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Review

Exploratory literature review of blockchain in the construction industry

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ABSTRACT

First academic publications on blockchain in construction instantiated in 2017, with three documents. Over the course of several years, new literature emerged at an average annual growth rate of 184%, surmounting to 121 documents at time of writing this article in early 2021. All 121 publications were reviewed to investigate the expansion and progression of the topic. A mixed methods approach was implemented to assess the existing environment through a literature review and scientometric analysis. Altogether, 33 application categories of blockchain in construction were identified and organised into seven subject areas, these include (1) procurement and supply chain, (2) design and construction, (3) operations and life cycle, (4) smart cities, (5) intelligent systems, (6) energy and carbon footprint, and (7) decentralised organisations. Limitations included using only one scientific database (Scopus), this was due to format inconsistencies when downloading and merging various bibliographic data sets for use in visual mapping software.

1. Introduction

Blockchain is the technology that enables triple entry accounting, which allows multiple parties to transact across a shared synchronous ledger. Each transaction is substantiated with a digital signature to provide proof of its authenticity [1]. Blockchain includes several key features, such as decentralised, distributed, and consensus [2]. A typical public blockchain is comprised of thousands of computer nodes connected through a decentralised network, and it does not require a central power of authority to manage the system [3]. Blockchain is a self-sustaining network that rewards users for participating in mining, which is the process of creating new blocks and distributing them across all nodes on the network [4]. Whenever transactions are sent to the network, they are placed in a pool of unverified transactions, where they are periodically collected and validated by miners before they are placed into a block [5]. Miners apply a consensus mechanism to check each other's results prior to the inclusion of new blocks, this is to ensure that there is only one version of the ledger in existence at any moment in time [6]. Bitcoin was the first blockchain which came into existence in 2009, since then, its protocol has proved immutable to hacks and has not suffered accounting errors, such as double spending [7]. Ethereum was the second blockchain to come into existence, which emerged in 2015 and introduced smart contracts, which allowed transacting parties to codify and deploy peer-to-peer agreements without the reliance of a trusted third party [8]. Smart contracts include a unique property, in that they cannot be changed once deployed, which mitigates against users unfairly withdrawing from signed agreements [9]. Smart contracts disallow external entities from interfering with peer-to-peer contracts and enables atomic transactability. The codified terms of a smart contracts are transparent and open for auditing, which allows transacting parties to verify agreements for consistency.

The timescale of this review spans from 2017 to 2021 and incorporates 121 academic documents. A bottom-up method was implemented to assess the existing environment through a literature review, which includes an exploratory investigation of the progression of the topic across a wide range of application categories. The document types used in the review are comprise of journal articles, conference papers, and book chapters. Non-academic sources such as company reports were not included into the review as they do not include the same level of scientific rigor as peer-reviewed content, furthermore, the quantity of documents attainable from academic sources were of sufficient quantity.

Two search queries were conducted on the Scopus scientific database, which was used to obtain all of the reviewed documents. The *research method* chapter displays the structure of these queries diagrammatically; furthermore, the search string for retrieving the results is available in the appendix, which allows users to replicate the search results. Other scientific databases that were considered include Web of Science (WoS), IEEE Xplore, Science Direct, Directory of Open Access Journals (DOAJ), and JSTOR [10]. Based on the topic of blockchain in construction, Scopus and WoS included the largest quantity of results by

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a substantial margin. In a comparison of these, it revealed Scopus with 53% more content, and with 85% of the WoS data already existent in Scopus. Both databases included a balanced range of top tier journals (top 25% based on Scientific Journal Ranking indicator), while Scopus included a larger number of mid to lower tier journals.

The first academic literature on blockchain in construction emerged in 2017 within the categories of Building Information Modelling (BIM) [11], smart cities [12], and peer-to-peer energy markets [13]. The quantity of new publications on topic increased at an annual growth rate of 184% each year since 2017. The quantitative aspect of this article provides data on the expansion of the topic through statistics and scientometrics. VOS-Viewer was used to present scientometric data through visual mapping. The literature review chapter was structured around application categories of blockchain in construction. Each category was substantiated by a minimum of three documents to ensure a level of academic consensus was achieved. Altogether, 33 application categories were investigated and organised into seven subject areas, which are (1) procurement and supply chain, (2) design and construction, (3) operations and life cycle, (4) smart cities, (5) intelligent systems, (6) energy and carbon footprint, and (7) decentralised organisations. An exploratory method was implemented to encapsulate a wide range of categories to investigate the existing environment through a macro-orientated approach. This method aligns with the quantitative analysis that was conducted as part of this review.

1.1. Related works

From the 121 reviewed documents in this article, six included reviews of similar nature and are displayed in Table 1. From these, four delimited their results to academic documents, while two incorporated a combination of academic and non-academic sources. The *N*on-academic material included company and organisation reports [14]. An expansive literature review of 121 documents on blockchain in construction from academic publications have only recently been feasible since 2021, as there is now an established body of work on the topic. Blockchain is a fast-evolving technology, and this article builds upon the work displayed in Table 1 to provide an updated review on the contemporary state of the topic.

Bhushan et al., conducted a comparative literature review of blockchain in smart cities, published in Sustainable Cities and Society journal, which outlined six subject areas and eight categories [15]. Hunhevicz & Hall, produced a literature review of blockchain in construction, published in Advanced Engineering Informatics journal, which included seven categories and 24 use-cases [16]. Kiu, et al., composed a systematic review of blockchain in construction, published in the International Journal of Construction Management, and outlined six subject areas [14]. Li et al., composed a systematic literature review published in Automation in Construction, which extrapolated seven built environment application categories; furthermore, three use-cases were substantiated through interviews with academics and industry practitioners, such as “automated project bank accounts”, “regulation and compliance”, and “single shared-access BIM model” [17]. Perera, et al., produced a literature review article on blockchain in construction published in the Journal of Industrial Information Integration, and identified 18 categories, extracted from academic and non-academic sources [7]. Yang et al., included a literature review in their blockchain proof of concept article published in Automation in Construction, which summarised four subject categories for managing business processes [18].

Table 1
Related works.

Author	Year	Categories	Use-cases	Ref. count	Review type
Bhushan, et al.,	2020	6	10	42	Literature
Hunhevicz & Hall	2020	7	24	15[a]	Literature
Kiu, et al.,	2020	6	[b]	57[a]	Systematic
Li, et al.,	2019	7	3	75	Systematic
Perera, et al.,	2020	18	[b]	27[a]	Systematic
Yang, et al.,	2020	4	[b]	83	Literature

Note:
[a] Includes content from non-peer reviewed sources (e.g., reports).
[b] Includes many use-cases that were not individually itemised by its author.

2. Research method

Content was collected from journal articles, book chapters, and conference proceedings. Scopus was selected as the scientific database for extracting documents, as it contained the largest bibliographic index of academic literature on the topic, and is reputably owned by publishing organisation Elsevier [19]. Reason for using only one scientific database is due to format inconsistencies when merging data sets from various databases. When conducting a parallel search on Scopus and Web of Science (WoS) (the top two largest academic indexes on the topic) [20], it revealed Scopus with 53% more content, and with 85% of WoS documents already existent in Scopus, thus Scopus was selected as the database of choice.

Fig. 1 displays the two search queries. Search one incorporated inputting the ISSN and ISBN numbers of journals and books within the subject category of architecture, building and construction, and civil and structural engineering, followed by the key words shown in the search query column in Table 1. The ISSN and ISBN number is a unique identifier given to each journal and book, which can be downloaded from https://www.scimagojr.com. The SCImago web portal provides an index of academic publishers for each specific subject area [21]. The Scopus web portal allows users to search for documents according to a predefined list of subject areas, in this case SUBJAREA(engi) was implemented into query two, with key terms such as blockchain and construction. Two queries were used to increase the accuracy of results from Scopus, which returned to a combined total of 412 documents. Upon removing duplicates and filtering content for suitability, the final result surmounted to 121 publications.

3. Quantitative analysis

Fig. 2 displays the quantity of documents published each year, documents types, and scientific journal rankings (SJR). SJR is the impact factor of each journal, which is calculated through a network analysis of citations [22]. SJR is measured in quartiles, whereby, Q1 represents the top 25% of journals, while Q4 is the lowest 25% [22]. The statistics in Fig. 2 were obtained through conducting a search using the queries listed in Fig. 1. The results in Fig. 2 are based on full complete years, in this case 2017–2020. This article was written in 2021, thus results from that year were not included.

The subject areas and categories of the literature review are displayed in Fig. 3. Each category was substantiated by a minimum of three documents to ensure a level of academic consensus was achieved. These categories were further organised into seven subject areas for the purpose of adding structure when organising correlating categories together.

Fig. 4 displays a timeline showing when each of the reviewed categories emerged in literature. The colours in Fig. 4 are assigned in conjunction with Fig. 3. The first publications on blockchain in construction instantiated in 2017 with three documents and six categories, 2018 included 9 new publications (200% increase from previous year) with nine new categories, 2019 displayed 33 new publications (267% increase) with 13 new categories, while 2020 included 69 new publications (109% increase) with five new categories. Altogether totalling the 33 categories. At time of writing this article in early 2021, there were no new additions to the category list.

The category with the highest number of publications include building information modelling (BIM) with 39 documents. Joint second

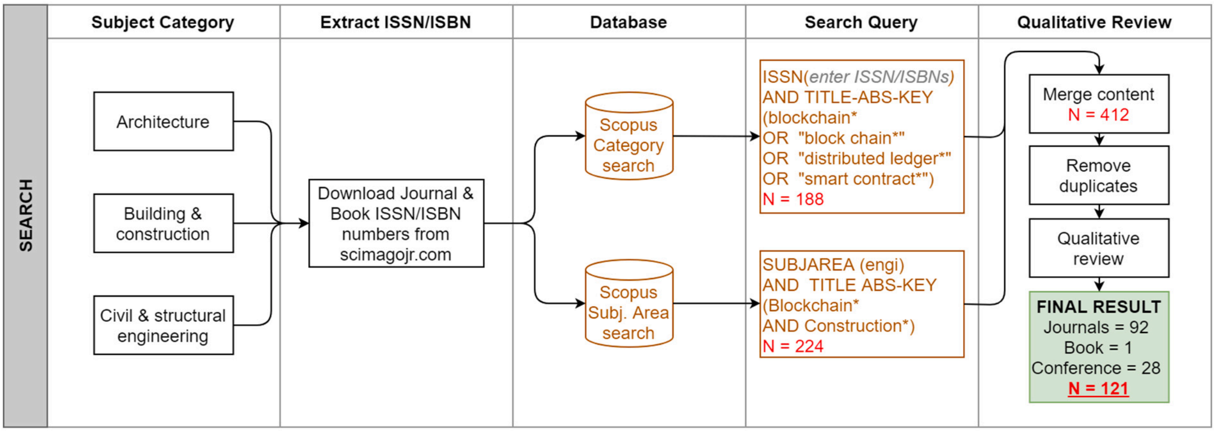

Fig. 1. Search query process that was used to obtain the results from Scopus.

