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From BIM to Web3: A critical interpretive synthesis of present and emerging data management approaches in construction informatics

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ABSTRACT

The field of construction informatics is fragmented and lacks clarity in understanding the interconnection of different data management strategies. This makes it challenging to address industry-specific data management issues. Using a critical interpretive synthesis, this study reviews and integrates both present and emerging data management approaches in construction informatics. The review is meant to be comprehensive, encompassing technologies and concepts such as Open Schema, Information Container, Common Data Environments, Linked Data, as well as cutting-edge Web3 technologies such as blockchain and decentralized data protocols. The different approaches are identified and classified into five categories and mapped into a two-dimensional framework that considers data storage and data processing modes. The systematic categorization provides a simple, but comprehensive understanding of data management strategies in construction informatics. Moreover, the framework allows to identify the state of the art and trends of data management approaches, providing guidance for future research perspectives, especially in the intersection with Web3 technologies.

1. Introduction

The complexity of construction projects requires the generation, revision and transfer of large amounts of data across different phases and disciplines. Data lifecycle management is essential for the intensive and continuous communication between stakeholders from the initiation until decommissioning of a facility [1,2]. Despite the adoption of digitization and data-driven processes in the construction industry, cross-phase and cross-party data integration remains a challenge. This is due to a fragmented industry structure characterized by non-standardized collaboration among many actors with diverse skills [3]. The use of multiple models and tools in different phases of the project generates extensive communication, resulting in large volumes of data in heterogeneous formats [4]. Integration between these models and tools remains difficult, resulting in information silos that limit opportunities for data processing, extractability, and usability [5,6]. Therefore, to overcome these challenges, it is essential to achieve interoperability during data integration [7]. This requires the development of effective data integration methods between different systems, tools, and stakeholders.

However, the current state of construction informatics manifests itself as an unintegrated and confusing system. It is increasingly difficult to understand how different data management approaches interact and contribute to data management challenges in construction informatics. This has been exacerbated by the adoption and adaptation of data management approaches from other industries [8,9]. The current landscape includes numerous concepts and technologies, such as Building Information Modeling (BIM), Common Data Environments (CDE), Information Containers, and Linked Data. At the same time, the emerging concept of Web3, including technologies such as blockchain and decentralized data protocols (DDPs), increases confusion by promoting novel approaches to data ownership, accessibility, and sharing control [10].

A comprehensive synthesis of the available data management landscape is missing. Existing research lacks contextualization with existing data management approaches [11]. For example, while current research explores the use of a specific Web3-based technology, such as blockchain, to improve data management in construction projects, there appears to be a lack of a broader integration with the data management landscape in construction informatics research [12]. There is

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a need for a comprehensive and technologically grounded synthesis of this landscape to promote a unified understanding of data management approaches, their underlying technological basis, and ongoing advances in the field.

To address this research gap, our paper provides a critical interpretive synthesis of previous research, current trends, and emerging developments in the field of data management for construction informatics. A critical interpretive synthesis is a research method that combines iterative literature review with interpretive analysis, allowing the development of novel theoretical frameworks by identifying patterns and integrating diverse insights, particularly suitable for complex fields like construction informatics.

To achieve this, we first provide background on the main challenges of data management in the construction industry (Section 2.1) and the predominant understanding of data management in construction informatics (Section 2.2). We then further clarify the research gap and scope of this study (Section 2.3) and describe the research design used to categorize and synthesize the data management landscape (Section 3). We then explain the basic elements of our framework, delineating two distinct dimensions: processing mode and storage mode (Section 4). This exposition is followed by a categorization of the prevailing methodologies within the framework, detailed in Section 5. We also bridge different concepts (Section 6) and illustrate the potential integration of emerging Web3 technologies within the framework (Section 7). Finally, we discuss the key lessons learned and future research areas (Section 8).

2. Background

2.1. Data management challenges in construction

The construction industry faces significant data management challenges that affect project delivery [13,14]. Although many researchers discuss the nature of these challenges, we simplify the challenge into two main issues: (1) managing data over the built asset life cycle due to data silos and automation islands, and (2) dealing with information loss and interoperability during data exchange.

