges” in GSCM. Öztürk and Yildizbaşı (2020) discussed 18 barriers in the field of supply chain management. According to the findings, high investment costs, data security, and utility are important factors.

Mathivathanan et al. (2021) identified nine barriers to DLT adoption in business supply chains. The results reveal that “lack of business awareness” and “low familiarity with blockchain’s potentials” are the most critical barriers that impede blockchain adoption in supply chains. In the manufacturing supply chains context, Vafadarnikjoo et al. (2021) used the neutrosophic analytic hierarchy process (N-AHP) to analyze five barriers to blockchain technology. The authors found that “transaction-level uncertainties” and “usage in the underground economy” are the most influential. Kouhizadeh et al. (2021) utilized the technology-organization-environment (TOE) framework, with slight modifications, to identify critical barriers in the field of blockchain adoption for sustainable supply chain management (SSCM). The authors analyzed barriers and evaluated interdependencies among them using the DEMATEL technique. The results showed that supply chain barriers and technological factors are the most challenging ones from academicians’ and experts’ perspectives. Kumar et al. (2021) identified barriers that impede the successful implementation and operation of industry 4.0 technologies for supply chains considering the circular economy approach. The authors used a hybrid approach of AHP and Elimination Et Choice Translating REality (ELECTRE) to rank barriers and sustainability parameters. The results show that “lack of budget” and “lack of strategic plan” are major barriers to technology application.

Farooque et al. (2020) utilized fuzzy DEMATEL to analyze barriers that impede blockchain adoption in life cycle assessment (LCA). According to obtained results, the immature underlying technology and technical issues for collecting real-time supply chain data are the highest in net cause-effect values. In parallel, the lack of organizational procedures and government regulations in using technology are the highest in prominence. In the construction context, Yang et al. (2020) discussed the challenges of adopting blockchain technology. According to the authors, the main challenges are variations of the construction industry, identity, cost and complexity in adoption, and scalability. Few researchers have addressed the barriers to successful DLT adoption at the time of writing, particularly in the construction industry and related fields. To address this research gap, the present study focuses on adopting distributed ledger technology for the sustainable construction industry and evaluating the barriers using the ordinal priority approach (OPA) in multiple attributes decision-making (MADM). To achieve the research objective, first, we formulated the following research questions (RQs):

- RQ 1. What are the barriers faced leveraging DLT in service sectors, particularly the construction context?
- RQ 2. How DLT contributes to sustainability, and what are the critical sustainability attributes?
- RQ 3. Which barriers are the most critical to achieving sustainability in the construction industry?

For this, we explored factors from previous literature. To assess the applicability of factors in the construction context, we collected opinions of experts specialized in emerging technologies, construction, and related disciplines. This study also used a recent method in the MADM context, which is known as OPA. OPA calculates the weights and ranks of experts, attributes, and barriers simultaneously. According to the mentioned novelties, the current study will help policymakers and practitioners who want to be early movers in the construction industry by embracing new technologies (i.e., DLT/BCT). This research will also broaden scholars’ horizons about critical barriers within DLT implementation as references for further examination. The rest of this study is organized into six sections. After the introduction, the literature review has been provided in the “Literature review” section. Then, the “Ordinal priority approach” section is allocated to methodology. The “Implementing the proposed framework” section presents the research framework, and the “Case study and discussion” section illustrates a case study and related discussion. Finally, the “Conclusion” section provides the conclusion.

Literature review

Distributed ledger technology for sustainability

Distributed ledger technology (DLT), or blockchain (BCT), is a decentralized database and shared computing infrastructure. The primary mission of DLT/BCT is generating, verifying, updating, sharing, transferring, and storing transactions within distributed ledgers without any trusted intermediaries (Tapscott and Tapscott 2016). Ozdemir et al. (2020) summarized key features of blockchains in speed, traceability, trust, security, disintermediation, immutability, transparency, and automation. According to Mougayar and Buterin (2016), DLT's features are crucial for basic functions like smart assets, timestamping, multi-signature transactions, smart contracts, and smart oracles. To date, this technology has experienced four consecutive versions: Blockchain 1.0 (cryptocurrency), Blockchain 2.0 (smart contracts), Blockchain 3.0 (distributed applications), and Blockchain 4.0 (interoperability among industry 4.0-based applications) (Bodkhe et al. 2020). This evolutionary trend shows that DLT can play a critical role in the “internet of value.” Within distributed ledgers, any real-world value—including (i) intangible (i.e., trust, ownership, and identity), (ii) tangible (i.e., real estate, equipment, and currency), and (iii) obligations (i.e., contracts and agreements)—can be digitalized and exchanged (Nawari and Ravindran 2019).

The first and well-recognized type of DLT is blockchain. Other alternatives, with the similar underlying technology, are hash graph, directed acyclic graph (DAG), Tangle, Holochain, and Radix. These DLT platforms differ in features, processing mechanisms, data structures, and consensus algorithms (O'Dair 2018). Hence, throughout the current study, the term “DLT” is referred to as any form of distributed ledgers, including blockchain technology. In the context of the DLT implementation, Hilton et al. (2019) proposed a roadmap with defined deliverables, such as (i) assessing viability and feasibility of use cases, (ii) developing a minimum viable product (MVP) and building “proof of concept,” and (iii) continuous scaling and running pilot blockchain solution in a real environment. Janssen et al. (2020) discussed a conceptual model for blockchain adoption based on process, institutional, market, and technological dimensions (PIMT). In the same line of thinking, Yang et al. (2020) presented an application framework for the construction industry. The authors asserted that four aspects of the regulation, industry trust, business, and technique, should be considered for a successful DLT adoption.

The previous studies show that there are various areas for DLT application, such as (i) smart cities and built environment (Marsal-Llacuna 2018); (ii) logistics, procurement, and supply chain management (Fosso Wamba et al. 2020; Kouhizadeh et al. 2021); (iii) smart homes, as microgrids in energy trading

(Petri et al. 2020); (iv) project value delivery, payments, finance management, and investment consistency (Penzes 2018; Hunhevicz and Hall 2020); (v) dispute resolution, tendering, and construction bid competition (Barima 2017; Leng et al. 2020); (vi) real estate and land registry (Bürer et al. 2019); (vii) project bank accounts (PBAs) (Li et al. 2019); and (viii) decentralized autonomous organizations (DAOs) (Nawari and Ravindran 2019).

DLT promises to enhance time efficiency, quality, productivity, cost savings, and transparency within processes and activities (Mougayar and Buterin 2016). Considering DLT's features and potentials, this technology can be employed for sustainable development goals (SDGs). Early application in the finance and banking industry shows that DLT/BCT has been a driving force of a new economic structure. With that in mind, DLT becomes highlighted for social and environmental sustainability, as well. However, this technology is relatively nascent, and it takes a while for companies to find out how to utilize DLT potentials for the sake of sustainability. The research works by De Giovanni (2020) and Kouhizadeh et al. (2021) emphasized the role of blockchain and smart contracts in the sustainability of supply chain management (SCM). Wamba and Queiroz (2020) stressed the convergence of blockchain and industry 4.0 technologies (i.e., big data, artificial intelligence (AI), internet of things (IoT), robotics, and so forth). This combined effort can result in a sharing economy, transparent operations, and sustainable supply chain management. Nandi et al. (2020) discussed how blockchain technology and the circular economy principles contribute to the localization, agility, and digitization (LAD) and sustainability of supply chain management.

Related studies show that DLT, directly or indirectly, leads to sustainability. In this regard, we identified 30 sustainability attributes in the following clustering: two project sustainability attributes, twelve social attributes, eight environmental attributes, and eight economic attributes. Detailed information and definitions are provided in Appendix A, Table A2. These attributes will be analyzed later in a case study (“Case study and discussion” section) using OPA.

Barriers facing DLT implementation in the construction industry

As mentioned in the introduction, some studies were discussing barriers facing DLT implementation in various sectors. According to Yang et al. (2020), one of the high potential areas for future research directions is the challenges of adopting blockchain technology in the construction industry. We still need further surveys to assess general and (non)construction-specific challenges and their applicability in the construction industry. In this regard, we identified challenges from previous studies. Based on their causes and nature, we

categorized them into project, organization, market, and industry levels.

Project level

Although employing blockchain systems for project management activities is still too early (Yang et al. 2020), it seems that some challenges emerge from operations, project activities, and processes. In this regard, 11 barriers have been identified, mostly in project integration, procurement, communication, time, and cost.

P1 Abuse and fraud: Installing faulty systems and software bugs can increase intentional abuse, fraudulent activities, and human error at the application level (i.e., payment and procurement practices) (Helliari et al. 2020).

P2 Manual processes and traditional practices: Digitalizing will challenge manual processes (e.g., purchase orders, accounting, invoicing, and payments) and traditional practices controlled by centralized systems (Hofmann et al. 2018).

P3 Irreversibility and immutability of the process: By employing smart contracts and automated processes, the chance for human intervention in changing coded documents and transactions will be reduced significantly (Biswas and Gupta 2019; McNamara and Sepasgozar 2021).

P4 Authenticity, consistency, and legitimacy of data: The excellent performance of distributed ledger is closely related to the availability and reliability of uploaded data to prevent any fraudulent activities (Li et al. 2019).

P5 Infrastructure for data management: In projects, there is a high need for robust devices and collaborators with minimum malfunctions, manipulation, and cyber-attacks. This paves the way for collecting, clustering, synchronizing, and storing data with maximum integrity and consistency (Penzes 2018).

P6 Contractual standards: When technology embeds into project management practices/processes, a standard contractual model with detailed milestones, deliverables are required to develop a smart contract (Penzes 2018).

P7 Multiple chains and private systems: When multiple blockchains versions and systems (i.e., enterprise resource planning (ERP)) engaged in a blockchain-based solution, poor integrity hampers cross-transactions and causes attacks, human errors, data loss, and fragmentation (Hofmann et al. 2018; Helliari et al. 2020).

P8 Fragmentation and complexity of activities: DLT implementation for the complicated and fragmented process (i.e.,

procurement and supply chain activities) requires significant effort, time, and resources (Hofmann et al. 2018).

P9 Scalability problems: Several factors intensified scalability issues: (i) data transmission latency, (ii) transaction processing rate (throughput), and (iii) duplicate information storage (Biswas and Gupta 2019; Yang et al. 2020).