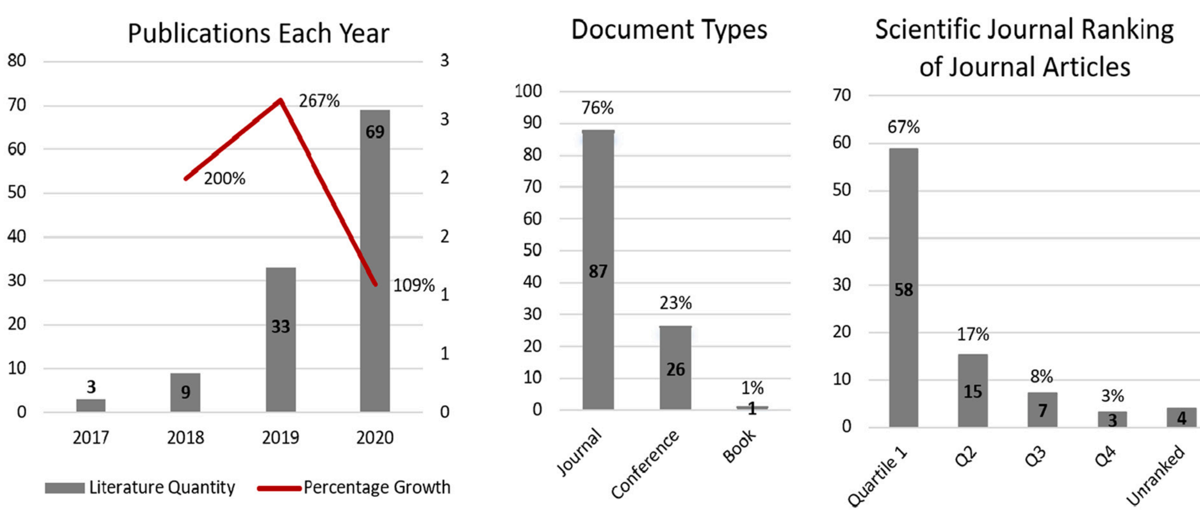

Fig. 2. Quantity of published content each year, document types, and SJR rankings.

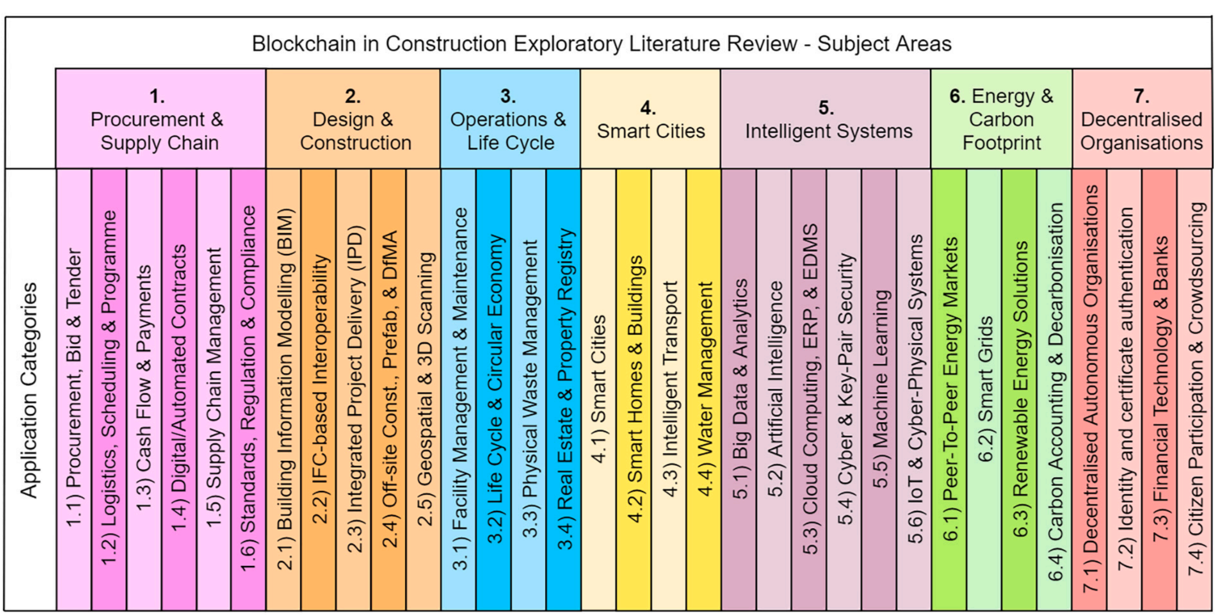

Fig. 3. The 33 reviewed categories organised into seven subject areas.

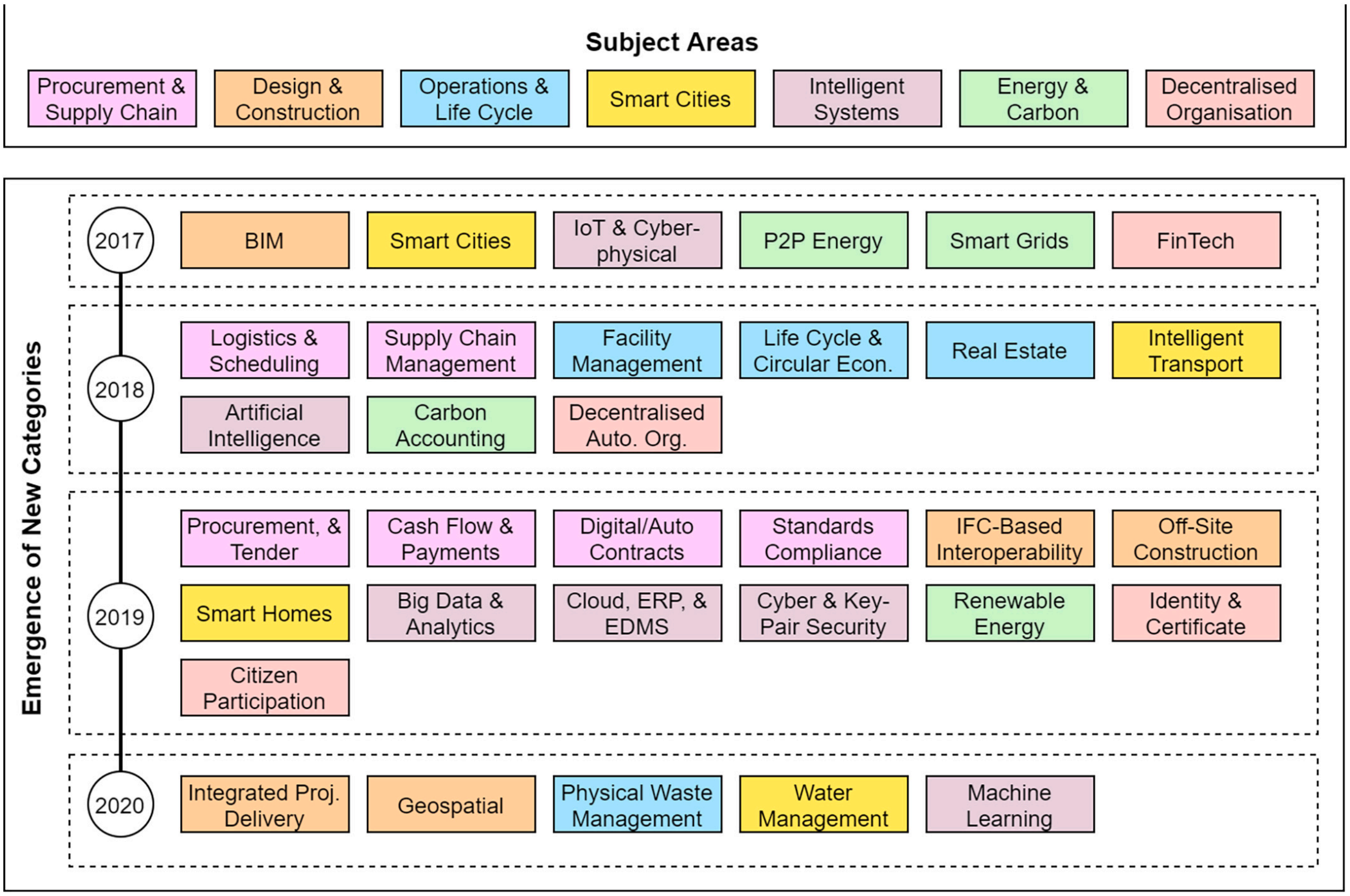

Fig. 4. Timeline showing the emergence of each category from 2017 to 2020.

with 28 documents each includes internet of things (IoT), supply chain management, and smart grids. While peer-to-peer energy markets is third place with 27 documents. The newest categories which emerged in 2020 included machine learning, water management, physical waste management, geospatial, and Integrated Project Delivery (IPD).

The topical coverage of each of the 121 reviewed documents were manually recorded and transferred into visual mapping software VOS-viewer, to produce the Fig. 6 visual map. VOS-viewer algorithmically maps data using natural language processing techniques [23]. Fig. 6 is broken down into three parts, which includes *categories* (shown as circular nodes), *colour clusters* (shown as the groups of nodes displayed in blue, green, yellow, or red), and *links* (which are the lines that connect the nodes together). Each of the reviewed documents typically covered a range of categories. Illustrating the overlap/co-occurence of these categories is the purpose of the Fig. 6 co-occurrence map. Colour clusters are assigned when a group of categories frequently co-occur in the reviewed documents. Categories with a high number of shared links naturally gravitate to the centre, as a central position has greater equidistance with its shared links. However, categories also gravitate to each other based on their link strength, whereby, if two categories appear frequently together in literature, they will be positioned close to each other on the Fig. 6 map. *Blockchain* was positioned most centrally as it shares links with all of the 33 categories. *BIM* was also positioned centrally as it shared links with 32 out of the 33 total categories. Whereas *IPD*, *carbon accounting*, *fintech* and *off-site construction* were all positioned in the outskirt, due to their low number of shared links with the overall categories.

Table 2 displays the results from Fig. 6. The table is sorted from largest to smallest according to *links*, followed by *link strength*, then *occurrences*. The *Link strength* is calculated by the number of times each category co-occurs with another. While the *occurrences* is calculated by the number of times each category appears in literature irregardless of its link strength. The results show that 89% of the reviewed documents included multiple categories in their paper, while 11% focused their attention solely on one category.

Fig. 7 displays which blockchain platforms were most utilised in the reviewed documents. 18 documents developed solutions for Ethereum [8], while 14 developed solutions for Hyperledger [24]; additionally, one publication investigated utilising both platforms [18]. Ethereum emerged in 2015 as a public blockchain platform; furthermore, it is currently the leading platform for decentralised applications and includes the largest population of blockchain developers [25]. Hyperledger, by the Linux Foundation, instantiated their own variant in the same year (2015) using a private blockchain protocol [26]. Less popular platforms in the reviewed material include Multiledger [27], Bitcoin [28], Corda [29], and IOTA [30].