First, data silos and islands of automation are common issues due to the use of specialized software by different stakeholders, who control their specific data without sharing them with others [6,8,15]. As a result, both research and industry are striving to formulate and develop an ideal data management approach that leverages data-driven insights and decision support through the use of various technologies [16]. The result is an expanding and never-ending ecosystem of frameworks and applications across the industry. However, with more specialized use cases, it becomes increasingly complex and confusing to understand which software to use and when to use it [17].

Second, the challenges of information loss and interoperability emerge when trying to exchange data between software applications and/or parties [18,19]. The quality of available data determines its usefulness, and changes across disciplines and phases are time consuming and costly, resulting in information loss. Poorly organized information or a lack of linkage between documents and information is estimated to be one of the leading causes of construction delays [20]. Some scholars search for the optimal interoperability scenario to simplify the extraction of information from unstructured data sources and connect related pieces of information [21], yet widespread industry acceptance of these approaches remains limited.

2.2. Predominant data management perspectives

Several research and industry efforts have attempted to create a data management methodology that provides unrestricted but controlled access to project data. Despite a shared vocabulary with common reference terms such as BIM, digital twins, or CDEs, we find data management scholarship incorporates widely different concepts, utilizes diverse technological methods, and differentiates in their usage depending on the context. None of these establishes formal definitions and clear scopes related to data management [22].

To further explain, we suggest that the predominant data management approaches can be understood through four perspectives: model, platform, knowledge graphs, and networks. Table 1 summarizes the key aspects described. Furthermore, it is essential to acknowledge that, while legacy data remain a significant consideration, it is not the primary focus of this work. Instead, we have chosen to prioritize forward-looking solutions that could potentially transform the way legacy data is integrated and utilized.

2.2.1. Model perspective

The model perspective is currently the most influential in construction informatics. The use of a digital model, often known as a Building Information Model (BIM), is the primary method of organizing data from a construction project. However, there exists a great variation in the scope and interpretation of what BIM entails, ranging from specific use cases such as design coordination, to comprehensive life cycle data management [23,24]. Additionally, the digital twin concept is sometimes used interchangeably with BIM as a model perspective [25]. However, digital twins are virtual replicas of physical assets, processes, or systems that maintain a bidirectional linkage between them [26]. While BIM provides a static representation, digital twins are continuously updated based on real-time data, such as sensor data from the physical asset, but also vice versa to optimize the physical product state based on analysis performed on the virtual model [27].

Model-based approaches for BIM utilize various technical approaches, with the most widely recognized being the Industry Foundation Classes (IFC) data format. Other technologies, including cloud platforms, information containers, and linked data, may also be used to generate and host digital models [28,29].

The utilization of digital models generally relies on the stakeholders involved as well as the implemented technology. Technology choice often depends on the capabilities and resources of the respective company [30], with larger companies generally having an advantage [31,32]. Usage challenges pertain to coordination mechanisms for organizing large data sets with one or multiple models [33] and to the seamless communication and data integration processes among different stakeholders [34] and the lifecycle phases [35]. Additionally, there is a tendency to centralize data management to those who control the models.

2.2.2. Platform perspective

Cloud platforms function as a central system for synchronizing the management, collaboration, and interaction with data and related applications [36]. They integrate platformization and cloud computing approaches [37,38]. These approaches emerged as a consequence of the evolution of the internet towards Web 2.0, which emphasizes interactive read-write capabilities, in contrast to the primarily read-only Web 1.0 [39]. This shift has fundamentally shaped the manner in which platforms facilitate enhanced interactivity and user-generated content management. In construction informatics, the most frequently cited notion is the Common Data Environment (CDE) [40], which promotes integration and data sharing across organizations [41,42], sometimes in conjunction with the BIM concept [43,44]. Additionally, digital twins are occasionally characterized as a platform for arranging data-driven management and control of cyber–physical systems [45,46], but there remains confusion around the concept, for example, in defining the boundaries between a digital model, a digital shadow, and a digital twin platform [47,48].

Different technical architectures of CDEs have emerged, some resembling cloud-based models described earlier, while others are complemented with information containers or linked data [28,29,49]. Additionally, the technical implementation of digital twins can include numerous components for data storage, analysis, and visualization [25].

Table 1
Summary of the four data management (DM) perspectives showing their complexity across concepts, technologies, and usage.