P10 Lower external accountability control: Blockchain-based financing tools carries uncertainty and risks due to lower external accountability controls on them (Mougayar and Buterin 2016).

P11 Financing models and debt instruments: There are various novel mechanisms to raise funds through blockchain-based platforms, such as supply chain finance (SCF). Lack of managerial perception and mindset about new fundraising tools in distributed platforms explain why decision-makers and practitioners resist adopting these novel DLT-based solutions for their businesses' needs (Hofmann et al. 2018).

Organization level

Organizational factors are often considered the most influential determinants of IT innovation adoption in firms and organizations (Clohessy and Acton 2019). Having this in mind, 13 barriers and challenges have been identified, majorly in men, machines, methods, materials, and money (5Ms) aspects.

O1 Organizational considerations: To reap DLT/blockchain's benefits, there is a high need for managerial support, staff's mindsets and cooperation, stakeholders' trust, and organizational maturity (Clohessy and Acton 2019).

O2 New business models: Organizations should determine the necessity of blockchain technology as their strategic needs and enhance services/products for customers accordingly (Penzes 2018; Clohessy and Acton 2019).

O3 Shared governance: The governance model is an integral part of an intra-/inter-organizational collaboration that determines how the platform is structured and controlled by parties (Penzes 2018; Helliari et al. 2020).

O4 Financial constraints and cost of adoption: Although platforms are mostly free open-source, it is required to consider initial investment, costs breakdown structure, and prediction of cost savings (Sawhney et al. 2020).

O5 Uncertain return of investment (ROI): Construction companies need a clear picture of the value proposition and (non)financial benefits offered by DLT adoption (Sawhney et al. 2020).

O6 Digital representation of real-world objects: A wide range of stakeholders and assets are involved in a construction ecosystem. For easy value exchange, organizations need to give access to people, create a native smart asset, or connect physical assets to the blockchain using RFID tags and digital identity (Mougayar and Buterin 2016; Yang et al. 2020).

O7 Negative perception and insufficient understanding: Organizations may take a wait-and-see attitude and postpone adoption until they gain in-depth knowledge of DLT/blockchain's potential (Barima 2017; Kshetri 2017; Saberi et al. 2019).

O8 Scarcity in multidisciplinary experts and developers: Organizations need multi-disciplined professionals and fresh new talent in cryptography science, smart contract and legal affairs, construction projects, and DLTs for successful implementation (Li et al. 2019; Yang et al. 2020).

O9 Legacy systems: Organizations need modern computer architecture and specialized equipment to reap DLT's benefits. This can be obtained through replacing or upgrading existing systems (Mougayar and Buterin 2016).

O10 System robustness and full technology stack: Adoption needs a set of technology stacks (i.e., software, hardware, middleware, and infrastructure) and continuous internet connectivity (Mougayar and Buterin 2016; Li et al. 2019).

O11 Lack of advanced applications and archetypes: The underlying technology is nascent; and, producing killer applications and successful archetypes takes a while (Mougayar and Buterin 2016).

O12 Wide rollout and large-scale technology adoption: Shifting from ideation to real-world applications needs a list of requirements, such as investment, the firms' readiness, and training staff (Sawhney et al. 2020; Yang et al. 2020).

O13 Compatibility and inoperability: Different applications/systems work together in construction projects. Poor interoperability and connectivity adversely affect transferring and storing data (Li et al. 2019).

Market/industry level

According to Michael Porter's framework, the main dynamics of industries or sectors are buyers, suppliers, partners, and rivals (Johnson et al. 2008). Considering the construction industry's state, eight barriers to DLT implementation have been identified considering the construction industry's condition.

M1 Network effects: Blockchain-based platforms need to engage sufficient users in the viable business-to-business (B2B) and business-to-community (B2C) ecosystems (Mougayar and Buterin 2016; Clohessy and Acton 2019).

M2 Lack of customers' demand, interest, and tendency: DLT technology requires customers' interest and stakeholders' support to flourish in industries and markets (Barima 2017; Saberi et al. 2019).

M3 Low usability: Low ease of use and high complexity of the DLT/ BCT adversely affect customers' journey experience and interaction with blockchain applications (Mougayar and Buterin 2016; Helliar et al. 2020).

M4 Limited access to lesson-learned and practices: Learning from previous mistakes and accessing the best practices of previous experience are necessary to reap DLT's benefits by industry players (Sawhney et al. 2020).

M5 Technical guidelines and standards: The construction sector needs globally agreed standards to run IT infrastructure for fewer overall risks, easier interoperability, data structure, and lower costs (Sawhney et al. 2020; McNamara and Sepasgozar 2021).

M6 Lack of insurance mechanism: The inadequate insurance coverage to address the technical and business risks may prevent DLT adoption within the construction industry (Nawari and Ravindran 2019).

M7 Technological state of the construction industry: The construction industry is not ready to embrace digital transformation due to traditional approaches and long-standing problems (Li et al. 2019; Sawhney et al. 2020).

M8 Market competition and heavily regulated segmentations: Some segmentations (e.g., infrastructure projects) are under pressure of market competition and heavy regulation due to their strategic place in society. These market forces might be barriers to adopt technological innovations (Kshetri 2017; Saberi et al. 2019; Bürer et al. 2019).

Macro-environment level

Organizations and their projects are influenced by political, economic, social, technological, environmental, and legal (PESTEL) environments (Johnson et al. 2008). Nine barriers have been identified at the macro-environment level.

E1 Technology accessibility: Digital divide varies among societies, countries, and governments in the years of growth, adoption, and acceptance of technology (Saberi et al. 2019).

E2 Lack of government support: Governments and policymakers are not interested in emerging technologies in the particular blockchain. This technology acts independently without the control of governmental entities (Mougayar and Buterin 2016).

E3 The volatility of cryptocurrency and fluctuating exchange rate: Cryptocurrencies are struggling with high volatility and fluctuations rates in the current years. It seems that underlying technologies of cryptocurrencies are not stable for use-cases and applications in the construction industry (Biswas and Gupta 2019; Li et al. 2019).

E4 R&D projects and higher training programs: With the arrival of construction 4.0, there is a high need for awareness-raising, investment in R&D projects, and professional training programs (Sawhney et al. 2020).

E5 Lack of incentive and encouragement programs: One reason that dissuades industries from employing green technologies for sustainability is the lack of incentive schemes offered by governmental bodies (Sabeti et al. 2019).

E6 High energy consumption: Some consensus algorithms (i.e., proof-of-work) are not environmentally friendly due to high energy consumption and greenhouse gas emissions (Biswas and Gupta 2019; Li et al. 2019).

E7 Legal issues: The construction industry heavily relies on laws and regulations for project execution and operation. Due to technology newness, there is a high need for new policies and technology laws (Li et al. 2019).

E8 Compliance requirements: Compliance requirements—for know your customer (KYC) and anti-money laundering (AML)—are critical processes to verify the due diligence of trading partners. The compliance requirements for onboarding stakeholders to the DLT platforms is accompanied by significant time, cost, and effort (Hofmann et al. 2018).

E9 Taxation and reporting: Aside from recording transactions, this technology still requires improvements in taxation, reporting, and auditing processes (Mougayar and Buterin 2016; Biswas and Gupta 2019).

It is worthwhile to mention that the technical problems are excluded from discussion in this paper. Some of these challenges are (i) immaturity of technology (Mougayar and Buterin 2016; Sabeti et al. 2019); (ii) vulnerability and confidentiality risks (Mougayar and Buterin 2016; Upadhyay 2020); (iii) coding of the smart contract (Yang et al. 2020; Sheng et al. 2020); (iv) theft of data, security issues, cybercrimes, system hacks, and hard forks (Li et al. 2019; Frizzo-barker et al. 2019); and finally (v) misconception between DLT/blockchain and cryptocurrencies (Sabeti et al. 2019).

Ordinal priority approach

In practice, it is impossible to consider all types of drivers and even barriers simultaneously due to the time, budget, and resource constraints in the industries. Hence, the process of identifying, prioritizing, and taking response action on critical factors becomes imperative (Biswas and Gupta 2019; Kouhizadeh et al. 2021). In the literature, we found that scholars used various tools to analyze challenges, barriers, and critical factors. Table 1 presents state-of-the-art researches that use the following methodologies.

Some decision-making approaches determine the weight of attributes (Mahmoudi et al. 2020), while some others assess and prioritize several possible alternatives based on decision-makers' preferences (Mahmoudi et al. 2019). This paper needs an innovative solution to handle both “sustainability” and “digitalization” concepts by adopting DLT/BCT in the construction industry. One of the best methods for this study is a novel decision-making approach that can evaluate the importance of barriers to DLT implementation based on sustainability attributes. Indeed, MADM methods can be employed to solve this type of problem. The ordinal priority approach (OPA) is a state-of-the-art technique proposed by Ataei et al. (2020) to figure out MCDM problems through a linear mathematical model. OPA calculates the weights of alternatives, experts, and attributes simultaneously in a straightforward manner. The authors illustrate the superiority of OPA over similar decision-making techniques to date, as mentioned below:

1. OPA calculates the ranks of alternatives (here, barriers and challenges), weights of experts, and weights of attributes (here, sustainability attributes) concurrently. Nevertheless, some decision-making techniques first calculate the weights of the attributes and then the rank of alternatives.
2. OPA needs neither normalization methods nor the negative and positive ideal solutions. Various results may be obtained using different normalization methods, and it is challenging to find the best normalization method for the situation (Palczewski and Sałabun 2019). Moreover, OPA can handle decision-making problems with incomplete data. When experts lack sufficient knowledge or relevant experience in the process of judgment, they are allowed to disregard some of the alternatives associated with a given attribute. This feature enhances the accuracy of the final results and the efficiency of decision-making.
3. In most cases, aggregation methods cannot obtain reliable results because the outliers can remarkably decrease their efficiency. OPA does not require averaging methods to collect experts' judgments in the group decision-making.
4. OPA does not use the pairwise comparison matrix of alternatives and attributes. Instead, ordinal data regarding