Fig. 8 displays the various types of data collection implemented in the reviewed documents. A conceptual framework was incorporated in 46% of documents, which was used as a foundation to formulate high-level ideas [31]. Case studies were also a popular method used in 27% of documents, which included joint ventures between academia and industry [32]. Literature reviews were used in 26% of the documents, which were typically implemented as a prerequisite to support the development of conceptual frameworks [33], such as with the Brooklyn micro-grid project, which used a literature review to assess the existing environment prior to the implementation of a case study [34]. Statistics was incorporated in 23% of documents, such as with measuring the performance of blockchain-based network systems [35]. The types of data collection which appeared less frequently included systematic reviews (12%), proof of concepts (12%), interviews (7%), surveys (7%),

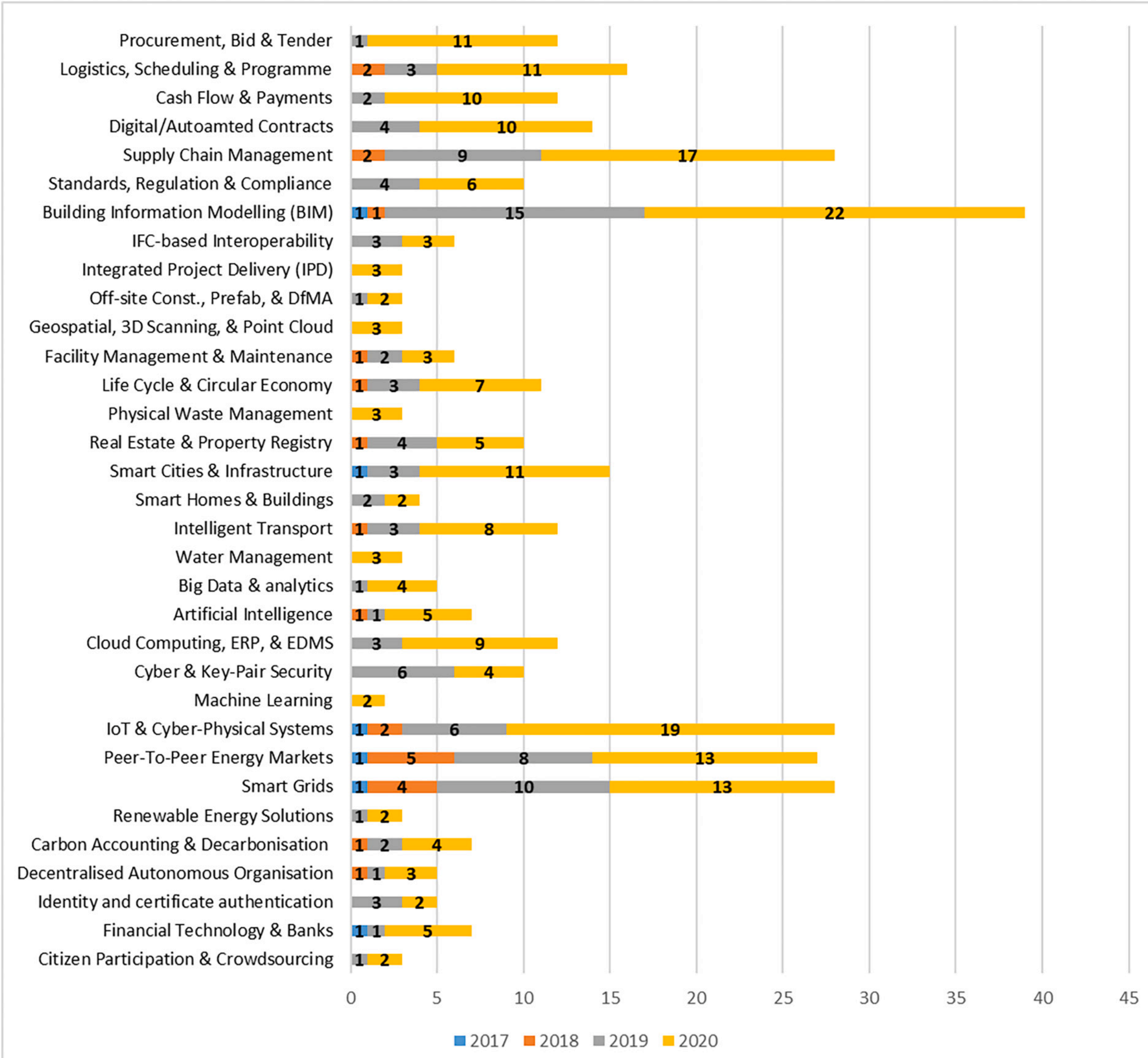

Fig. 5. Quantity of publications published for each category from 2017 to 2020.

and questionnaires (1%).

Fig. 9 displays a visual map showing the co-occurrences of the data collection types shown in Fig. 8. Fig. 9 displays *links* shown in red numerals and *link strength* shown in blue numerals. From analysing the diagram, the top three data collection types which co-occurred most frequently in the reviewed literature included conceptual frameworks, statistics, and case studies, demonstrated through their high *link strength* count shown in blue numerals. The outer position of systematic reviews revealed that it co-occurred less frequently than literature reviews, however, this particular statistic can be misleading, as both *systematic* and *literature* reviews are terms used interchangeably throughout research; however, the author ensured not to interfere with the terminologies provided in the reviewed documents. 12 publications conducted a proof of concept (PoC), which surmounts to 10% of the reviewed documents. The data collection types with the least number of co-occurrences included questionnaires, systematic reviews, and surveys. Altogether, 55% of the reviewed documents incorporated multiple data collection types in their research, while 45% included only one. Through conducting this review, the author noticed that papers which included higher numbers of data collection types were typically less technical overall, such as literature/systematic reviews. While papers which included only one data collection type were typically more in-depth, such as with a PoC.

Table 3 is to be read in conjunction with Fig. 9, and is organised according to *link count*, *total link strength*, and *occurrences*. Link count refers to the quantity times a particular type of data collection co-occurs with another; however, it does not take into account the weight if each link. Whereas *link strength* factors in the weight, which refers to the cumulative total of when each link co-occurred with another. The *occurrences* column represents the quantity of times each data collection type occurred in literature regardless of its links or link strength.

4. Literature review

The literature review is broken down into seven sections, which is represent by the seven subject areas listed in Fig. 3, these are (1) procurement and supply chain; (2) design and construction; (3) operations and lifecycle; (4) smart cities; (5) intelligent transport; (6) energy and carbon footprint; and (7) decentralised organisations. Each subject area includes several application categories, these were grouped according to their correlation. The subject areas and categories were selected following a bottom-up approach. This was conducted without a predefined or systematic strategy on which topics to cover, provided that it was in conjunction with the construction industry or built environment.

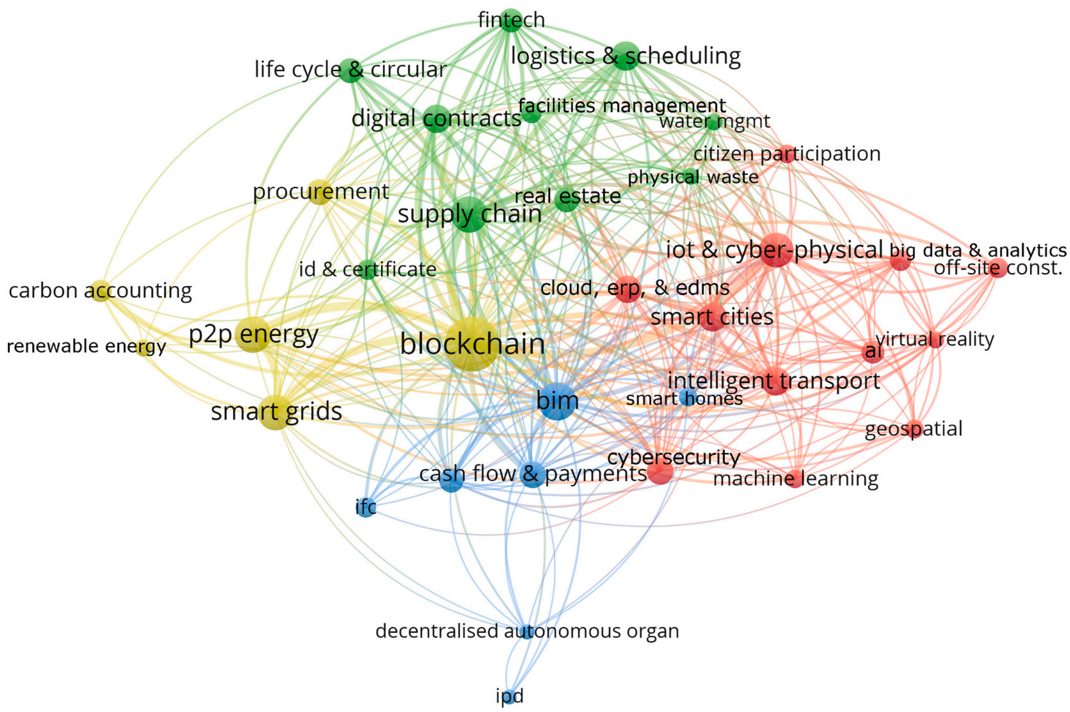

Fig. 6. Co-occurrence map of the 33 reviewed categories.

Table 2
Presents the values of the categories displayed in Fig. 6. The colours labelled in the 'Clusters' column is representative of the colour clusters shown in Fig. 6.

Categories	Link	Total link strength	Occurrences	Cluster
BIM	32	146	37	Blue
Supply chain	29	132	31	Green
IoT & cyber-physical	27	131	27	Red
Intelligent transport	27	79	15	Red
Smart cities	25	73	15	Red
Cybersecurity	25	54	12	Red
Logistics & scheduling	24	81	16	Green
Cash flow & payments	24	56	12	Blue
Smart grids	23	84	29	Yellow
Digital contracts	22	70	14	Green
Cloud, ERP & EDMS	22	61	13	Red
FinTech	21	57	9	Green
Standards	21	40	9	Blue
Real estate	20	48	10	Green
AI	20	47	8	Red
Physical waste	20	28	3	Green
Water mgmt	20	28	3	Green
P2P energy	19	95	31	Yellow
Citizen participation	19	26	4	Red
ID & certificate	18	29	5	Green
Big data & analytics	17	39	6	Red
Smart homes	17	26	4	Blue
Facility mgmt	16	25	5	Green
Life cycle & circular	14	44	10	Green
Procurement	14	36	11	Yellow
Geospatial	14	25	4	Red
Machine learning	14	21	4	Red
Off-site const.	11	27	5	Red
Decentralised Autonomous Organisation	10	12	3	Blue
Carbon accounting	8	19	7	Yellow
IFC	8	16	5	Blue
Renewable energy	6	8	3	Yellow
IPD	4	6	3	Blue

The process followed an organic progression through manually making note on a spreadsheet the topical coverage of each of the review documents, as shown in the shared Google spreadsheet following the link provided below.

https://docs.google.com/spreadsheets/d/1V4UICRdoyWycaGENH9rnuxukRNQJFIArQ-feV7NM0a4/edit?usp=sharing

4.1. *Procurement and supply chain*

This section is comprised of six application categories grouped into the procurement and supply chain subject area. Altogether, this subject area was discussed in 57 out for the 121 documents and is focused on pre-construction activities.