DM Perspective	Concept	Technology	Usage
Model	- Building Information Modeling (BIM) uses a digital model to combine data and visualization. - BIM represents a broad data management concept but is often focused on design.	- Open-source IFC is the most common data standard. - Other technologies (e.g., closed-source cloud, linked data) can also host and describe the models.	- Dependent on individual project setup. - Challenges include coordination across models, data exchange, and centralization of DM.
Platform	- Common Data Environments (CDEs) and other platforms use the cloud for data storage, computation, and data exchange - Digital twin (DT) platforms enable data-driven system management and control.	- There is a heterogeneous technology landscape, mostly using the cloud, but often with different data storage and system standards. - Occasionally overlap with BIM technology concepts (e.g., DT utilize BIM models for real-time building analysis).	- Broad usage for data integration and exchange over all building lifecycle phases, - Challenges include information centralization and lock in to third-party systems.
Knowledge Graph	- Semantic integration makes data readable by computers using advanced data mapping. - Also known as Semantic Web or Web 3.0.	- Linked data enables data entities to be semantically linked using standardized ontologies.	- Can potentially achieve automated reasoning and improved information discovery in DM concepts such as BIM, digital twins, or CDEs. - The challenge is that integration into practice is still very early.
Network	- Web3 technologies promise more control and ownership for DM. - The infrastructure is decentralized and trust is shifted to technology itself rather than intermediaries.	- Blockchain and decentralized data protocols. - Technologies are rarely combined with each other or with other DM approaches such as BIM.	- Transparency and Peer-to-Peer transactions are promising for DM. - Challenges includes that implementation remains mostly theoretical or prototype-based. There also remain many socio-technical usage questions.

While CDEs primarily focus on the early stages of project development, with limited application in later phases [50], digital twins are widely used for decision support, data monitoring, and digital replication in the usage phase of built assets [51–53]. Usage challenges arise from information centralization and lock-in to particular solutions [54]. Participants need to transfer their data from their proprietary systems to a third-party controlled system, requiring resource-intensive mapping procedures [55].

2.2.3. Knowledge graph perspective

The concept of knowledge graph attempts to enable a more cohesive search and linking of information [56], sometimes also referred to as the Semantic Web or Web 3.0 [57]. Although Web 2.0 has been transformative in promoting user-generated content and extensive platforms, it has also been criticized for lack of comprehensive data integration and interoperability. The concept of Web 3.0 addresses these limitations by allowing for the creation of more connected, semantically rich, and machine-readable data [58].

The main underlying technological concept is linked data, where data entities are linked using standardized ontologies, enabling seamless integration and meaningful relationships between different data sources [59,60]. Ongoing research focuses primarily on semantic interoperability [61,62] and the implementation of ontologies [63–67].

Knowledge graphs can facilitate automated reasoning and improved information discovery in a variety of data management scenarios, encompassing concepts such as BIM, digital twins, or CDEs throughout the complete built asset life cycle. However, their integration into practice is still in the early stages. Ongoing research investigates the practical implications, challenges, and opportunities of employing Semantic Web technologies for effective data management in the construction industry [68].

2.2.4. Network perspective

The latest data management perspective involves the use of networked technologies such as blockchain and distributed data systems, commonly referred to as Web3 [69]. This should not be confused with Web 3.0, which refers to the Semantic Web as previously described. Web3 introduces peer-to-peer (P2P), transparent and trusted approaches to managing digital artifacts and transactional processes with smart contracts [70,71]. Most of the work is now focused on more transparent and automated payments [72], as well as on supply chain traceability [73,74]. But on a data level, Web3 seeks to offer a novel method for trusted storage, processing, and management of data, while retaining a decentralized infrastructure, meaning not controlled by any single party. Therefore, Web3 technologies shift trust from intermediaries to the technology.

The main two technological components are blockchain and decentralized data protocols (DDPs). Most of the applications explored in construction informatics focus on blockchain [75–77]. But the two technologies are complementary in the sense that DDPs enable secure and privacy-preserving data sharing over a peer-to-peer network [78], for example, the InterPlanetary File System (IPFS). Such data-intensive operations on blockchains tend to be inefficient and expensive, where DDPs can offer added value for large data sets [79–81].