Table 1 The list of methodologies used in previous studies

Author/year	Research methodology	Objective(s)
Biswas and Gupta (2019)	DEMATEL	To rank ten barriers based on their prominence and relationships
Clohesy and Acton (2019)	A multiple-case study approach	To investigate the impact of organizational factors on blockchain adoption
Ozdemir et al. (2020)	IF–DEMATEL and IF–ANP	Exploring the relationships and interdependencies among barriers in humanitarian supply chain management (HSCM) based on blockchain benefits and attributes weighting
Bag et al. (2020)	Fuzzy-DEMATEL	To analyze barriers to blockchain technology adoption in green supply chain management
Ghode et al. (2020)	Grey relational analysis (GRA)	To rank the eight factors influencing the BCT adoption in SCM
Öztürk and Yıldızbaşı (2020)	Integrated MCDM: Fuzzy AHP and fuzzy TOPSIS	To analyze 18 barriers to blockchain technology adoption in SCM
Sahebi et al. (2020)	Fuzzy Delphi and best-worst method (BWM)	To analyze 14 barriers to blockchain adoption in the HSCM
Yadav and Singh (2020)	Principal component analysis (PCA) and fuzzy-DEMATEL	To assess critical success factors in the blockchain-based sustainable SCM
Farooque et al. (2020)	Fuzzy-DEMATEL	To prioritize 13 critical factors that overshadow blockchain adoption
Erol et al. (2020)	MCDM method combining fuzzy AHP and fuzzy TOPSIS	To assess 15 indicators affecting blockchain applications in industries
Orji et al. (2020)	Analytic network process (ANP)	To prioritize 18 critical TOE factors (technology, organization, environment) impacting BCT adoption in the freight logistics industry
Ozkan-Ozen et al. (2020)	Fuzzy analytical network process (ANP)	To prioritize 12 barriers that impede circular SCM in the industry 4.0 era
Kouhizadeh et al. (2021)	DEMATEL approach	To evaluate prominence and net effect values for factors that impact blockchain technology in the sustainable supply chain
Mathivathanan et al. (2021)	TISM and MICMAC	To examine the interrelationships between nine barriers to blockchain technology in the business supply chain
Vafadamikjoo et al. (2021)	N-AHP	To analyze five barriers to blockchain technology adoption in manufacturing supply chains

the attributes and alternatives are required. The problems associated with the pairwise comparison matrix were discussed by Munier and Hontoria (2021).

In this context, Mahmoudi et al. (2021b) extended OPA to Fuzzy OPA (OPA-F) for using fuzzy linguistic information in the OPA model. In another study, Mahmoudi et al. (2021a) employed grey systems theory in the OPA model to consider multiple ranks for attributes and alternatives. Grey OPA (OPA-G) was suitable for uncertain conditions when experts were unsure about their opinions and suggest multiple ranks. In another research, Mahmoudi et al. (2021c) utilized OPA to address the project selection problem under big and incomplete data. Here, the current study aims to utilized the original OPA as a powerful approach for ranking the alternatives and calculating the weight of attributes. To explain OPA steps, we first need to know the variables, parameters, and sets (Table 2).

It should be noted that weight of expert/attribute in OPA shows the role of expert/attribute on results. Hence, an expert/attribute with a higher weight has a higher impact on the results. Therefore, two experts with the same priority (input) and various weights (output) have various roles on the results,

which depend on their opinions. OPA is composed of several simple steps, which have been explained as follows:

- Step 1. Determining the attributes: At this step, the attributes should be specified. In the current study, we have already explored sustainability attributes in the “Literature review” section and “Distributed ledger technology for sustainability” section.
- Step 2. Nominating and ranking the experts: Based on decision-making type (single or group), a scenario will be defined to specify and rate the experts based on indicators, such as academic qualification, professional experience, familiarity with the research topic, and so forth.
- Step 3. Ranking the attributes: At this step, the attributes are prioritized through single/group decision-making. The expert(s) with insufficient knowledge or irrelevant experience can skip commenting on a particular attribute and exclude those attributes in the ranking.
- Step 4. Ranking the alternatives in each attribute: At this step, expert(s) sort the alternatives in each attribute.
- Step 5. After solving Model (1), the optimal values for W_{ijk} will be obtained.

Table 2 Sets, variables, and parameters in OPA (Ataei et al. 2020)

Sets	
I	Set of experts $\forall i \in I$
J	Set of attributes $\forall j \in J$
K	Set of alternatives $\forall k \in K$
Indexes	
<i>i</i>	Index of the experts (1, ..., <i>p</i>)
<i>j</i>	Index of preference of the attributes (1, ..., <i>n</i>)
<i>k</i>	Index of the alternatives (1, ..., <i>m</i>)
Variables	
Z	Objective function
W_{ijk}^r	Weight (importance) of k^{th} alternative based on j^{th} attribute by i^{th} expert at r^{th} rank
Parameters	
<i>i</i>	The rank of expert <i>i</i>
<i>j</i>	The rank of attribute <i>j</i>
<i>r</i>	The rank of alternative <i>k</i>

Max *Z*

S.t :

$$\begin{aligned} Z &\leq i(j(r(W_{ijk}^r - W_{ijk}^{r+1}))) \quad \forall i, j, k, \text{ and } r \\ Z &\leq \sum_{i=1}^p \sum_{j=1}^n \sum_{k=1}^m W_{ijk}^m \quad \forall i, j, \text{ and } k \\ \sum_{i=1}^p \sum_{j=1}^n \sum_{k=1}^m W_{ijk} &= 1 \\ W_{ijk} &\geq 0 \quad \forall i, j, \text{ and } k \end{aligned} \quad (1)$$

where *Z*: Unrestricted in sign

Equation (2) can determine the weights of the barriers based on the optimal solutions of Model (1).

$$W_k = \sum_{i=1}^p \sum_{j=1}^n W_{ijk} \quad \forall k \quad (2)$$

To calculate the weights of the attributes, Eq. (3) should be employed.

$$W_j = \sum_{i=1}^p \sum_{k=1}^m W_{ijk} \quad \forall j \quad (3)$$

In the OPA, the experts' weight can be obtained using Eq. (4). It is worthwhile to mention that calculating the weight of the experts is optional and depends on the need, which is unnecessary in the current study.

$$W_i = \sum_{j=1}^n \sum_{k=1}^m W_{ijk} \quad \forall i \quad (4)$$

Considering this novelty and simplicity, we selected OPA for solving the MCDM problems.

Implementing the proposed framework

As shown in Figure 1, we integrated the research framework with the OPA flowchart, presented by Ataei et al. (2020), to show stages and deliverables of the current study.

According to the above flowchart, we first defined the research objective, and formulated research questions RQ1, RQ2, and RQ3 accordingly. Following that, we conducted keyword-based searches on the scientific databases: Web of Science (WoS), ScienceDirect, IEEE Xplore, John Wiley & Sons, Inc., Springer, Emerald, and Taylor & Francis. For this, we used the following keywords and terms: construction 4.0, construction industry, distributed ledger technology (DLT), blockchain, smart contract, challenges, and barriers. The literature search resulted in roughly 250 publications. Then, criteria for inclusion and exclusion were applied in the title, abstract, methodology, and quality of the research to filter relevant and appropriate studies. Furthermore, the scope of the review got more limited by using a particular date (2015 afterwards) as one of the key criteria (Gough et al. 2012). In the “[Distributed ledger technology for sustainability](#)” section, we based our foundation on identifying sustainability attributes. Following that, in the “[Barriers facing DLT implementation in the construction industry](#)” section, we identified the barriers to the DLT implementation.

Due to limitations caused by the pandemic (COVID-19), we arranged multiple virtual meetings with experts to discuss factors. We established this process a couple of times to compile experts' feedbacks and finalize the identified factors. To assess the applicability of factors in the construction industry, we considered real-case studies (“[Case study and discussion](#)” section) in a group decision-making approach. Then, we followed OPA steps to figure out our decision problem.

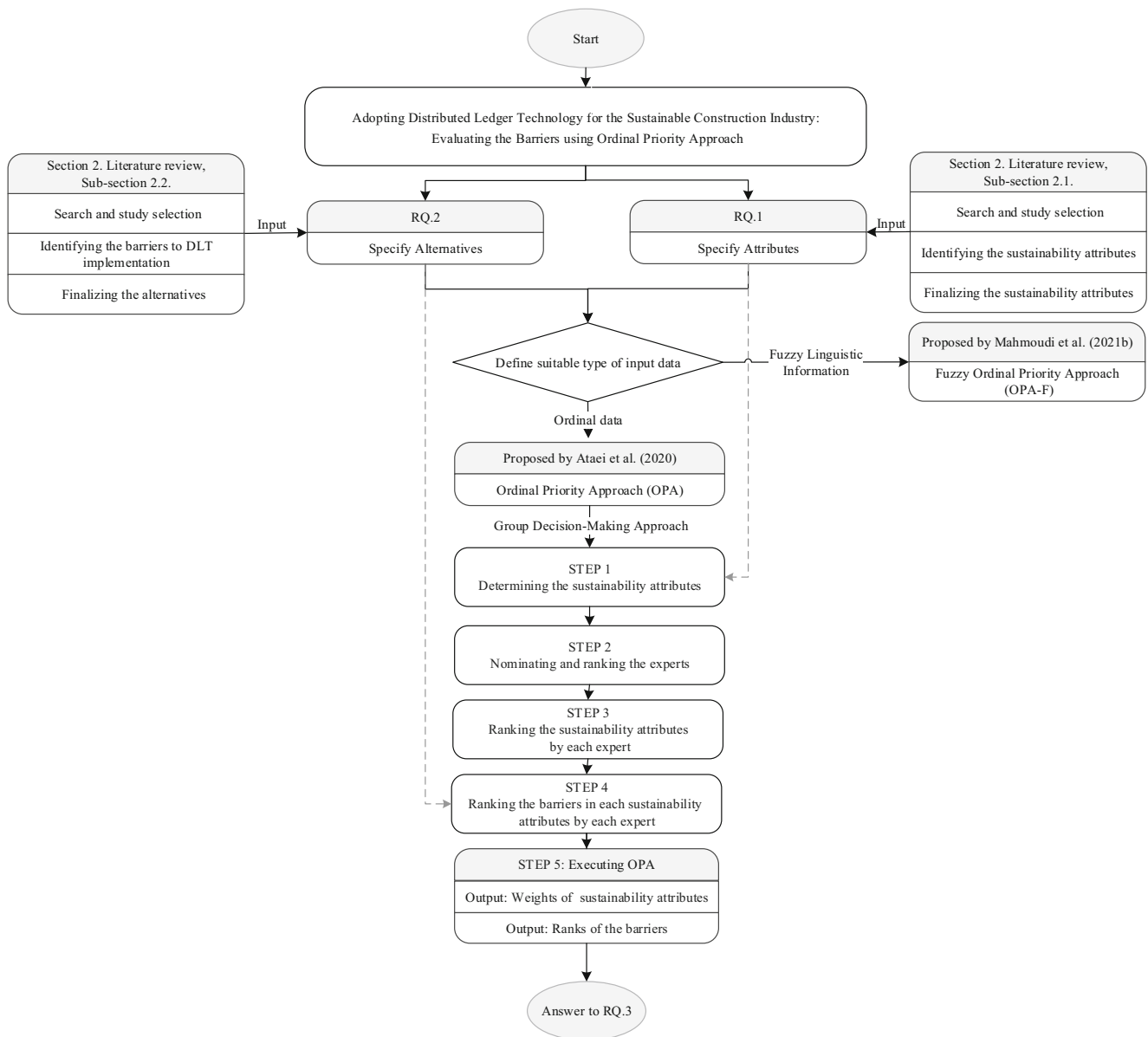


Fig. 1 Flowchart of the stages for our research study

OPA provided us with the weights of attributes and ranks of alternatives.