Procurement, bid, and tender (discussed in 12 documents). In a survey conducted by Kim, et al., based on theme of lifecycle, project management, and blockchain, and from respondents in construction industry, the top three applications for blockchain emerged as bidding, procurement, and change management [36]. Lack of trust is particularly evident in procurement, and current management practices requires innovating to improve the ability to track provenance of faults, trace contract alterations, and drawing revisions, while minimising information asymmetry during the tender process [37]. Based on a questionnaire and survey by Isikdag, of 64 industry practitioners in construction industry, consisting of architects, engineers, contractors, and subcontractors, e-procurement appeared to offer very few benefits compared to its non-electronic counterpart, furthermore, the primary barrier to e-procurement includes a lack of trust in supply chain, unsatisfactory legal infrastructure, and inadequate cybersecurity for storing confidential data [38]. Moreover, Isikdag, stated that blockchain can potentially be used to provide the vital infrastructure required to support privacy without the risks associated with centralised storage; furthermore, he discussed how e-procurement lacks standardisation from regulatory bodies [38].

Logistics, scheduling and programme (discussed in 16 documents). Logistics management has become increasingly complex due to globalisation [39]. Kifokeris, et al., performed a case study of seven Swedish logistics consultancies, which outlined that "delivery failure, imprecise

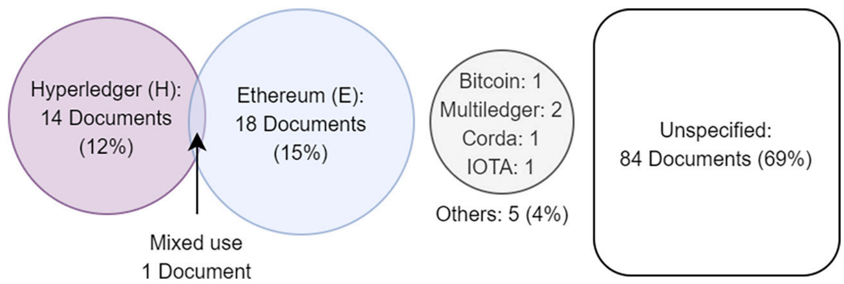

Fig. 7. Utilisation of blockchain platforms in the reviewed documents

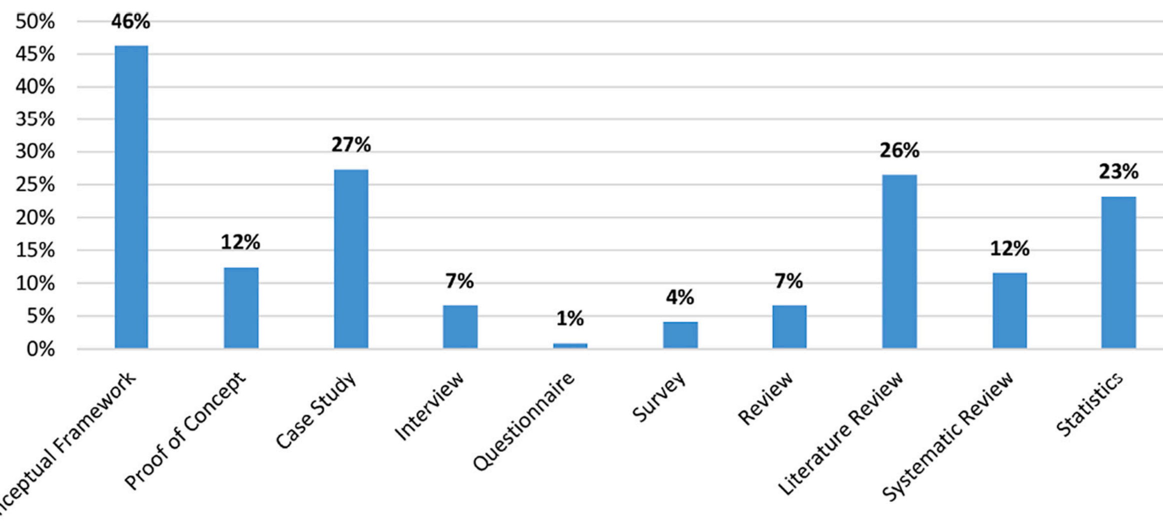

Fig. 8. Data collection types existent in the reviewed documents.

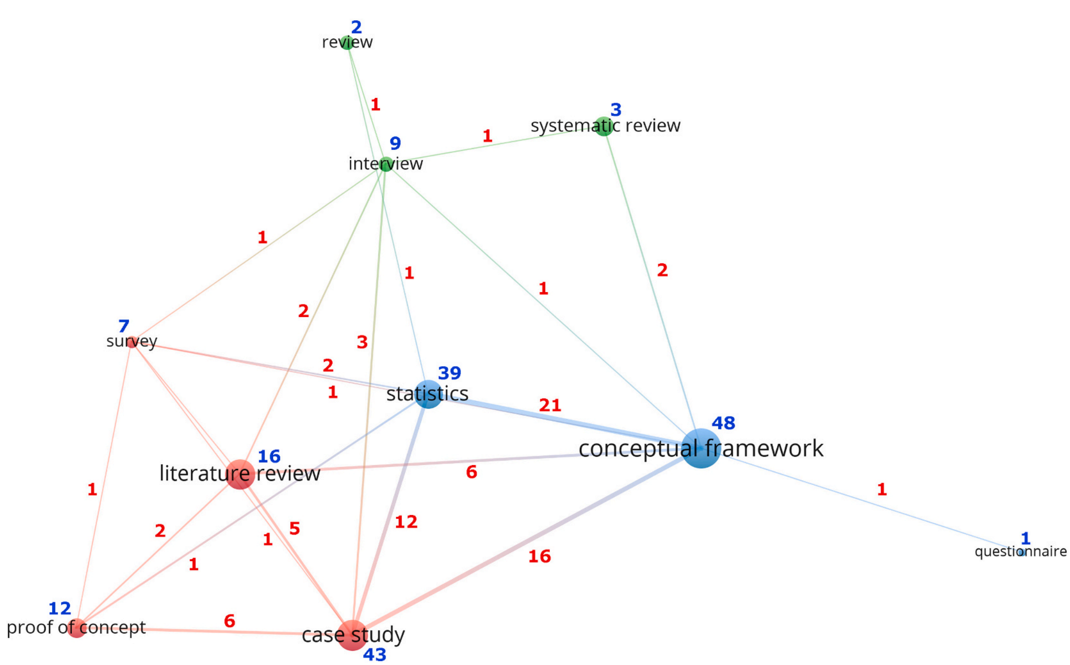

Fig. 9. Co-occurrence map of the data collection types.

data, delays in time, inefficient flows and data transfers between systems" are limitations in existing logistics processes, and discussed the lack of cyber-physical systems integration and analytics in managing on-site assets [39]. Moreover, he proposed a blockchain solution for logistics, using a crypto-economic model to incentivise collaboration [39]. Lanko, et al., considered that existing centralised computer systems are

Table 3
Presents the values of the data collection types displayed in Fig. 9. The numerals highlighted in bold in the 'Total link strength' column are the same values as the blue numerals shown in Fig. 9.

Data collection type	Link count	Total link strength	Occurrences
Conceptual framework	7	**48**	52
Case study	6	**43**	32
Interview	6	**9**	8
Survey	6	**7**	5
Statistics	5	**39**	27
Literature review	5	**16**	31
Proof of concept	4	**12**	13
Systematic review	2	**3**	12
Review	2	**2**	7
Questionnaire	1	**1**	1

susceptible to data manipulation, and proposed a framework which incorporated blockchain with RFID for managing logistics of ready-mixed concrete on-site, whereby, RFID tags are used to record stages of delivery, such as pouring, transportation, handling, quality inspections, and mould forming, with all data exchanges recorded on the blockchain [40]. Blockchain in logistics provides opportunities in offering improved service to clients through automating the process of storing and authenticating data with increased trust, furthermore, decentralised applications potentially reduce the resource requirements in managing systems efficiently [41].

Cash flow and payments (discussed in 14 documents). Chong & Diamantopoulos conducted a case study on a project in Melbourne, Australia, that used blockchain to automate payments; Furthermore, works included the delivery of 5000 building façade panels tracked with Bluetooth sensors to monitor live location of each panel from factory in China to on-site, with BIM used to monitor installation of each panel, while smart contracts executed payments at delivery checkpoints [42]. Additionally, this integrated with a mobile phone application which allowed project participants to view progress of installation in real-time [42]. Ahmadisheykhsarmast developed an add-in for Microsoft Project using programming language C-sharp and Visual Studio, which allowed smart contracts to integrate with mainstream project management software; furthermore, blockchain platform Ethereum, with its native programming language Solidity, was used to link the front and back-end functions of the user application that connected blockchain to Microsoft Project [43].

Late payments is a major problem in construction, caused by contractors performing cash farming, which is the process of withholding supply chain payments to sustain positive cashflow while aggressively investing in new work [44]. Das, et al., proposed a conceptual framework that enabled smart contracts to control the release of payments to supply chain which includes integration with banking systems, furthermore, he discussed the potential to integrate with strategies such as Project Bank Account (PBA) [45].

Digital and automated contracts (discussed in 14 documents). McNamara & Sepasgozar conducted an interview of industry practitioners in the construction industry and derived that trust, risk, and dispute management were ubiquitous concerns in almost all projects, with main contractors exerting dominance through unfair contract conditions [46]. In a survey conducted by Badi et al., of 104 respondents in the UK construction industry, regarding the use of smart contracts, the main factors which determined its adoption in enterprise is competitive edge and commercial value [47]. Hunhevicz, et al., proposed a digital contracting framework which simulated the decision points of a typical design-bid-build project in Switzerland, which included the client, owner, planner, contractor, and supplier, all interacting with smart contracts to control the approvals and validations process of contract activities, such as project definition, design coordination, tendering, supplier selection, and contract signing; furthermore, this was prototyped through a web-based application connected to the Ethereum blockchain [48].