The use of Web3 technologies in the built environment is currently mostly theoretical or prototypical and driven by research, but blockchain technology has been theorized to have numerous benefits for digital processes in this domain [10,82]. However, significant knowledge gaps, socio-technical issues, and legal and regulatory challenges still need to be addressed in order to realize successful industry transfer [12,83]. Some usage challenges arise in managing private keys with blockchain wallets, signing transactions, and orchestrating these processes using decentralized applications [84,85]. In addition, it is crucial to assess compatibility and interfaces with existing data management processes, such as BIM [86].

2.3. Gap and scope

In order to address the various challenges in data management (see Section 2.1), construction informatic research addresses its approaches from different data management perspectives (see Section 2.2). As shown in the previous sections, this leads to a non-integrated and confusing ecosystem that makes it difficult to capture the overarching context of data management. Additionally, it is difficult to categorize and compare new data management approaches, such as Web3, alongside established concepts, such as BIM, without a clear benchmark or comparative metric.

There is a need for a comprehensive and integrated data management framework that captures the technical denominators between different data management approaches. Therefore, the scope of this study lies in synthesizing data management approaches into such a framework, so that researchers and practitioners will be able to understand the interactions, interdependencies, and compatibility of different

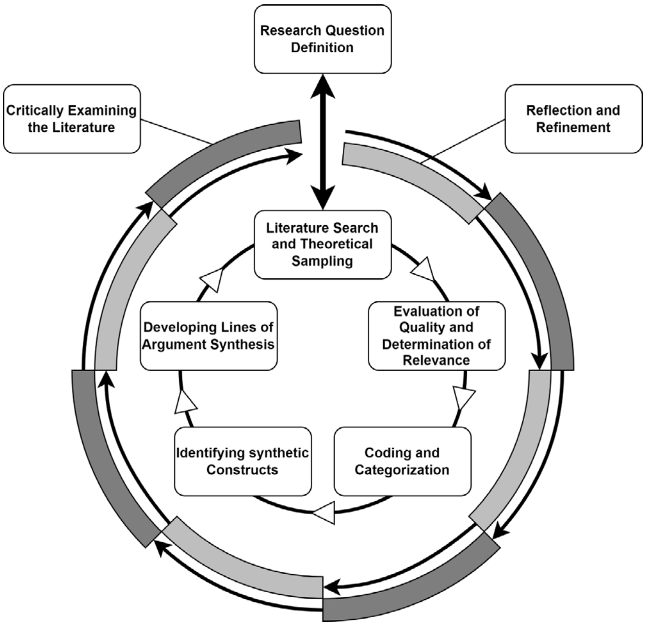


Fig. 1. The iterative and recursive process of critical interpretive synthesis (CIS) is used in this study. More details to the specific steps can be found in Appendix.

technologies. In addition, a common foundation will help select appropriate data management practices and identify relevant research areas for future exploration.

3. Research design

This study uses a method known as *"critical interpretive synthesis"* (CIS), a common approach in medical research [87]. We discovered this method, tested it for effectiveness and found it to be very suitable for our purposes. Consequently, no changes to the method were required as it proved to be an appropriate approach for our analysis. In addition it has recently been adapted for several studies in the built environment [88,89] and for construction automation research [90]. This method facilitates both the review of theoretical and empirical literature as well as an iterative and interpretive engagement with it. Whereas traditional systematic literature reviews (SLR) focus primarily on data aggregation, CIS aims to identify patterns in the data through induction and interpretation [91]. As a result, CIS is useful for developing a novel theoretical framework or constructing a theory that integrates different perspectives and insights [92]. We first applied the CIS method to a subset of relevant literature, confirming its effectiveness in meeting our research objectives without any modifications. The authors' decision to use CIS rather than systematic literature reviews facilitated a more nuanced and context-specific analysis of the research, which is particularly relevant in the field of construction informatics, where intricate data management approaches exist within a complex ecosystem.