Case study and discussion

Given the “Literature review” section, 30 sustainability attributes and 41 alternatives are considered in our decision problem. For more clarification, the structure of the decision problem is illustrated below (Figure 2).

According to the decision problem, a questionnaire was designed in three parts (Appendix A). To assess barriers in the construction industry, we invited 15 high-ranked executives in the construction industry willing to adopt DLT

into their businesses and firms. However, we decided to consider the data of six respondents after an initial review of their competencies and responses (Appendix B, Table B1, and Figure B1). More information about demographic profiles and geographical locations of the respondents are presented in Appendix B, Table B2, and Figure B2. Then, we followed step 2 of OPA to sort experts, as below:

$$\text{Expert 4} > \text{Expert 1} > \text{Expert 6} > \text{Expert 2} > \text{Expert 5} \\ = \text{Expert 3}$$

In the last step, OPA is solved to obtain “weight of sustainability attributes” and “ranks of the barriers.”

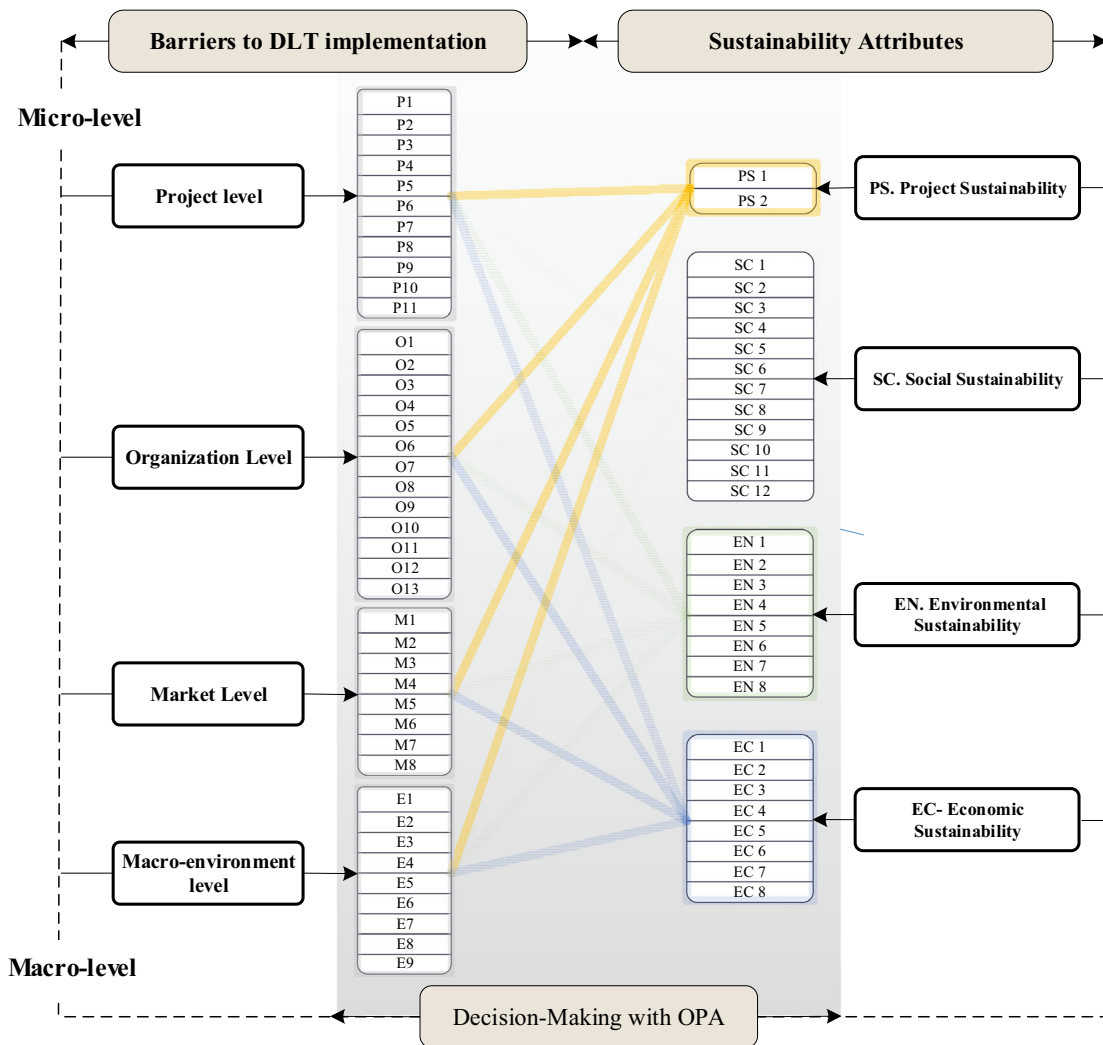


Fig. 2 The structure of the decision problem

Weight of sustainability attributes

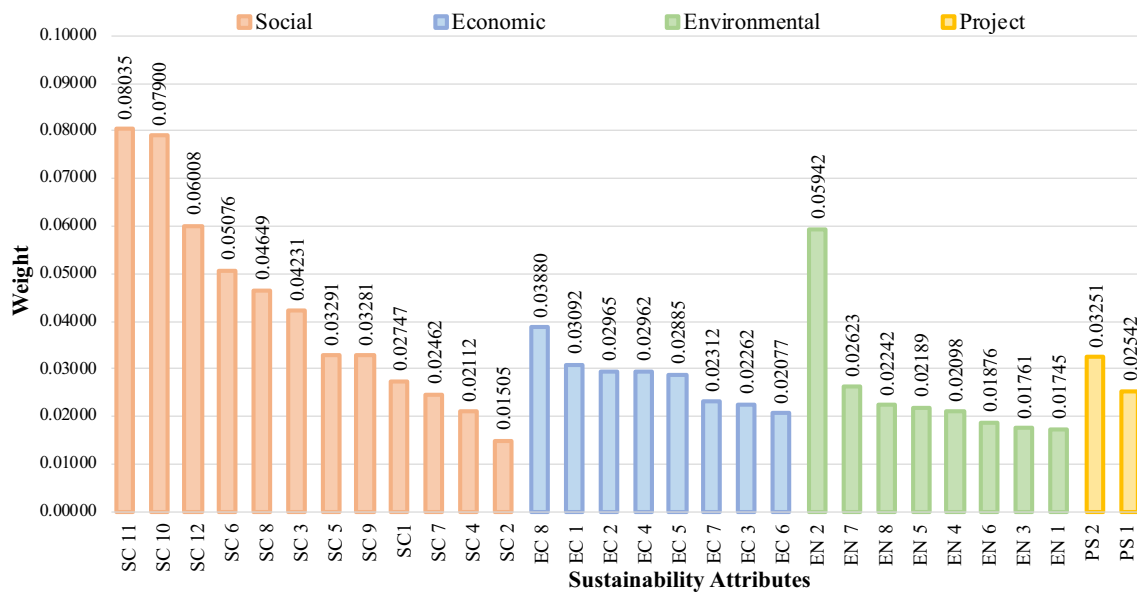
In Step 3 of OPA, experts were asked to determine and sort 30 sustainability attributes in order. After solving OPA in step 5, the results are illustrated in Figure 3 for the project (Fig. 3a), organization (Fig. 3b), market (Fig. 3c), and macro-environment level (Fig. 3d). The findings show that the implementation of DLT can result in social sustainability mostly.

The outputs of the OPA model highlight that the top three attributes in social sustainability are SC10, SC11, SC12; the top attribute in economic sustainability is EC8; the top attribute in environmental sustainability is EN2; the top attribute in project sustainability is PS2. This implies that removing obstacles, regardless of what level they are, can primarily result in sustainability in the factors above.