Supply chain management (discussed in 30 of documents) Qian & Papadonikolaki conducted interviews of industry practitioners in the construction industry that are knowledgeable in supply chain and blockchain, and identified that blockchain can potentially be used to mitigate the trust problem in construction, through data traceability, non-repudiation, and disintermediation; furthermore, it was projected that blockchain can save up to 70% on costs associated with data processing and management, through automating compliance checking, payments, and analytics on project performance [49]. Sheng, et al., proposed a framework which allowed project participants to assess compliance to standards and monitor information exchanges through a user application, where project participants would upload data associated with contract documents, project schedule, and cost; furthermore, the application would autonomously notify users of their responsibilities to upload or approve works, which automated the processing of payments and completion certificates [50]. Dutta, et al., conducted a systematic review of blockchain in supply chain and identified several key attributes where blockchain can improve performance, such as evidentiary trail of delivered works substantiated with immutable data, resilience from network disruption, improved data synchronicity, data trust in cyber-physical systems, business process automation through smart contracts, and improved tracking of product revisions [51].

Standards, regulation, and compliance (discussed in 10 documents). The transparent and irrefutable properties of the blockchain make it a suitable technology for trialling whether smart contracts can be used to automate the compliance checking of objects in BIM models [52]. Nawari & Ravindran proposed an automated regulation and compliance checking framework for BIM, whereby, modelling elements are scanned and cross-checked with client specifications, which autonomously notifies designers of their obligations to make design alterations [53]. Blockchain can also be used as a decentralised authority to provide BIM objects with copyright verification, through a lookup service that checks the intellectual property signature of a BIM object, and cross-checks it with data stored in a distributed database; furthermore, designers and contractors working on a BIM model can be instantaneously notified of any copyright infringement of model objects [54].

4.2. Design and construction

The design and construction subject area consists of five application categories discussed in 44 of the review documents. This section is focuses on the capital expenditure stage of construction projects.

Building Information Modelling (BIM) (discussed in 41 documents). One of the fundamental reasons for the slow adoption of BIM is a lack of traceability in model revisions, as the current systems is based on manual data entry and relies on trust from designers to keep track of changes [55]. The ability for multiple users in a project to update a BIM model simultaneously is extremely challenging using existing centralised cloud systems, furthermore, the coupling of BIM with blockchain further creates bandwidth limitations, which is due to blockchain's consensus properties, whereby, majority of the nodes on the network need to agree on changes before data can be revised [56]. Zheng, et al., proposed a mobile device application which allowed users to verify on their portable computing device (e.g., phone, tablet, laptop) whether a BIM model is the most recent version, whereby, a hash of the BIM model is stored on the blockchain which allows a lookup service to cross-check the hash of a downloaded model with the hash stored on-chain, afterwards, the application would provide users with a verification receipt stating the model's validity [57]. On another note, a case study by Mason, et al., discussed how the effective logging of geometry and volume in BIM models can transition effectively into computable code for smart contracts [58].

IFC-based interoperability (discussed in 6 documents). IFC is a data standard format registered by the International Standards for Organisation (ISO), which is used for saving BIM model files [59].

BuildingSmart is an organisation that promotes digital workflow through utilisation of IFC, while OpenBIM is a set of common agreed workflow standards for BIM projects, for the purpose of increasing supply chain collaboration and standardising data exchange processes [59]. Hunhevicz, et al., produced a prototype which incentivised users to produce high quality data sets following the OpenBIM standard, this incorporated the use of smart contracts to provide financial rewards based on the quality of data provided by its users [48]. Ye, et al., produced a prototype which incorporated an IFC model that interoperated with smart contracts, which executed payments autonomously based on elements quantified within the BIM model; furthermore, readable text was maintained as it transferred into smart contracts, which allowed users the ability to intuitive cross-reference IFC data in blockchain code [60]. A study was conducted by Xue & Lu which investigated whether IFC semantics can be substantially minimised to allow for potential storage of IFC code on-chain, and whether small portions of the IFC code can be partitioned away from its original syntax while still remaining readable for purpose of isolating model revisions, which resulted in a semantic reduction of 99.98% of its original size; however, the consensus properties of blockchain proved to be problematic due to its low throughout with data processing, even when tested on a private blockchain network [56].

Integrated Project Delivery (IPD) (discussed in 3 documents). IPD operates through onboarding the construction supply chain with a shared risk and reward contract for the purpose of promoting collaborative workflow [61]. Hunhevicz, et al., discussed how the characteristics of IPD integrate effectively with the ideologies of common pool resource (CPR) and the Ostrom principles for flat organisational structures, which incorporates mutual and economical benefit for project participants who work together to achieve a common goal, whereby, projects which implement blockchain in IPD contracts include potential to reward participants with tokenised and non-tokenised incentives, such as financial rewards for collaborative delivery, transparent agreements, and automated payments upon validated completion of works [62]. Elghaish, et al., conducted a simulated proof of concept which incorporated blockchain in an IPD contract for managing supply chain payments, using private the blockchain platform Hyperledger Fabric (HLF); Whereby, financial operations such as reimbursed cost, profit pool, cost saving pool, and risk pool, were programmed into smart contracts which automated the dispensation of funds according pre-agreed terms, such as validated completion of works from appointed authorities and project milestone dates [61].

Off-site construction (discussed in 4 documents). Off-site construction includes strong topical overlap with Internet of Things, blockchain, BIM, AI, robotics, and 3-D printing [63]. According to Turk, R. Klinc, the primary application for blockchain in off-site construction is supply chain management, with a projected average saving of 70% through reduced processing costs, which is amassed through improved systems integration, automation through smart contracts, and real-time data traceability [63]. Wang et al., proposed a framework using blockchain platform Hyperledger Fabric for the management of precast construction activities through a user interface, which allowed real-time querying of scheduling, production, and transportation [64]. Additive manufacturing, synonymously called 3-D printing, includes potential to integrate with off-site construction and blockchain for the production, cataloguing, and copyrighting of customised building components [65].

Geospatial, 3-D scanning, and point cloud (discussed in 4 documents). Geospatial technologies such as “remote sensing, LiDAR, internet mapping, GPS and GIS” have strong implications working in conjunction with autonomous vehicles due to their rapid response in scanning geographical landscapes; furthermore, it interoperates effectively with BIM models, smart infrastructure, and cyber-physical systems [66]. 3-D scanning allows assets and geographical locations to be imported into BIM models; however, there is currently a lack of technological capacity for scanned objects to be autonomously cross-referenced with registered objects in a database [63]. Copeland and Bilec proposed a conceptual framework which integrated assets with geospatial sensors and blockchain to produce what they called “buildings as material banks”, which utilises sensors affixed to building components which records metadata regarding its condition for reusability, using blockchain as the trusted system for authenticating components and materials within built assets [67].

4.3. Operations and lifecycle

The operations and lifecycle subject area is comprised of four categories and consists of 24 documents. This section is focused on the operational expenditure stage of an asset’s lifecycle.

Facilities management and maintenance (discussed in 6 documents). Li, et al., proposed a framework for the semi-automated procurement of replacement parts during the operations phase of a built asset, which includes the integration of Internet of Things (IoT) sensors and a computer aided facilities management system (CAFM) for the automated identification of faulty parts; furthermore, a request for replacement parts is processed through a decentralised autonomous organisation, while an e-marketplace handles the bidding and appointment of prospective contractors [68]. Blockchain includes the ability to transact on and off-chain for the purpose of increasing the performance of data exchanges in a decentralised network. Bai, et al., proposed a framework for managing the communications between IoT and blockchain for asset maintenance, which uses on-chain for immutable hash storage and smart contracts, while off-chain handles data storage, computational processing, and analytics [69]. Integrating off-chain applications with blockchain allows for greater transaction throughput, lower transaction fees, and greater control over system operations such as privacy controls.

Life cycle and circular economy (discussed in 11 documents). Shojaei discussed how metadata recorded of raw materials extracted from source can be appended onto the blockchain for end-to-end lifecycle assessment, which allows for a complete and uninterrupted data stream from each handling merchant to end-user to provide proof of provenance from source to construction [70]. Asset data such as specifications, standards, and contract agreements include potential to integrate with blockchain for post-occupancy evaluation, utilising BIM as the data repository for the built environment asset and blockchain as its corresponding data validator [71]. Copeland & Bilec proposed a framework which utilised RFID, BIM, and blockchain to provide components with an evidentiary trail of data throughout its lifecycle, through sensors periodically recording data at key stages, such as installation, decommission, provenance, and metadata regarding supplier, manufacturer, and handling checkpoints [67]. This includes potential to integrate with a crypto-economic incentive scheme for the recycling of assets, with data verified by blockchain.

Construction waste management (discussed in 3 documents). Surplus waste generated by the construction industry is a global issue; furthermore, there is a lack of systems that can accurately account for material waste, which make it an acceptable by-product despite its carbon impact and incurred costs on projects [7]. However, blockchain includes potential to increase the accountability of waste through its ability to verify its lifecycle from source to disposal [7]. Despite this, a proposed solution on who would supply the systems which allows supply chain to quantitatively account the unused material was not discussed in the reviewed papers.

Real estate and property registry (discussed in 10 documents). Dakhli, et al., conducted a case study of 56 residential properties and concluded that blockchain has potential to achieve construction cost savings of 8.3%, which is higher than a typical property developer’s net margin of 6%; furthermore, the projected cost savings were attributed to the use of smart contracts and a decentralised autonomous organisations (DAO) to manage and automate business processes [72].

The management of land registries in many developing countries is an unnecessarily complicated process which is prone to fraud and manipulation [73]. Land management was identified in the World Bank's Ease of Doing Business report as a one of the main services that affects the economic growth of a country, furthermore, blockchain was discussed as having the potential to provide a single source of truth to land records, thus reducing administrative overheads in data processing and alleviating risk of fraud [73].

4.4. Smart cities

The smart cities subject area is comprised of four categories and consists of 27 documents. This section is focused on how city infrastructure networks can interoperate to provide a data-rich ecosystem of connect devices for managing built environment assets.

Smart cities (discussed in 16 documents). Ahad, et al., conducted a literature review on the topic of smart cities and suggested that they are driven by network-based technologies that integrate to support the delivery of industry 4.0 [66]. These technologies include Internet of Things (IoT), big data, cyber-physical systems, 5-G technology, artificial intelligence (including machine learning and deep learning), blockchain, cloud/edge computing, and geospatial technologies [66]. The interconnected network of devices in a smart city increases the demand for trusted data, therefore, a new business model is required that is more resilient to hacks and central point of failure [74]. This can potentially be supported through the traceable, immutable, and decentralised properties of blockchain [74]. Fu & Zhu proposed a conceptual framework which integrated technologies such as cloud platforms, blockchain, and IoT to form a trusted platform for monitoring live data from infrastructure services, such as geographic information systems (GIS), safety devices, and weather monitoring systems that relay information to city infrastructure services such as transport, communication, and utility [75].

Smart homes and buildings (discussed in 4 documents). Moretti, et al., proposed a conceptual framework that incorporated the use of ultrasonic sensors for the purpose of monitoring indoor activity of a building, which includes sensors placed in rooms to monitor usage, occupancy, and maintenance, which integrate with analytics to provide automated reporting of indoor activity; furthermore, the author discussed the potential to incorporate a blockchain-based management system, through using smart contracts to provide automated payments upon successful delivery of maintenance works [76]. Roy, et al., proposed a prototype for a smart home ecosystem, which included the aggregation of a home device network, blockchain platform, and maintenance service system; furthermore, the home network was comprised of smart meters, IoT, and actuators; the blockchain was used to store and validate results received from the home devices; while the maintenance system provided facility management through identifying when replacement parts were required and provided credentials of prospective suppliers [77].