CIS is not only a process applicable to the synthesis of findings but is applied throughout the review of the literature. It involves an iterative method to refining the research question, searching and selecting from the literature, and defining and applying codes and categories. Additionally, CIS assesses the quality of individual studies based solely on their relevance, that is, their likely contribution to theory development [93]. A distinctive feature of CIS is its critical perspective on the literature [94], i.e., existing research traditions or theoretical assumptions are dissected or deconstructed in order to better understand the findings and place them in the broader context of the research field. Overall, CIS follows a method of continuous refinement of the targeted synthesis. The authors applied the process shown in Fig. 1 in a recursive and non-linear manner, involving theoretical sampling of the literature and evaluating studies based on their relevance to theory development, coding and categorizing emerging themes, identifying constructs, and synthesizing arguments to develop a framework, while critically examining the literature and refining our analysis throughout the process. Due to space limitations, a more comprehensive description and systematic listing of each process step is not presented here, but can be found in Appendix.

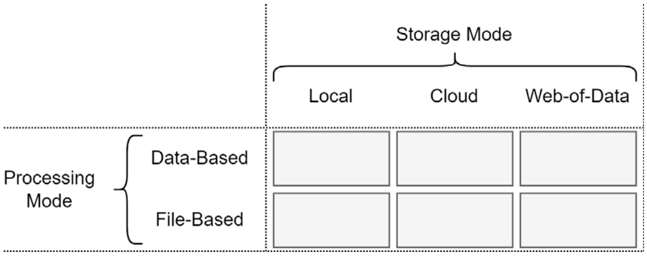


Fig. 2. The two dimensions identified: storage and processing mode, to classify data management approaches into our established framework.

4. Dimensions of data management in construction informatics

The thematic analysis identified two main dimensions of data management approaches in construction research: storage and processing mode. These were used to categorize technological approaches as visually depicted in Fig. 2. The dimensions stem from our comprehensive review and analysis of the literature, as described in Appendix, point 5. In this fifth step of our research method, we carefully reviewed the literature to identify overarching interpretations or concepts and, in particular, to capture recurring themes.

4.1. Storage mode

This paper identifies three main differentiations of the storage mode in construction informatics: Local, Cloud, and Web-of-data. These indicate where data are stored, how they can be accessed, and also reflect the evolution of technology and the increasing online availability of generated data.

4.1.1. Local

In local mode, data are stored on devices such as laptops, desktops, and mobile devices, and can include on-site data such as measurements and inspection reports, as well as project documentation and records. Standardization enables different participants with varying systems and applications to share information and collaborate effectively [95,96]. Although local storage provides fast access to data, it also poses risks such as data loss, hardware failure, and theft.

4.1.2. Cloud

In the cloud-based mode, data is relegated to remote servers managed by third-party service providers to facilitate access from anywhere, allowing for the storage of vast amounts of data. Despite these advantages, this model can raise concerns about data security, privacy, and ownership [44,97].

4.1.3. Web-of-data

The Web-of-data paradigm integrates heterogeneous data from multiple sources into a unified, interconnected data network. This integration facilitates advanced analytics, machine learning, and artificial intelligence applications, enabling the extraction of insights and data-driven decision making [98]. To ensure interoperability and maintain data quality within this model, standardization of data formats and protocols is critical.

4.2. Processing mode

In the context of construction informatics, data processing involves the use of technology and analytical methods to transform, manipulate, and analyze data to extract insights for informed decisions to support business operations. Data processing plays a critical role in improving project management, quality control, safety, and sustainability in construction by providing real-time insights into project performance, identifying areas of improvement, and predicting potential problems before they occur. In this dimension, the authors distinguish between file-based and data-based processing approaches.

4.2.1. File-based

File-based processing refers to the traditional approach of managing data in individual files, such as spreadsheets or documents, and manually processing and analyzing the data. This approach is often time-consuming and prone to errors, as it requires manual data entry and lacks the ability to quickly and easily analyze large datasets.

4.2.2. Data-based

Data-based processing involves the use of advanced technologies to automate data processing and analysis. This approach involves storing data in a structured format, such as a database, and using software tools to process and analyze the data. Data-based processing can include techniques that identify patterns and insights that may not be immediately apparent through manual analysis.

5. Classification of existing data management approaches

The critical interpretive synthesis also identified six distinct categories of data management: closed schema, open schema, open source frameworks, information containers, traditional software, and Web3. These categories can be mapped using the two dimensions of data management approaches: the storage and processing modes.

In this section, we describe the first five categories, each represented by a horizontal bar in Fig. 3. As will be described later in this paper, Web3 is a cross-cutting category. Web3 will be introduced in a later section to explain how the groundwork of this categorization also allows the integrating of Web3 technologies into the same framework (see Section 7).