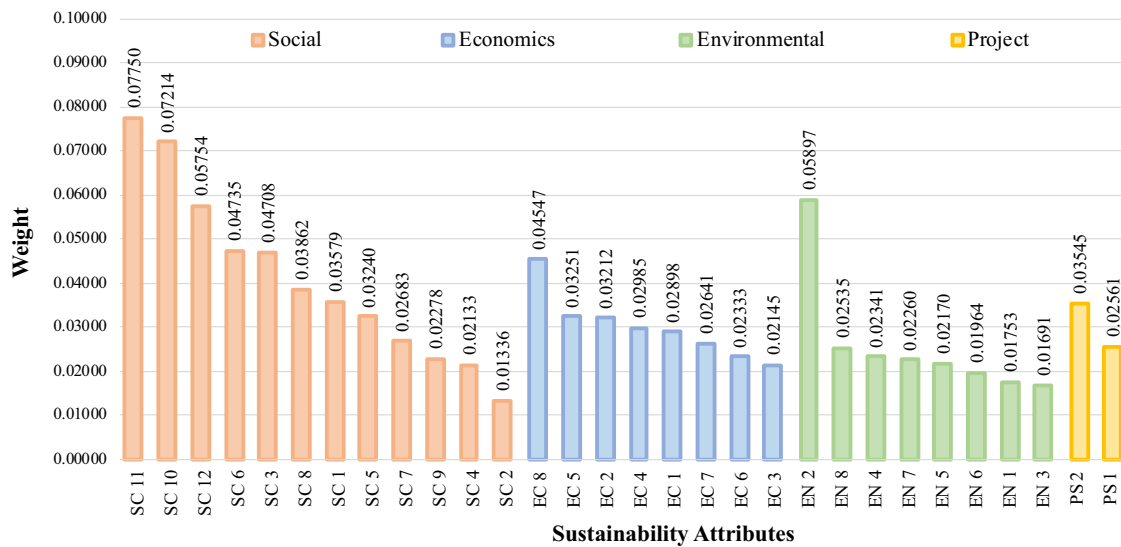
DLT/BCT can play a dominant role in social sustainability. First, it improves “SC10: supply chain management and procurement.” This technology enables effective procurement management and (semi)automated sourcing of products/

services with high traceability, visibility, and accuracy. Second, it enhances “SC11: transparency, anti-corruption, and anti-counterfeiting.” Providing transparent communication and fully auditable information eliminates the risks of corruption and fraudulent claims. Third, this technology promises to “SC12: fair operation and honest competition.” With the help of DLT, it is possible to monitor participants’ behavior in a P2P network to ensure that the nodes do not engage in anti-competitive behavior. Or, suppliers are selected based on fair competition and key performance indicators.

DLT can contribute to “EC8: circular economy” significantly. Companies can harvest technologies like DLT/blockchain for providing services/products based on circular economy principles (reusing resources, reducing waste, recycling materials, and minimizing carbon footprints) in a transparent and traceable way. DLT’s role in “EN2: digital communication” is also notable. DLT provides collaborative synergy and digital communication through distributed networks. Last but not least, it takes a while for emerging



a Weight of sustainability attributes for the project level



b Weight of sustainability attributes for the organization level

Fig. 3 The weight of sustainability attributes. **a** Weight of sustainability attributes for the project level. **b** Weight of sustainability attributes for the organization level. **c** Weight of sustainability attributes for the market

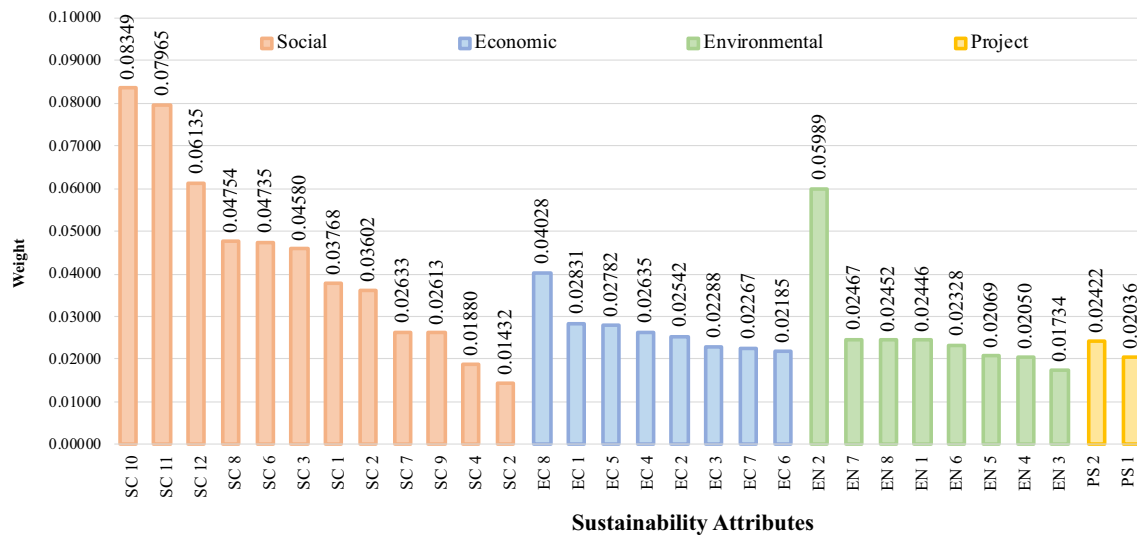
level. **d** Weight of sustainability attributes for the PESTEL-Macro environment level

technologies to enter the scene and presents new applications for construction projects. Accordingly, DLT has not proved its potentials on “PS1: product impacts” and “PS2: process impacts.”

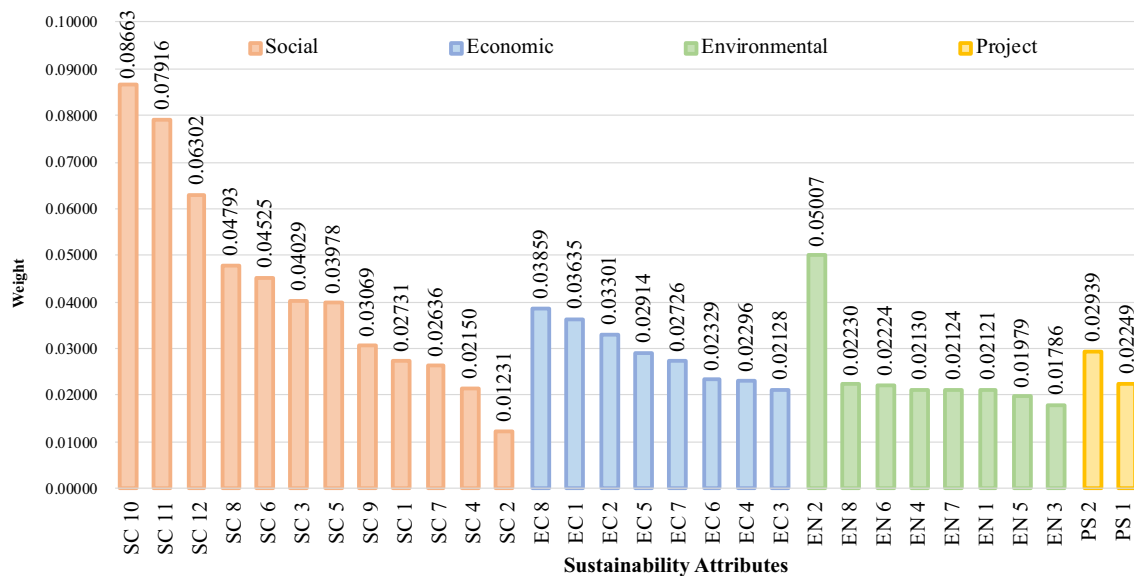
Ranking the barriers at the project level

In step 4 of OPA, experts were asked to rank 11 barriers for each sustainability attributes at the project level. After solving OPA in step 5, the result is illustrated in Figure 4.

As shown in Figure 4, “P5: infrastructure for data management” is the highest-ranked alternative with a weight of (0.10228). The integration of DLT and other technologies provides factual and real-time data on a large scale that can be used in the executive dashboard and data-driven decision-making. This technology requires infrastructure for data management, such as global positioning system (GPS) technology, protected collaborators, and sensors on project sites with sustainable connection and minimum shutdown. Both software and hardware should be resistant to any malfunctions and manipulations to capture, cluster, and store data



c Weight of sustainability attributes for the market level



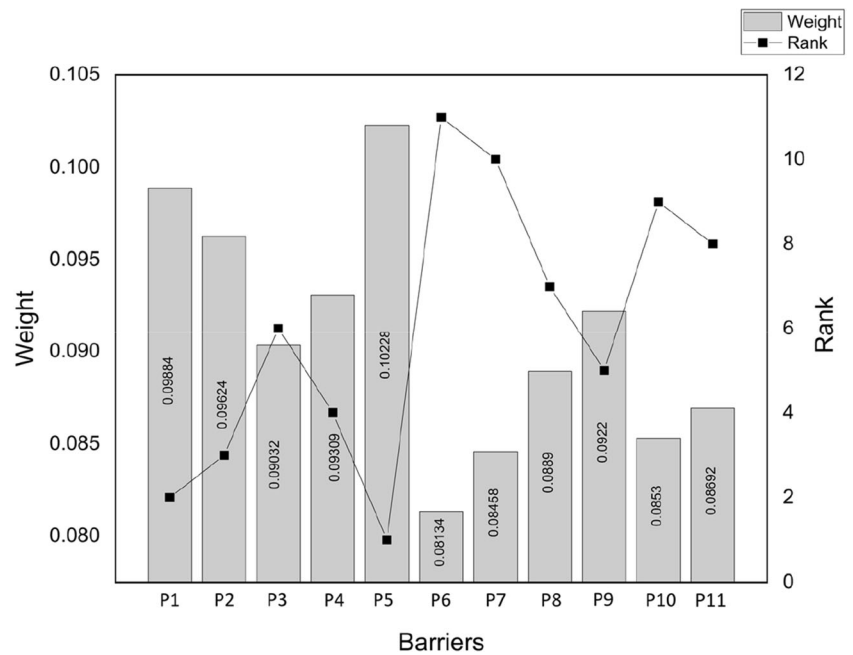
d Weight of sustainability attributes for the PESTEL-Macro environment level

Fig. 3 continued.

throughout the project life cycle for future business usage (Zhang et al. 2020). The next influencing alternative is “P1: abuse and fraud” with a weight of (0.09884). Shortly after the DLT/BCT penetration in projects, users will identify system bugs. As a result, scams and fraud are not entirely eradicated with this technology. “P2: manual processes and traditional practices” take third place with a weight of 0.09624. Automation may challenge traditional tools and techniques controlled by closed ledgers. In this case, companies may prefer commonly used practices like enterprise resource planning (ERP) due to the enormous effort and investment in implementing (Sheng et al. 2020) and trust in their efficiency (Wang et al. 2019).