Intelligent transport (discussed in 15 documents). López & Farooq proposed a smart mobility blockchain framework for managing transportation data, which was comprised of five layers such as (1) privacy, which gives users control of their data when using location revealing applications such as Google maps; (2) contract layer, which controls how smart contracts use user data; (3) communication layer, which appends digital identifiers to communication channels between network nodes; (4) incentive layer, which rewards users for participating in the blockchain network; and (5) consensus layer, which allows nodes to upload data verified by its users [24]. Implications of this included privacy between users and transportation system hosted on a decentralised network [24].

Supplying battery recharge to electric vehicles based on a fast-charge system is technologically challenging, as current recharge systems need to be designed for both intermittent and continual usage [78]. Zhang, et al., conducted a 15 month study at University of California, Los Angeles (UCLA), which implemented a blockchain platform that incentivised users to charge their electric vehicles at specific timescales, which mitigates energy providers having to store unused energy in batteries for extended periods of time; moreover, a user interface provided users with a ranking system based on their record of renewable energy consumption, which rewarded users with discounts and the ability to choose flexible recharge schedules [78].

Water management (discussed in 3 documents). The infrastructure for wastewater management in cities is reaching the end of its lifespan in many countries, which is caused by old treatment plants and damaged pipes which excrete sewage into environmentally sensitive areas that cause health and safety and wildlife concerns [79]. Berglund, et al, discussed how the construction of new water management systems can potentially benefit through innovations such as Internet of Things (IoT), smart meters, and blockchain, to provide live data feed on the performance of water management systems, with implications in improving lifecycle maintenance of infrastructure assets [79]. Perera, et al., discussed how WaterChain, a water utility blockchain network in the United States, allows their participants to invest in water recycling plants and allows them to benefit through the dividends supplied by its service; furthermore, the management of the plant is transparent and can be investigated by the community at any time and dividends are automated through smart contracts, this merges the boundary between consumer and producer and allows the opportunity for communities to self-sustain and self-own their utilities [7].

4.5. Intelligent systems

The intelligent systems subject area includes six categories and consists of 46 documents altogether. This section focuses on advanced computer systems, information processing, and the benefits of data-rich networks.

Big data (discussed in 6 documents). The amount of new data produced each year is increasing exponentially, furthermore, the construction industry is under additional pressure to exploit the benefits of data-driven economies whilst in a resource deficit caused by poor margins in construction projects [80]. Blockchain offers a new type of data model which reduces the resource requirements for storing data securely, through bypassing the need to use heavily centralised systems to authenticate data [66]. Network systems such as internet of things (IoT) and smart technologies include the potential to integrate with blockchain to provide increased trust in authenticating data, which is achieved without reliance on oversight from centralised technology companies [24]. Concerns regarding privacy is mitigated through private blockchain protocols such as Hyperledger Fabric, which uses an enterprise-centric model that provides platform developers with control over the privacy features on their network [81]. Alternatively, public blockchain protocols, such as Ethereum, include advanced cryptographic methods such as zero-knowledge-proofs which allow private data exchanges to occur on a public network [82]. Big data integrated with blockchain includes practical applications in off-site construction and supply chain management, through improved contract management, compliance checking, traceability of data in project reports, and reliable data for use with analytics [63].

Artificial intelligence (AI) (discussed in 8 documents). AI, alongside additive manufacturing (synonymously called 3-D printing), autonomous vehicles, blockchain, drones, and Internet of Things, are the fundamental components that form to create the emerging industry 4.0, which were points first discussed in the 2011 report by Germany's economic development agency [65]. Car manufacturers use AI powered robots that work alongside humans in production plants; furthermore, companies such as General Electric and Caterpillar are developing AI solutions to equip workers with robotic exoskeletons to assist with labour intensive jobs [65]. AI is progressively being used in industries to streamline workflow and improve decision making, such as with JP Morgan, who developed a software algorithm called COIN, that scans thousands of contract documents instantaneously to provide judgement on written agreements [83]. A practical use-case for blockchain in AI is the ability to safeguard its coding through placing it in a smart contract, which mitigates the risk of unauthorised manipulation of the code without permission from authorised actors, effectively, creating unbreakable codified laws which govern the functionality of AI; simultaneously, AI can also be used to debug smart contracts and improve blockchain's protocol design [84].

Cloud computing and electronic document management system (EDM) (discussed in 13 documents). EDM allows companies to manage, store, and process documents electronically [30]. EDM platforms are limited with their potential to interoperate with other technology suppliers, which is due to its centralised systems architecture; conversely, a blockchain-based EDM is built with interoperability as its core and is not financially driven by sales of its product [14].

Cloud computing is a fundamental driver of logistics 4.0 (a branch of industry 4.0), which encompasses global standards, digitisation of business processes, and cyber-physical systems that interoperate with supply chain and logistics networks [14]. Blockchain-based decentralised cloud platforms provide the ability for users and enterprises to store data with greater privacy, this is achieved without risk of hacks or data mining from service providers; however, due to its nascency, decentralised storage solutions may lack in its ability to modularise its functions to suit business workflows [85]. Singh, et al., proposed a framework for managing the data flows of cyber-physical systems in a smart city network, which integrates cloud computing, software-defined networking, and blockchain for trusted data exchanges [29].

Cybersecurity (discussed in 12 documents). The decentralised characteristics of blockchain puts the responsibility in the custody of its users to manage their digital keys competently, which requires users to keep their private-key secret and not reveal the personal identity behind their public-key [86]. Xiong, et al., proposed a "secret-sharing-based key protection" protocol which allows users with compromised or lost private-keys to retrieve access to their account, which involves a step-by-step multiparty verification process, whereby, each party anonymously and privately reveals a small portion of the key, which altogether combines to produce the entire lost private-key [28].

The immutable property of blockchain also comes at the cost of low scalability (measured in transactions per second) and limited capacity to store large amounts of data on-chain [87]. To mitigate this, Bai, et al., proposed a framework which consists of on-chain and off-chain functionalities, which included a "smart predictive maintenance" and a "sharing service of equipment status data" model, whereby, the hashes (unique identifiers) of files are stored on-chain, while off-chain handles high-volume data storage and computational processing [69]. This includes the use of a lookup service which connects the hashes stored on-chain to data repositories off-chain, which amalgamates the immutable properties of blockchain with large capacity data storage [69].

Machine learning (ML) (discussed in 3 documents). The procurement and management process of road construction in India is challenged with political corruption and fraud, through lack of compliance checks, material fraud, and unsupervised labour that leads to incomplete works [88]. Shinde, et al., discussed how ML can be used to forecast material quantities, labour requirements, and delivery schedules, while blockchain can be used as the trusted system to verify the authenticity of data sets without reliance on a trusted third party; furthermore, ML coding can be stored in a smart contract or decentralised repository, which can be designed to allow authorised parties to jointly contribute to updating and verifying the code through consensus [88]. ML is used in construction for statistical decision making, irregularity detection, and deriving insight from historic records [89]. Woo, et al., identified five software applications that use ML in the construction industry, these are (1) GenMEP, by Building Systems Planning, which uses ML for the automation of mechanical, electrical, and plumbing data in a Revit model; (2) BIM 360 IQ, by Autodesk, which uses ML to forecast and calculate the impact of subcontractor risks in construction projects; (3) SmartTag, by Smartvid.io, uses ML to automate the process of labelling/tagging of site assets from pictures and videos; (4) Smart Construction, by Komatsu and NVIDIA, uses ML to simulate the construction process for health and safety and programme analysis; followed by, (5) IBM Watson IoT, who uses ML for proposing energy efficiency and occupancy enhancing solutions in buildings [89].

Internet of things (IoT) (discussed in 31 documents). Wang, et al., discussed how IoT and blockchain can potentially integrate with building information modelling (BIM) to provide a central hub for managing and authenticating data received from built environment sensors; furthermore, the BIM model can be used to map the position of each sensor in a digital model, which provides a 3-D map for maintenance suppliers to utilise [63]. IoT can also be fitted onto the wearables of personnel on construction sites to provide quantitative insight on the environmental conditions and geographic positioning of on-site workers, with blockchain used to hash and timestamp data received from the IoT [30]. Fu & Zhu proposed a smart city framework which incorporates the use of IoT to provide a system which integrates and monitors geographic, safety, and weather, which altogether feed data to a user interface to provide live analytics for use in construction and asset management [75].

4.6. Energy and carbon footprint

The energy and carbon footprint subject area includes four categories and consists of 38 documents altogether. This section is focuses on how blockchain can integrate as part of a system to better manage energy, renewables, and carbon.

Peer-to-peer (P2P) energy markets (discussed in 30 documents). P2P energy markets are designed around homeowners buying and selling excess renewable electricity through a local network, which provides neighbourhoods with self-sufficiency and promotes decarbonisation [90]. Esmat, et al., proposed a conceptual framework for a P2P energy marketplace hosted on blockchain, which includes automated uniform pricing and real-time settlements [91]. Ableitner, et al., conducted a 4-month field study of 37 households in Switzerland to assess the outcome of a micro-grid prototype, which was a joint effort between academia and industry; furthermore, each of the households were supplied with renewable energy production technologies, smart meters, and a P2P energy trading application hosted on the blockchain [92]. Afterwards, the results were analysed through questionnaires, interviews, and statistics, which displayed active involvement from the participants with the blockchain application and an eagerness from the households to continue with the study after it concluded [92]. Energy trading can also occur between machine-to-machine (M2M) for the purpose of achieving full automation without the reliance of appointing users to authorise the trade, as shown in a conceptual framework by Sikorski, et al., which included a study of two energy suppliers that operate in tandem to provide consumers with the most economically priced electricity [13]. Despite the immutable property of blockchain, P2P markets are at potential risk from producers manipulating the power measurements recorded at connection points; However, to mitigate this, Saha, et al., proposed a blockchain-based distributed verification algorithm that penalises inconsistent measurements of current [93].

Smart grids (discussed in 29 documents). 'Peer-to-peer (P2P) energy' and 'smart grids' are discussed interchangeably; however, the former relates to trading markets, while the latter relates to energy infrastructure and smart meters. The integration between decentralised micro-grids and the main power grid is made possible through a demand-side management (DSM) application proposed by Noor et al., whereby consumers are able to supply their own smart energy appliances and battery storage and utilise the DSM application to connect their local grid to the main grid [94]. Christidis, et al., conducted a case study of 63 solar panel fitted homes, situated in Texas, United States, which compared the efficiency of a semi-centralised versus a decentralised energy grid market, which included the former consisting of high transactions speeds with lower security, while the latter included low transaction speeds with higher security, which resulted in the blockchain approach being less efficient due to its high latency in processing transactions [81]. A similar framework was proposed by Foti & Vavalis, which investigated how a blockchain-based smart grid would perform with 1000 participants transacting on the Ethereum blockchain test-network, which resulted in the centralised grid being efficient at providing lower cost electricity due to the mining fees associated with blockchain, however, when factoring in the lifecycle cost of managing systems, the decentralised approach was discussed as potentially being more cost-effective and resilient to external threats such as cyber-attacks [95].