5.1. Closed schema

Closed schemas, also known as closed data models, are rigid, predetermined, and governed by a fixed set of rules and definitions [99]. They are commonly used in the construction industry to manage data in specialized software applications designed for project management, scheduling, cost estimation, or BIM. Closed schemas ensure that data is organized in a standardized and consistent way. Numerous specialized software applications in the construction industry have led to a fragmented technological environment. Many of these applications use closed schemas to consistently structure data.

The emergence of cloud-based platforms has further popularized the use of closed schemas in construction data management. These platforms provide a central location for data storage and collaboration between multiple stakeholders, increasing the utility and interoperability of data.

Although closed schemas can offer benefits in terms of data consistency and standardization within a given software application, they can also present limitations in terms of interoperability and lock-in [100]. They limit the ability to share data between different software applications, as the data may be structured in a way that is specific to the software application in which it was created. This can result in data silos that are difficult to integrate and analyze, limiting the overall effectiveness of data management.

In addition, the use of closed schemas can lead to a lock-in effect, where users become dependent on a particular software application or vendor due to the structured nature of the data. This can limit flexibility and hinder innovation, as users may be unwilling to switch to new software applications or vendors due to the costs and risks associated with migrating data from one closed schema to another.

5.1.1. Categorization within the proposed framework

Closed schemas are considered data-based because they use structured data formats that enable efficient data processing and analysis. In addition, they are categorized as either local or cloud-based, depending on where they are deployed. When data is stored on individual devices or corporate servers, it is considered local. On the contrary, when closed schemas are deployed within cloud-based platforms that provide centralized data storage, they are classified as cloud-based. In general, we classified closed schemas such as Revit as data-based and stored locally or in the cloud (see Fig. 3, blue category).

5.2. Open schema

5.2.1. IFC

Researchers have addressed the limitations of closed schemas through efforts to develop more open and interoperable data schemas and standards, such as the Industry Foundation Classes (IFC) or the BIM Collaboration Format (BCF) format [101,102]. Using open schemas for standardized data structure, information can be shared and analyzed between software and vendors, thus improving collaboration and reducing vendor lock-in. These schemas are applied in both on-premises applications and cloud platforms. The main limitation of IFC is its focus on the geometric representation of building elements, which may hinder its effectiveness for project management and cost estimation data. Although useful for depicting physical characteristics, IFC may be less suitable for data related to scheduling or cost.

Another limitation of IFC is its ability to handle data that are stored in proprietary formats, as different software applications and vendors often use their own proprietary data formats. This makes it difficult for IFC to fully capture and integrate knowledge from different sources [103], limiting its ability to effectively manage data from multiple sources and resulting in a significant challenge in a highly fragmented technology landscape.

Finally, IFC does not currently have a standardized query language. This can make it difficult to search and analyze data across different software applications, limiting its usefulness for certain data management tasks, particularly data analysis and visualization [104].

5.2.2. Linked Building Data (LBD) e.g., BOT

The evolution of data management strategies has led to the exploration of alternative schema configurations, particularly those of an open nature. This shift in focus was inspired by the concept of a more intelligent and open internet, a vision proposed by the inventor of the World Wide Web, Tim Berners-Lee, which he termed the Semantic Web [57]. The Semantic Web departs from rigid schemas, enabling flexible data interactions. Its objective is to improve data management by semantically storing information in a format readable by machines, thereby permitting programs to process and share content like humans. The Resource Description Framework (RDF) and the Web Ontology Language (OWL) have emerged as standard formats [105].

A first investigation considered a generic approach to transforming IFC using RDF [61]. The result was the ifcOWL ontology, which directly translates the IFC data format. It generates an RDF graph from an IFC-based dataset, allowing individual elements to be linked to separate product or material data. In this context, it has been conceptually illustrated that the application of Web-of-data technologies (e.g., RDF, OWL) can offer significant benefits for BIM [60].