“P4: Authenticity, consistency, and legitimacy of data” is the fourth important barrier that reminds the “garbage in, garbage out” concept. Poor data quality and corrupted inputs (Schmidt and Wagner 2019) and dispersal of inaccurate information (Saberri et al. 2019) will result in network failure. Information redundancy may also adversely impact the systems’ performance (Sheng et al. 2020) while transferring and storing large-size files (e.g., BIM documents). DLT/BCT requires sensitive data protection (Yang et al. 2020), information disclosure policy (Farooque et al. 2020), and consistent data for the execution of smart contracts (Li et al. 2019). With a slight difference, “P9: scalability problems” ranks fifth. It takes seconds to settle transactions, which is a long time for

Fig. 4 The weight and rank of barriers at the project level



construction projects where timing matters. This challenge may disrupt the performance of the internet of things (IoT), where a massive amount of data exchange continuously with DLT platforms (Tapscott and Tapscott 2016). Indeed, intelligent algorithms and high computational power for safe and secure transaction settlement are highly required (Chang et al. 2020a). “P3: irreversibility and immutability of the process” comes next, in the sixth rank. DLT/BCT has been struggling with long-lasting issues that may discourage stakeholders from using this technology which is the immutability of automated tasks and smart contracts (Saber et al. 2019; Sheng et al. 2020) and the lack of controlling mechanisms for automated tasks (Expert opinion).

P8, P11, P10, and P7 are alternatives with moderate importance on sustainability. Finally, “P6: contractual standards” is considered the least influential barrier with the lowest weight of 0.08134. According to the experts, construction projects need standard contractual models when technologies play a dominant role. This requirement is about agreement provisions, responsibilities of automated actions, risk distribution, change management, the parties’ right to issue a claim, and protocols to resolve disputes. It seems that experts did not find any association between this challenge and sustainability attributes.

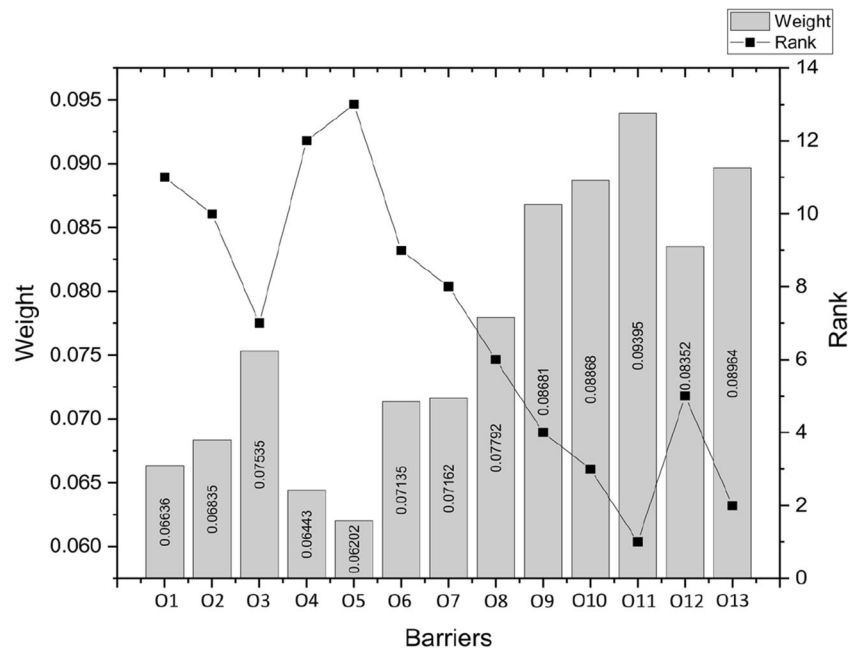
Ranking the barriers at the organizational level

In step 4 of OPA, experts were asked to assess 13 barriers and sort them in each sustainability criterion at the organizational level. After solving OPA in step 5, the result is illustrated in Figure 5.

As shown in Figure 5, O11, O13, and O10 are the three top-ranked barriers based on the obtained weights. “O11: lack of advanced applications and archetypes” is the most challenging, with a score of 0.09395. However, the Java Virtual Machine (JVM) enables programmers to develop various distributed applications (DApps); it seems that running applications still need a vibrant ecosystem. Moreover, the number of successful archetypes is not remarkable when the underlying technology is nascent (Mougayar and Buterin 2016). “O13: compatibility and inoperability” has a second position with a value of 0.08964. A decentralized network requires a complete series of digital levers (e.g., oracles, API solutions, and standardization) and data processing technologies (e.g., BIM, IoT, and AI) to operate efficiently (Wang et al. 2019; Chang et al. 2020b). Since these technologies are developed by various manufacturers and operate under specified protocols, architecture, engineering, and construction (AEC) entities will witness low compatibility among existing systems. “O10: system robustness and full technology stack” attained the third highest rank with a weight of 0.08868. Network stability, server capacity, internet bandwidth, continual connectivity, and trustworthy systems are required for data exchange with transparency, stability, and security without intermediaries (Yadav and Singh 2020). Lack of minimum technological requirements will result in data loss, break down the supply chain, and poor provenance of goods/services.

“O9: legacy systems” places as the fourth priority. Organizations are trying to address seamless integration of blockchain with available IT infrastructure (Wang et al. 2019) by upgrading existing legacy systems or replacing some pieces (Tapscott and Tapscott 2016; Saber et al. 2019). “O12: wide rollout and large-scale technology adoption” comes in

Fig. 5 The weight and rank of barriers at the organizational level



the fifth position. Organizational readiness, training staff, robust technology stack, and selecting appropriate DLT/blockchain systems are the requirements for real-scale adoption (Yang et al. 2020). “O8: scarcity in multidisciplinary experts and developers” ranks in sixth place in this group. Construction 4.0 is on the way, and organizations need well-trained teams of qualified individuals to address this new market (Chang et al. 2020a; Lohmer and Lasch 2020). Organizations also can alleviate this problem by outsourcing the implementation of DLT to qualified third-party consultants (Chong and Diamantopoulos 2020) or technology providers (Farooque et al. 2020).

O3, O7, O6, O2, and O1 come in seventh, eighth, ninth, 10th, and 11th rank as moderate-important barriers. “O4: financial constraints and cost of adoption” and “O5: uncertain return of investment (ROI)” are the least challenging barriers with the weights of 0.06443 and 0.06202, respectively. Although DLTs are free open-sourced platforms, top managers need a vivid picture of the cost breakdown structure (CBS) to allocate enough financial resources on platform development, operation, and maintenance (Esmaeilian et al. 2020; Chang et al. 2020a; Zhang et al. 2020). Nevertheless, prospect consequences, earned value, the return of investment (ROI), and sustainability contributions might be covered until the wide-scale deployment of DLT/blockchain (Bai et al. 2020; Chang et al. 2020b). It can be perceived that experts did not find any association between this challenge and sustainability attributes.

Ranking the barriers at the market level

In step 4 of OPA, experts were asked to sort eight barriers for each criterion, at the third layer of the construction ecosystem.

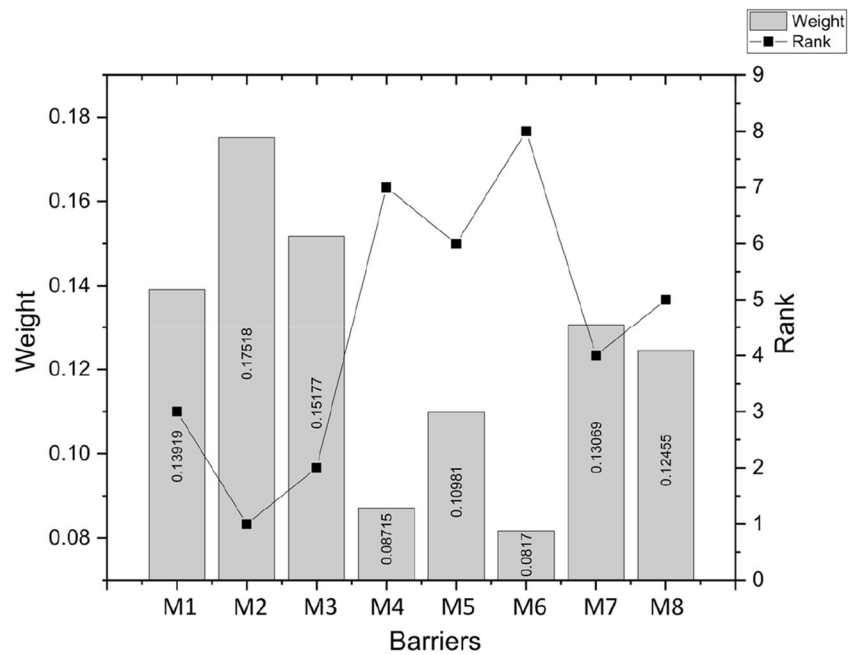
After solving OPA in step 5, the result is illustrated in Figure 6.

As shown in Figure 6, M2, M3, and M1 are the top-rated barriers with the weights of 0.17518, 0.15177, and 0.13919, respectively. According to “M2,” DLT/BCT adoption may not have stakeholders’ support and interest due to insufficient knowledge around underlying technology. Chang et al. (2020a) asserted that DLT adoption is a step-by-step process for high-quality products/services realized by communities’ support. “M3: low usability” comes in the second rank. The current DApps and software still need to improve customers’ journey and user interface (UI). “M1: network effects” comes in the third rank. DApps need critical mass users for better performance in the business environment (Wang et al. 2019).

In this order, “M7: technological state of the construction industry” comes in fourth place. In the digital transformation era, the construction industry may face skepticism, resistance, or ignorance toward technologies (Sawhney et al. 2020). Shifting from legacy systems to the distributed ledger is likely costly and accompanied by delays or even failures, particularly in the initial years for this industry. “M8: market competition and heavily regulated segmentations” comes in fifth place. Infrastructure and industrial construction projects have been in the government spotlight due to their pivotal role in producing strategic products, such as water, energy, electricity, and telecommunications. These segmentations are highly regulated, with no freedom for technology penetration like DLT/BCT, since the governing bodies set strict rules to secure the industries, market players, and customers (expert opinion).

The sixth sub-barrier is “M5: technical guidelines and standards.” DLT/BCT implementation is slowed down by the

Fig. 6 The weight and rank of barriers at the market level



absence of the technical guidelines, standards, and detailed roadmap for construction entities. Typically, standards are adopted from other industries or generated within the international collaboration, standard institutes, cross-industry strategic partnerships, or professional syndicates. In this particular case, the synergy between sectors or companies can provide solutions to technical challenges and make reference points more available (Bürer et al. 2019; Lu et al. 2019).