Renewable energy solutions (discussed in 3 documents). The energy industry is experimenting with new business models that transition from centralised to decentralised, which includes the integration of smart devices, micro-grids, blockchain, and energy recycling technologies [96]. A combined heat and power (CHP) system provides energy recycling through combining electricity and heat generation into one system, which integrates fittingly with renewable production technologies such as photovoltaic and wind turbines for the purpose of reducing carbon footprint [97]. Furthermore, in the event of natural disasters such as flooding, high winds, earthquakes, wild fires, snow/ice, and extreme temperature, CHP maintained performance most consistently in comparison with photovoltaic, wind turbine, standby generators, and biogas [97]. The demand for renewable energy increases with the depletion of oil and rise in global warming. Perrons et al., stated that the geothermal energy sector has received pressure from stakeholders to innovate renewable production methods and management systems, with blockchain discussed as a potential candidate to improve the software aspect of it [98]. Keivanpour investigated two off-shore wind farms in United Kingdom, called Robin Rigg, and Walney Phase 1, and concluded that the current delivery method of industrial scale renewables is unnecessarily expensive due to longstanding supply chain processes, and discussed the innovation potential with blockchain, Internet of Things, and big data [99].

Carbon accounting and decarbonisation (discussed in 7 documents). Khaqqi, et al., proposed a carbon emission trading framework, where a government organisation would issue construction companies with a limited number of carbon credits to expend on a construction project, whereby, each credit is representative of a tonne of carbon emissions; furthermore, companies are able to buy or sell excess carbon credits to each other through a decentralised online marketplace, which incentivises renewable companies, while at the same time penalises non-renewable companies [27]. Rodrigo, et al., conducted an interview with three industry practitioners, each with over 13 years of experience in information technology, which concluded that the inherent properties of blockchain, such as auditability, security, and decentralisation, is a suitable tool for embodied carbon estimating [100]. Hua, et al., proposed an energy trading framework that rewards carbon credits to prosumers of a micro-grid network, whereby, energy producing technologies are linked to the blockchain to record the carbon footprint at time of production; furthermore, each prosumer is provided a set quantity of carbon credits which their permitted to expend during production, which incentivises prosumers to act sustainably [101].

4.7. Decentralised organisations

The decentralised organisations subject areas is comprised of four categories and consists of 19 documents altogether. This section is focused on decentralised services and autonomous organisations. Some of the topics in this section are more general purpose than the previous sections, nevertheless, they included strong overlap with the construction industry and each category was discussed several times in the reviewed documents.

Decentralised Autonomous Organisation (DAO) (discussed in 5 documents). DAO is an autonomous blockchain entity with decentralised governance at its core, which rewards users with tokenised incentives for participating in the network and operates entirely through smart contracts [102]. The construction industry is particularly known for incurring change orders and programme alterations, which is problematic for smart contracts due to their unalterable properties once deployed; furthermore, translating written agreements into codified form creates linguistical challenges between contract managers and programmers, whereby, each party may not understand the industry-specific culture differences of the other, such as terminologies and processes [68]. Dounas, et al, produced a prototype which utilised DAO and smart contracts to automate the awarding of works for architectural design submissions, which involved a simulated study where stakeholders submit a request for a built environment asset through a DAO platform, followed by submission of the designs from prospective contractors or architects, and finally, the autonomous calculation of the winning proposal through a predefined scoring system and awarding of work through a smart contract [103]. Similarly, DAO also includes the potential to integrate with the construction or operations phase of a built asset, through semi-automating the procurement process for obtaining new materials or replacement parts, whereby, DAO is used as the medium for connecting prospective suppliers to new work, managing payments, cross-checking compliance certificates, and quantitatively assessing the risk of each supplier through their track record of delivered works [104].

Identity and certificate authentication (discussed in 5 documents). The fundamental properties of blockchain (traceability, transparency, and immutability) make it a suitable technology for incorporating identity authentication services, as centralised systems are prone to hacks and data manipulation [86]. Private blockchains include privacy controls as a fundamental feature to its protocol. Whereas, public blockchains include cryptographic functions such as zero-knowledge proofs which permit private transactions to occur on a public network, however, this incurs additional transaction fees added onto the existing mining fee [82]. Nawari & Ravindran discussed how private blockchain Hyperledger is suited for identity management services in construction due to its modular architecture, which allows automated compliance checking of identities on the network [53]. Similarly, Shojaei, et al., discussed how Hyperledger's certificate authority can be used to maintain an active lists of supply chain participants in a construction project, which can be reused across multiple projects [105].

Blockchain allows the creation of non-fungible tokens (NFTs), which can be used as a digital certificate that represents the ownership of a physical asset; furthermore, this NFT can hold additional data such as title deeds, lifecycle data, building certificates, and any other associated data [106]. Implications include substantial reductions in data retrieval for insurers, estate agents, facility managers, and building inspectors [72]. Due to the immutable properties of blockchain, data stored in the NFT is append only, thus leaving an intact evidentiary trail of data throughout its lifespan.

Financial technology & banks (discussed in 7 documents). The emergence of decentralised finance in 2020 allows banks to extend their portfolio to include additional commercial products for customers [12]. Yao, et al., proposed a conceptual framework which discussed the viability for banks to provide blockchain-based supply chain finance, through using blockchain to verify the regulatory compliance of their customers, track signed agreements, and trace pending invoices [107]. Blockchain can be used to maintain an accurate and irrefutable record of transactions without risk of ledger inconsistencies, such as reconciliation errors and double spending; furthermore, banks can potentially provide escrow services through smart contracts, which allows transacting parties to formalise agreements amongst themselves while under oversight from regulatory controls, this ensures compliance to fair business terms and legal standards [15]. Smart contracts also include the potential to automate tax duties, such as with the legal movement of goods across international borders, whereby compliance certificates would be autonomously awarded upon payment of taxes [108].

Crowdsourcing (discussed in 4 documents). Blockchain-based crowdsourcing is a decentralised alternative to acquiring project funding, which includes benefits such as providing opportunities for skilled talent in economically disadvantaged nations, reduced intermediaries, and codified agreements with auditable terms for the purpose of supporting fair contract executions [109]. Public blockchains provide free protocol infrastructure that allows users to develop platforms and raise funds through initial coin offerings (ICOs), which is similarly compared to the initial public offerings (IPOs) offered in stock markets when private companies transition to PLC [110]. However, ICOs have been a target for criminal activity due to their ability to raise funds from anonymous users and lack of regulation checks, such as know your customer (KYC) and anti-money laundering (AML). Hassija, et al., discussed how the crowdfunding platform, BitFund, allows investors to propose a problem to a public community of programmers and include project-specific parameters such as budget, timescale, use-case, etc., afterwards, the awarding of works is conducted algorithmically through smart contracts to ensure a fair selection process of the development team [109].

5. Discussion

An exploratory approach was implemented into this review for the purpose of understanding which categories in construction are most influenced by blockchain. This review explored 33 application categories of blockchain in construction. Each category was substantiated by a minimum of three documents. These categories were further organised into seven subject areas, which include (1) procurement and supply chain, (2) design construction, (3) operations and life cycle, (4) smart cities, (5) intelligent systems, (6) energy and carbon footprint, and (7) decentralised organisations. When assessing the types of data collection used in the reviewed documents (as shown in Fig. 8), synonymous data collection terminologies were merged together for simplicity, such as conceptual frameworks, which included conceptual models and theoretical frameworks. Similarly, proof of concepts (PoC) included pilot studies and prototypes. The first three subject areas of this review are sequential stages that occur in a construction project, such as subject area one *procurement and supply chain*, which includes implementing blockchain in the digital tendering process [111], contract and cashflow management [43], and automated checking of compliance to standards [68]. Subject area two *design and construction*, incorporated using blockchain for trusted data exchanges [112] and traceability of deliverables throughout the supply chain [113]. While subject area three *life cycle and circular economy*, included how blockchain can be used as part of the assessment and management of a built asset during its operational expenditure stage [114]. Subject area four *smart cities*, and subject area five *intelligent systems*, included a macro-orientated approach, assessing how multiple built environment assets and services interact through a smart city network, which includes the interoperability of various systems such as utility [115], transport [116], Internet of Things (IoT) [117], and smart technologies [88]. Subject area six *energy and carbon,* focused attention on peer-to-peer energy trading models [118], sustainable technologies for the built environment [119], and carbon accounting strategies [120]. And finally, subject area seven *decentralised organisations*, incorporated decentralised autonomous organisations (DAO) and decentralised services [103]. DAO is difficult to precisely classify in the current environment, as its definition is dynamic in translation and its development is constantly evolving; however, in construction, many of its activities (for now) overlap with the responsibilities of a main contractor, therefore, for simplicity, DAO can be described as a decentralised contractor.

The aforementioned 33 categories and seven subject areas were not distinctly siloed and included substantial topical crossovers. E.g., the supply chain management category overlapped with all of the subject areas, however, based on the scientometric analysis conducted (as per Fig. 6), it was positioned most quantitatively relative in the procurement subject area, due to its high number of shared link with other categories in that area [121,122]. IoT also strongly overlapped with several subject areas, which include smart cities [7], energy and carbon [123], design and construction [113], procurement [85], and decentralised organisations [79]; however, IoT was placed in the intelligent systems subject area due to its strong correlation with the other categories in this area. The categories electronic document management systems (EDMS) and digital/automated contracts were placed in separate subject areas despite their similarities, as the former is characterised by the digital management of documents on a centralised system, while the latter utilises smart contracts on a decentralised protocol, thus dissimilar systems architecture [124].

A smart medical record system, which includes managing patient records and sharing healthcare data with hospitals, is a category supported by two authors [15,75*]; however,* blockchain for healthcare is an entirely different subject area and a vast topic suited for a separate literature review altogether [115]. Health and safety monitoring of site conditions and historic records of on-site accidents were discussed in two documents [79,102*]*; however, despite its practical applications in construction, it also lacked content for substantiation. Another topic that was excluded despite its interest in two documents is smart governance, which incorporates governmental organisations implementing blockchain to automate the compliance checking and auditing of built environment assets [17,115]. Multi-category applications of blockchain in construction that were not included due to its general-purpose nature include transaction immutability, digital notarisation, decentralised applications (dApps), smart contracts, and information sharing, as effectively, these topics are already integrated within all of the reviewed categories and do not require itemising [102].