Carrying along the disadvantages of IFC, the direct translation of IFC into a web ontology language still has complexity that cannot be

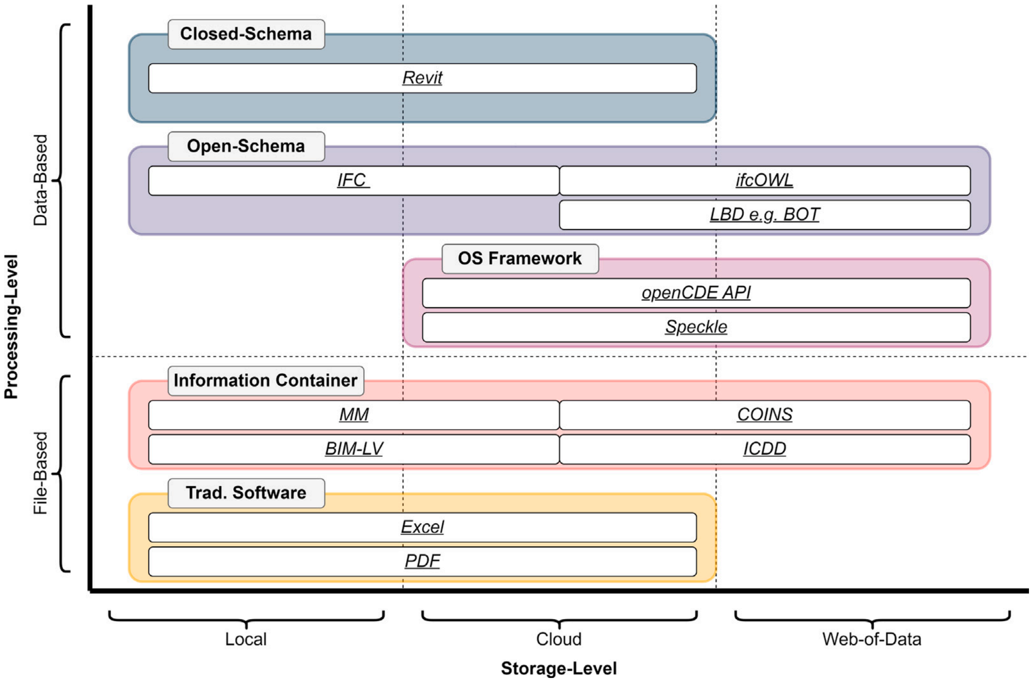


Fig. 3. Overview of our classification of existing data management approaches in construction informatics, grouped into five categories positioned in the two dimensions of processing and storage.

extended and, therefore, is difficult to standardize [64,66]. Similarly, it has previously been reported that in the early stages of ontology development, both generic and domain-specific ontologies largely ignored the guidelines of the World Wide Web Consortium (W3C) for ontology implementation [106]. To address this, the Building Topology Ontology (BOT) was created with an emphasis on simplicity and usability. This served as the foundation for today's Linked Building Data (LBD). LBD aims to provide a standardized way to represent and exchange information about buildings and their components. This information can include physical characteristics, performance data, and other relevant details. With LBD, it is possible to create a single, interconnected record that can be accessed and shared by multiple stakeholders [107].

In addition, this approach initiated a paradigm shift towards the development of smaller, modular ontologies, each addressing a specific aspect of the building lifecycle. This results in a flexible and effective knowledge modeling methodology when these domain-specific ontologies are integrated with others. Furthermore, this facilitates the implementation of extensions, as adaptations are also built on the foundational RDF schema. This methodology, characterized by its inherent dynamism and flexibility embedded in data modeling procedures, represents a promising alternative to centralized models [108].

5.2.3. *Categorization within the proposed framework*

The open schema approach is referred to as data-based because its primary focus is on organizing data into a cohesive and interpretable schema. More specifically, open schemas, including IFC and BCF, provide a structured data model that standardizes the representation of data, thus facilitating computational processing of the data. The storage modality can be categorized as local, as these schemas are often deployed within software applications or systems, with no inherent dependence on web-based data storage or access. The cloud dimension of this approach, on the other hand, arises from its use in document-centric, cloud-based platforms. Therefore, we see open source approaches like IFC as data-based and stored locally or in the cloud (see Fig. 3, purple category). Furthermore, the approach is also consistent with the dimension Web-of-data. In particular, the implementation of Semantic Web technologies illustrates the application of Web-of-data principles to data modeling, emphasizing the creation of federated data structures. Therefore, we classified open source approaches such as ifcOWL or LBD as data-based and stored in the cloud or Web-of-data (see Fig. 3, purple category).