Finally, M4 and M6 are the least influencing alternatives in the implementation of DLT. Considering “M4: limited access to lesson-learned and practices,” not all technology firms have necessarily achieved fruitful results. They are often unwilling to share the lean knowledge and first-hand experiences gained through failure or success. Moreover, innovative concepts are isolated within industries, large-sized companies, and technology giants (Lohmer and Lasch 2020). Lastly, “M6: lack of insurance mechanism” comes as the least value in the order. Insurance is an undeniable part of the construction industry to protect projects from various risks and address claims based on factual data (Nawari and Ravindran 2019). One reason that can dissuade organizations from using emerging technologies is the low insurance coverage to address cyberattacks’ risks in the projects. It can be perceived that experts did not find any association between this challenge and sustainability attributes.

Ranking the barriers at the PESTEL-macro-environment level

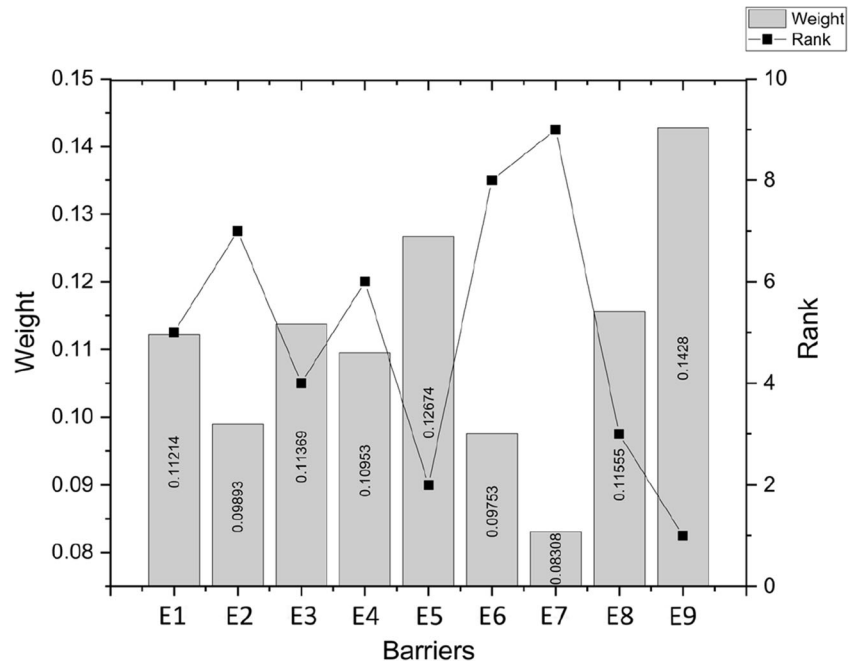
We identified nine barriers to DLT adoption at the macro-level of the construction ecosystem. In step 4 of OPA, the experts were asked to assess nine barriers and sort them in

each sustainability criterion. After solving OPA in step 5, the result is illustrated in Figure 7.

As shown in Figure 7, the top three barriers are E9, E5, and E8, with the weights 0.14280, 0.12674, and 0.11555, respectively. According to “E9: taxation and reporting,” this technology still requires development in capabilities like taxation, reporting, and auditing (Mougayar and Buterin 2016). “E5: lack of incentive and encouragement programs” comes in the second rank. Until recently, the construction industry has not demonstrated excellent performance in adopting corporate social responsibility (CSR) and sustainability principles. Lack of incentive/penalty system and limited resources and budget are some factors that impede implementing technology for sustainability (Zhang et al. 2020). “E8: compliance requirements” is the third most crucial barrier. Either compliance or non-compliance are overhead costs that squeeze profit margins. Compliance also keeps a business updated on related regulations and policies, with examples such as ISO, ASME, and OSHA in the construction industry and NEC3 and NEC4 for smart contracts (Penzes 2018).

E3, E1, E4, and E2 come in fourth, fifth, sixth, and seventh barriers with moderate importance. The last two less challenging barriers in the implementation of DLT/BCT are E6 and E7. “E6: high energy consumption,” in an eighth rank, discusses high energy consumption by DLT for computational power. Among consensus algorithms, the “proof-of-work” model consumes high energy for the hashing process and solving the cryptographic puzzles, which seem to be not economical, ecological, and environmental friendly (Mougayar and Buterin 2016), and organizations need sufficient electrical supplies for adopting blockchain (Chang et al. 2020a). “E7: legal issues” attained the last position in this group. DLT/BCT is independent of any central controls, and policymakers seek a way to regulate this

Fig. 7 The weight and rank of barriers at the PESTEL-macro-environment



technology to observe autonomous agents. On the other side, construction firms need laws and regulations for project execution. Hence, industries like the construction industry need governmental policies and transparent regulatory systems regarding emerging technologies (O’Dair 2018).

As mentioned in the research contribution, the current study is a pioneering attempt to evaluate the barriers and challenges of DLT application in the construction industry without any similar work. Nevertheless, a brief comparison has been conducted between the findings of the present paper and previous studies. The studies by Saberi et al. (2019), Biswas and Gupta (2019), Lohmer and Lasch (2020), and Kouhizadeh et al. (2021) mentioned that technical aspects of DLT prevent industries from adopting this innovative technology, while in this study, technical and technological challenges were out of scope. Our findings at the market level, such as “M8: market competition” and “M2: lack of customers’ demand, interest, and tendency” conform with findings of Biswas and Gupta (2019) and Bag et al. (2020), respectively. At the project and organization level, we found that challenges of “P5: infrastructure for data management” and “O10: system robustness and full technology stack” are in harmony with issues addressed by Farooque et al. (2020) about the immature underlying technology and collecting real-time supply chain data. The coverage of other aspects can be evaluated in future studies.

Conclusion

Distributed ledger technology, often called blockchain, is among the most disruptive forces that have revolutionized project

delivery, business models, and industries. The construction industry has no way to embrace technological breakthroughs for higher efficiency, productivity, smarter products, and services. A recent literature review shows that several barriers and challenges are facing the construction industry while adopting DLT. In this regard, we base the study’s foundation on identifying barriers and prioritizing them based on the sustainable development approach. To achieve the research objectives, we identified several barriers and sustainability attributes from the literature. To assess the applicability of factors in the construction sector, we targeted real-world case studies and gathered data from experts specialized in construction projects, sustainability, and emerging technologies.

This study’s contributions are employing OPA and solving model for ranking 41 barriers, weighing 30 sustainability attributes based on six qualified experts’ opinions. The findings revealed that “P5: infrastructure for data management” is the top-ranked barrier at the project level. At the organization level, “O11: lack of advanced applications and archetypes” is the most challenging alternative. At the market level, it can be perceived that “M2: lack of customers’ demand, interest, and tendency” is the most critical barrier. And finally, in the top layer of the construction ecosystem, DLT requires improvement in “E9: taxation and reporting.” Meanwhile, the obtained results show that addressing the high-ranked barriers can result in social sustainability in the most, then economic and environmental sustainability, and the least impact on project sustainability. In other words, alleviating challenges can result in “SC10: supply chain management and procurement,” “SC11: transparency, anti-corruption, and anti-counterfeiting,” and “SC12: fair operation and honest competition.”

Last but not least, we encountered some limitations within this study. The pandemic (COVID-19) overshadowed our virtual meetings to gather comments about alternatives and sustainability attributes. Second, to collect the data based on the sustainability approach, finding qualified and selecting experts took a long time. Experts should be chosen carefully based on competency requirements, including academic qualification, knowledge in construction, general understanding of DLT/blockchain, and relevant experience. Third, organizations that have already started to employ DLT were conservative in talking about their projects due to the loss of competitive advantages. In future studies, OPA can be utilized for making the optimal decision toward identified barriers and take response action accordingly. In a broader sense,

more research is needed to provide a detailed decision framework using OPA to help the project team and organization executives to implement DLT technology based on their preference and the needs of real-world situations. In addition, future studies can focus on the synergy between DLT and sister technologies; the challenges they may encounter; and the benefits they can bring to the construction industry.

Appendix A

Considering the fact that DLT can contribute to sustainability, how much the following ATTRIBUTES are important? Please sort the following SUSTAINABILITY ATTRIBUTES from 1 to 30

1. Name and Family Name Male Female Prefer not to say

2. Age range

<input type="checkbox"/> Below 18	<input type="checkbox"/> 19 ~ 25	<input type="checkbox"/> 26 ~ 30	<input type="checkbox"/> 31 ~ 35	<input type="checkbox"/> 36 ~ 40
<input type="checkbox"/> 41 ~ 45	<input type="checkbox"/> 46 ~ 50	<input type="checkbox"/> 51 ~ 55	<input type="checkbox"/> 56 ~ 60	<input type="checkbox"/> above 60

3. Country:

4. What is your academic qualification?

Bachelor Graduation Ph.D. candidate Ph.D.

5. What is your field of study?

6. Years of professional work experience:

<5 5~10 11~15 16~20 20 <

7. What is your current position?

8. Which Industry/ segmentations have you been working?

Construction IT/ Technology industry Start Ups: PropTech, FinTech, ConTech

	Very Poor	Poor	Medium Poor	Fair	Medium Good	Good	Very Good
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
9. Your general knowledge of Distributed Ledger Technology (DLT)/Blockchain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10. Your general knowledge of other emerging technologies (i.e., AI, ML, IoT, BIM)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