As blockchain is a decentralised technology, appropriate incentivisation techniques must be applied to encourage platform interaction through a crypto-economic model [102]. The integration of blockchain in enterprise in the current environment is reliant on dApps harmonising with existing centralised systems, however, as blockchain matures, the transition to complete decentralisation is likely to increase. This assumption is based on assessing the growth and expansion of blockchain in construction since its emergence in academic literature, and the intensifying global interest in blockchain. In a report regarding impact of blockchain, it was identified as potentially transforming 58 industries globally, which includes the construction industry [125].

Business operations are entirely based on risk management activities, which includes economic risks through investments in new business models, social risk through job losses, legal risk through dispute resolution and corporate liability, environmental risk through sustainability and ecological sensitivity, and technical risk through increased pressure to integrate systems and provide data-driven solutions [85]. Blockchain mitigates against centralised hacks, data manipulation, accounting errors, and provides a foundation for trusted data without reliance on a trusted third party [126]. An area which lacked discussion from the review documents was the integration capabilities of blockchain with existing enterprise systems, as blockchain is considered a high-risk technology due to its decentralised design and lack of standards. *Trust* is a term that appeared most frequently in the reviewed literature when describing the characteristics of blockchain, such as "stakeholder trust" [122], "peer-to-peer trust" [127], "trust in collaboration" [128], "information trust" [26], "removal of trusted authority" [11], and "trusted distributed ledger" [129]. Other commonly used terms include transparency, traceability, immutability, security, automation, auditability, decentralisation, and disintermediation [9,118–120,123,130,131].

Over the course of 2017–2020, the rate at which new documents were published on blockchain in construction was recorded at an average of 184%; however, the sample number of years is small, and this level of growth cannot be maintained long-term. A 10-year period would provide a more statistically comprehensive result. Fig. 4 documented the annual expansion of new categories on topic since its emergence in 2017, which displayed six new categories in 2017, nine in 2018, 13 in 2019, followed by five in 2020. It is likely that the expansion of new categories on the topic has almost reached a plateau, therefore, over the next consecutive years, it is envisaged that existing categories will undergo maturity as more attention is focused on testing and developing earlier ideations.

6. Conclusion

New academic documents on blockchain in construction increased at an average of 184% each year since 2017, surmounting to an accumulated total of 121 documents at time of writing this article in 2021. An exploratory approach was implemented to investigate all 121 publications to examine the contemporary environment of the topic. This review identified 33 application categories, these were organised into seven subject areas and included (1) procurement and supply chain; (2) design and construction; (3) operations and life cycle; (4) smart cities; (5) intelligent systems; (6) energy and carbon footprint; and (7) decentralised organisations. To support the literature review, statistics and scientometrics were incorporated to display the progression of the topical area. This includes visual maps that display the co-occurrences of the categories (as shown in Fig. 6) and data collection types implemented in the reviewed documents (shown in Fig. 9). A complete list of the 121 reviewed documents, along with their category coverage, document type, data collection type, and impact factor, is provided in the shared Google spreadsheet link provided below.

https://docs.google.com/spreadsheets/d/1V4UICRdoyWycaGENH9rnuxukRNQJFIArQ-feV7NM0a4/edit?usp=sharing

Limitations included using only one scientific database, Scopus, due to the inconsistencies which emerged when amalgamating information from various scientific databases for use in visual mapping software. In a comparison of the search results from seven scientific databases and based on the topic of blockchain in construction, Scopus overshadowed its competition by a large margin; furthermore, up to 85% of the documents indexed in other scientific databases were already existent in Scopus. Another limitation was the restricted capacity to conduct in-depth investigation on one particular subject area within the topic, this was due to the exploratory nature of the study, which covered a wide range of application categories. Despite this, the findings provided a solid foundation for aggregating all of the research areas of blockchain in construction in the contemporary environment.

Content for this exploratory review was obtained predominantly from documents published from 2017 to 2020, as this article was written in early 2021; however, further work includes an extended review following the progression of the topic over the next consecutive years.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Search query one

Search query one isolated the ISSN numbers of all academic documents in the subject areas of architecture, building & construction, and civil & structural engineering, followed by specific key words, such as *TITLE-ABS-KEY ("blockchain*" OR "block chain*" OR "distributed ledger*" OR "smart contract*",* which was inputted into the Scopus search to obtain the results.

The exact string of text for query one consists of:

ISSN(08950563 or 17433509 or 23848898 or 23639075 or 20361602 or 20299990 or 23352000 or 17246768 or 22150900 or 22150897 or 24208213 or 23851546 or 20966717 or 08602395 or 25448870 or 19401507 or 19401493 or 02658135 or 0142694X or 23527102 or 15417808 or 15417794 or 23520124 or 14356066 or 09349839 or 15583066 or 15583058 or 17527589 or 17452007 or 1365232X or 09699988 or 15710882 or 17453755 or 14770857 or 14714175 or 17481317 or 20952635 or 09603182 or 15731529 or 23635150 or 23635142 or 23537396 or 20952430 or 20952449 or 20755309 or 1000131X or 10760431 or 19435568 or 07181299 or 07188358 or 02632772 or 00038628 or 17589622 or 26316862 or 19387806 or 02663511 or 09560599 or 20598033 or 20297947 or 20297955 or 22133038 or 2213302X or 19434618 or 15526100 or 21952701 or 18864805 or 18877052 or 13001884 or 15224600 or 13472852 or 13467581 or 23034521 or 14370980 or 01715445 or 18269745 or 22832998 or 1450569X or 22178066 or 22882987 or 12268046 or 2239267X or 21753369 or 18818153 or 13404202 or 19461194 or 19461186 or 24751448 or 2475143X or 00200883 or 19883234 or 22321500 or 18234208 or 22502157 or 22502149 or 18558399 or 03536483 or 10067930 or 13602365 or 14664410 or 18285961 or 01466518 or 22390243 or 07182309 or 16744764 or 01682601 or 22546103 or 11336137 or 18818188 or 13419463 or 00379808 or 20612710 or 03055477 or 17496292 or 19895313 or 16952731 or 22889930 or 22347224 or 23321091 or 23321121 or 00139661 or 15882764 or 23202661 or 00448680 or 13591355 or 14740516 or 07187262 or 0718204X or 13028324 or 19346026 or 15499715 or 20696469 or 20690509 or 18085741 or 22147233 or 22123202 or 00392553 or 00038504 or 20507836 or 20507828 or 10464883 or 1531314X or 14665123 or 07380895 or 20455895 or 20455909 or 2325159X or 23251581 or 23870346 or 23410531 or 0066622X or 13300652 or 0007473X or 20137087 or 14929600 or 02585316 or 23251395 or 23251379 or 25317644 or 26117487 or 07160852 or 07176996 or 20505833 or 11239247 or 23251662 or 23251670 or 23251638 or 2325162X or 21736723 or 20419112 or 20419120 or 0951001X or 23413050 or 23412747 or 23090103 or 19360886 or 19346832 or 02677768 or 20390491 or 18751490 or 18751504 or 15263819 or 16068238 or 01696238 or 23093072 or 23074485 or 12282472 or 19357001 or 00038520 or 0003858X or 00038695 or 03899160 or 10934421 or 11249064 or 22546332 or 11385596 or 21716897 or 21731616 or 23409711 or 23867027 or 23322578 or 23322551 or 00012505 or 08950563 or 01932527 or 17433509 or 01642006 or 7314906 or 03622479 or 10412336 or 20361602 or 20299990 or 23352000 or 24208213 or 23851546 or 20966717 or 00088846 or 03062619 or 09589465 or 18736785 or 03605442 or 03787788 or 01674730 or 08867798 or 03601323 or 17499518 or 17499526 or 09265805 or 07339445 or 01407007 or 0143974X or 10900268 or 19435614 or 09500618 or 15452263 or 15452255 or 02638231 or 13595997 or 18716873 or 10840702 or 19435592 or 19401507 or 19401493 or 09056947 or 16000668 or 09613218 or 14664321 or 1570761X or 03931420 or 17448980 or 15732479 or 07339364 or 19435533 or 08991561 or 13632469 or 1559808X or 12299367 or 19968744 or 19963599 or 1751763X or 00249831 or 23527102 or 14644177 or 17517648 or 08893241 or 01446193 or 1466433X or 15417808 or 15417794 or 19435509 or 08873828 or 23520124 or 16713664 or 1993503X or 02194554 or 09517197 or 17517605 or 0889325X or 17527589 or 17452007 or 13694332 or 1365232X or 09699988 or 20962754 or 24679674 or 14371006 or 00059900 or 12254568 or 23767642 or 00138029 or 14006529 or 14036835 or 19883226 or 04652746 or 20714726 or 20710305 or 14770857 or 14714175 or 2374474X or 23744731 or 2041420X or 20414196 or 00056650 or 2287531X or 22875301 or 15623599 or 20952635 or 13468014 or 13473913 or 22049029 or 14770849 or 01436244 or 1816112X or 10002383 or 23635150 or 23635142 or 23537396 or 20755309 or 17550750 or 17550769 or 22973362 or 1000131X or 09650911 or 17517702 or 19375247 or 19375255 or 10760431 or 19435568 or 23984708 or 17512549 or 17562201 or 24705322 or 24705314 or 10006869 or 17442591 or 02632772 or 21628246 or 01430750 or 12266116 or 20369913 or 2533168X or

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07162952 or 07185073 or 17400694 or 18753507 or 17568404 or 13681494 or 12295515 or 22342842 or 18029876 or 16744764 or 00465828 or 19918747 or 22243429 or 14439255 or 00194565 or 14412713 or 18022308 or 26007959 or 21803242 or 09700137 or 22889930 or 22347224 or 23321091 or 23321121 or 22926062 or 23361182 or 1802680X or 16106199 or 13028324 or 00060208 or 12104027 or 18052576 or 00174653 or 01580728 or 00392553 or 09568700 or 20449283 or 02755823 or 14665123 or 02126389 or 0923666X or 10093443 or 10155856 or 13003453 or 03002721 or 00137308 or 12313726 or 21959870 or 21959862 or 0376723X or 20817738 or 23007591 or 18825974 or 13443755 or 00333840 or 17593433 or 23662565 or 23662557 or 03731995 or 00105317 or 09745904 or 17452058 or 00124419 or 22783075 or 23793244 or 23793252 or 00263982 or 01665766 or 00333735 or 00348619 or 16954408 or 0149337X or 09698213 or 00097853 or 08857024 or 03600556 or 08919526 or 0267825X or 01426168 or

00284939 or 22113444 or 13693999 or 20541236) AND TITLE-ABS-KEY ("blockchain" OR "block chain*" OR "distributed ledger*" OR "smart contract*")*

Search query two:

Search query two used a simpler method, which included using one of the predefine subject areas available on Scopus, followed by specific key words. The limitation to using this search query is the high number irrelevant documents that accompany the results.

The string of text for query to consists of:

SUBJAREA(ENGI) AND TITLE-ABS-KEY("Blockchain" AND "Construction").

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