11. According to Questions 6,7, Do you have a similar professional experience?

11.1. Distributed Ledger Technology (DLT)/Blockchain Yes No

11.2. Emerging technologies Yes No

Rank	Sustainability attributes	DLT's contribution	References
PS. Project Sustainability			
	PS1. Product impacts	DLT tracks the lifecycle and servicing of the product.	R1, R2, R3, R5, R7, R10
	PS2. Process impacts	DLT controls the safety, effectiveness, efficiency, and fairness of the project processes.	R1, R3, R4, R5, R6, R7, R10
SC. Social Sustainability			
	SC1. Human resource management	DLT can be used throughout the acquisition and development of human resources within an organization.	R1, R3, R10
	SC2. Local competence development	DLT is a driving force to empower local resources, knowledge, and skills necessitated for technology adoption.	R1, R2, R6, R9
	SC3. Health and safety	DLT Ensures the health and safety of the end-users by providing traceable and reliable data of products.	R1, R3, R5, R7, R8, R10
	SC4. Community support and involvement	Collaboration among stakeholders will be increased through distributed ledgers.	R1, R2, R6, R8
	SC5. Public policy and compliance	DLT revolutionized regulatory compliance that accelerates complying with laws and regulations using smart contracts.	R1, R2, R5, R7
	SC6. Product and service labeling	DLT helps customers to obtain necessary information about ethical, sustainable, and green products and services.	R1, R5, R7, R9
	SC7. Flexible and innovative marketplace	DLT brings itself new market opportunities by promoting new products and services.	R1, R2, R3, R4, R6, R7, R8
	SC8. Customer care	DLT protects customer information and their financial transactions and provides personalized services accordingly.	R1, R2, R3, R4, R7, R9
	SC9. Age-appropriate and voluntary labor	This technology monitors fairness, non-discrimination, and equal opportunity for labors.	R1, R3
	SC10. Supply chain management and procurement	DLT integrates supply chain flows (products, financial, and information) in an automated, secure, and transparent manner	R11
	SC11. Transparency, anti-corruption, and anti-counterfeiting	DLT minimizes the risk of corruption and fraudulent activities by transparent information stored on the distributed ledgers.	R1, R3, R4, R5, R7, R9
	SC12. Fair operation and honest competition	Market players can easily monitor any anti-competitive behaviors and moral hazards using DLT.	R1, R2, R3, R4, R5
EN- Environmental Sustainability			
	EN1. Local procurement	DLT enables local and small suppliers to deliver their products and digital services in minimum time, cost, and transportation.	R1, R2, R6, R8, R9
	EN2. Digital communication	This technology can be leverage for communications and information-sharing among stakeholders.	R1, R3, R5, R8, R9
	EN3. Logistic and transportation	DLT enables the digital exchange of value within the P2P networks, which reduces unnecessary physical transportation and travel-related resources.	R1, R2, R3, R9, R10
	EN4. Energy and	This technology provides real-time data throughout the demand,	R1, R2, R3, R6, R7, R8,

Rank	Sustainability attributes	DLT's contribution	References
	materials consumption	supply, and consumption of energy and materials.	R9, R10
	EN5. Greenhouse gas emissions	Green certificates can be issued for activities based on historical information on greenhouse gas emissions.	R1, R2, R3, R5, R6, R7, R8, R10
	EN6. Contamination, pollution, and waste	Automated services and real-time control reduces pollution and wastes significantly.	R1, R2, R3, R5, R6, R7, R9, R10
	EN7-Natural resource management	DLT revolutionizes the way natural resources (i.e., water) are managed. It can digitalize supply, demand, and displacement of resources (i.e., water).	R1, R3
	EN8- Renewable and green energy	One potential use-case of DLT is distributed energy system (DES) to produce and distribute clean energy.	R1, R2, R3, R6, R8

EC- Economic Sustainability

	EC1. Modeling and simulation	Stored data can be utilized in organizational decision-making and business operations.	R1, R4, R6
	EC2. Financial benefits	DLT improves cash liquidity and enables near-zero transaction fees.	R1, R3, R4, R6, R7, R8, R10
	EC3. Return on investment (ROI)	Decentralized financial system and streamline investment evaluation in the long run	R1, R8
	EC4. Benefit-Cost Ratio	The value-added and benefits of DLT adoption is higher than the cost of development and implementation	R1, R2, R4, R5, R7, R9, R10
	EC5. Strategic value	Employing emerging technologies, like DLT, improves brand and business core values	R1, R4, R7
	EC6. Innovative business models	DLT offers new business models for new services and new products.	R1, R2, R3, R7, R8, R9
	EC7. Local economic growth	DLT impacts the nearby businesses and local community. It enables access to resources/ services and improved living standards.	R1, R3, R6
	EC8. Circular economy	The continual reuse, repair, and recycling practices in a closed-loop economic system	R1, R2, R3, R5, R7, R9, R10

R1 (GPM Global, 2019; Silvius et al., 2012), R2 (Esmaelian et al., 2020), R3 (Bai et al., 2020), R4 (De Giovanni, 2020), R5 (Kouhizadeh et al., 2021; Saberi et al., 2019), R6 (Petri et al., 2020), R7 (Farooque et al., 2020; Zhang et al., 2020), R8 (Bürer et al., 2019), R9 (Nandi et al., 2020), R10 (Kumar et al., 2021), R11 (Hofmann et al., 2018).

Table A3: List of barriers and challenges

	PS1	PS2	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	EN1	EN2	EN3	EN4	EN5	EN6	EN7	EN8	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8
Barriers to DLT implementation at the project level																														
P1. Abuse and fraud																														
P2. Manual processes and traditional practices																														
P3. Irreversibility and immutability of the process																														
P4. Authenticity, consistency, and legitimacy of data																														
P5. Infrastructure for data management																														
P6. Contractual standards																														
P7. Multiple chains and private systems																														
P8. Fragmentation and complexity of activities																														
P9. Scalability problems																														
P10. Low accountability control																														
P11. Financing models and debt instrument																														
Barriers to DLT implementation in Organization																														
O1. Organizational considerations																														
O2. New business model																														
O3. Shared governance																														
O4. Financial constraints and cost of adoption																														
O5. Uncertain return of investment (ROI)																														
O6. Digital representation of real-world objects																														
O7. Negative perception and insufficient understanding																														
O8. Scarcity in multidisciplinary experts and developers																														
O9. Legacy systems																														
O10. System robustness and full technology stack																														
O11. Lack of advanced applications and archetypes																														
O12. Wide rollout and large-scale technology adoption																														
O13. Compatibility and inoperability																														
Barriers to DLT implementation in Market/Industry																														
M1. Network effects																														
M2. Lack of customers' demand, interest, and tendency																														
M3. Low usability																														
M4. Limited access to lesson-learned and practices																														

Note! Sort alternatives from 1 to 11 based on their importance for each sustainability attribute.

Note! Sort alternatives from 1 to 13.

Note! Sort alternatives from 1 to 8.

	PS1	PS2	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	EN1	EN2	EN3	EN4	EN5	EN6	EN7	EN8	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8	
M5. Technical guidelines and standards																															
M6. Lack of insurance mechanism																															
M7. Technological state of the construction industry																															
M8. Market competition and heavily regulated segmentations																															
Barriers to DLT implementation in PESTEL macro-environment																															
E1. Technology accessibility																															
E2. Lack of governments' support																															
E3. Volatility of cryptocurrency and fluctuating exchange rate																															
E4. R&D projects and higher training programs																															
E5. Lack of incentive and encouragement programs																															
E6. High energy consumption																															
E7. Legal issues																															
E8. Compliance requirements																															
E9. Taxation and reporting																															

Note! Sort alternatives from 1 to 9.

Appendix B

following alternatives for each SUSTAINABILITY ATTRIBUTE based on procedures.

It seems that solving barriers to DLT implementation causes sustainability in the construction industry. Please, sort the

Table B1: List of Experts involved in survey

Experts ID	Academic qualification	Field of study	Experience in construction engineering or project management			Knowledge of DLT/blockchain	Experience in DLT implementation	Experience and knowledge in other emerging technologies (not mandatory)	Overall score
			Years of experience	Current Position	Industry/segmentations				
E1	Ph.D. candidate	Project management and construction engineering	8	Project coordinator and scholar	Construction: Project Financing	Very Good	Design Specification and Sprint Plan for business use-cases	BIM	18
E2	Graduation	Project management and construction engineering	18	Project manager	Construction: building and real estate	Satisfactory	Academic Research	BIM, drones, and 3-D printing	15
E3	Ph.D. candidate	Electrical engineering (control systems) (Prince II certified)	5	Technologist and scholar	PropTech, ConTech, and Fintech	Good	Developing and technical supporting	Oracles, sensors, clouding, big data, AI, and ML	14
E4	Ph.D.	Computer engineering	25	Project manager	PropTech, ConTech, and Regtech	Excellent	Whole PLC (Scaling and commercialization)	-	22
E5	Ph.D. candidate	Engineering management (PMP Certified)	11	Project manager	PropTech, ConTech, and Fintech	Good	Feasibility study and applied research	-	14
E6	Graduation	Project management and construction engineering	20	Portfolio manager	Construction: building and real estate	Good	Academic Research	BIM	16

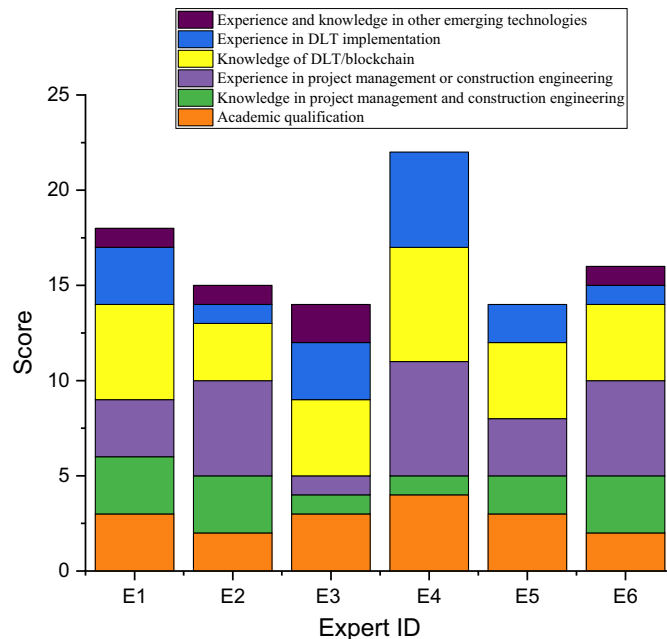


Figure B1: Comparison of exporters' competencies

Table B2: Demographic profile of the respondents

Experts ID	Gender	Age Range	Country
E1	Female	30- 35	China
E2	Female	35- 40	Canada
E3	Male	30- 35	USA
E4	Male	45-50	Iran
E5	Female	35- 40	Azerbaijan
E6	Male	50-55	Iran



Figure B2: Demographic profile and geographical locations of the respondents

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Author contribution Mahsa Sadeghi: conceptualization, methodology, software, and writing—original draft. Amin Mahmoudi: conceptualization, methodology, software, and writing—original draft, review, and editing. Xiaopeng Deng: validation, writing (review and editing), and supervision.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human participants or animals performed by any of the authors. All authors participated in this article.

Consent for publication All the authors consent to publish this research paper.

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