5.3. *Open source frameworks*

Open source frameworks provide a flexible and customizable approach to data management, because the basic schema structure is not limited to proprietary or industry-standard formats. Instead, their development approach is based on freely available source code, allowing anyone to view, use, modify, and redistribute the code as they see fit. This is intended to allow data to be exchanged between different software applications, enabling interoperability and cross-software working practices [109]. Speckle [110] and the openCDE API initiative [111] are examples of this.

Speckle, in particular, provides a platform for sharing 3D design and engineering data in real time, enabling collaboration between multiple stakeholders [112]. The framework uses a common data schema that can be easily customized to meet specific project needs. This architecture facilitates the separation of the authoring tool, or data creation, from data storage. Furthermore, individual data creators can be identified through hashes generated by encoding specific changes [113]. This characteristic highlights the trend that Speckle is moving towards a Web-of-Data approach, where data can be stored locally but made available within a network.

The openCDE API initiative provides a set of APIs that can be used to integrate data from disparate sources and software applications into a single centralized data management system [114]. This framework enables seamless data exchange between different applications, making it easier to manage and analyze data from multiple sources [115].

Both frameworks are designed to address the challenges associated with closed schema systems, such as limited interoperability and data lock-in. In addition, they offer a more flexible and adaptable solution for managing construction data by providing an open source, customizable approach to data management. However, despite their adaptability, open source frameworks are often criticized for their lack of consistency and support mechanisms. The inherent openness of these frameworks can make it difficult to maintain a consistent data schema across different implementations. Furthermore, reliance on community-based support rather than professional support can lead to delays in problem resolution. In order to address these challenges, Speckle, for example, offers optional paid support solutions similar to those provided by larger projects such as Ubuntu or Red Hat. Additionally, open-source frameworks often struggle to gain traction in the industry due to a perception of being niche, overly complex, and suitable only for experts [116].

5.3.1. Categorization within the proposed framework

Open source frameworks lend themselves to data-driven classification due to their core focus on managing and structuring data. This is illustrated by examples that leverage cloud-based infrastructure to improve real-time collaboration and data sharing among multiple stakeholders. Providing APIs in these frameworks to assimilate data from disparate sources into a unified system underscores the focus on interoperability by data centralization. This attribute places this approach within the cloud-based storage mode of the proposed classification scheme. In addition, this approach embodies characteristics consistent with the Web-of-data paradigm. Openness fosters an environment conducive to integrating data across disparate applications, thereby clustering a network of linked data. Overall, we see open source frameworks such as openCDE API and Speckle as data-based and stored in the cloud or a Web-of-data system (see Fig. 3, pink category).

5.4. Information containers

Information containers aim to address the problems associated with file sharing while using collaboration platforms, including the phenomenon of ‘‘data island’’ and data loss during phase transitions, as described in Section 2.1. Rather than solving fragmentation, complex versioning, and data linkage problems through centralized model collaboration, the focus shifts to data organization through the use of information containers [117]. The information container paradigm is not limited to the storage of three-dimensional model files. Instead, it encompasses a range of documents, schedules, and tables [118]. Consequently, the approach provides a comprehensive and organized solution for managing different types of data.

The information container improves interoperability by allowing different building and application models to be packaged and shared in a single container. Each elementary model is stored and maintained separately and linked by an identifier through separate link models. The elementary models remain in their original state and are not specialized for practical applications, allowing them to be independent models for their respective domains. Linking the base models enables the representation of cross-model relationships and the manipulation and querying of the entire information space. Metadata records help infer content and provide information about resources without having to open all the documents involved.

One limitation is container size, which is determined by the number and granularity of application models. Therefore, creating and maintaining multiple models can be time consuming and resource intensive. Additionally, each model must be created and maintained separately, which can be significant for large and complex projects. Second, ensuring the consistency and accuracy of the information in the different models is a challenge. This requires strong communication and coordination between the different disciplines involved in the project. Finally, semantic querying across different domains is problematic, because it must be performed using metadata. However, this is addressed by combining the information container approach with semantic technologies (see Section 5.4.4).

5.4.1. Multi-model approach (MM)

The multimodel (MM) approach allows the integration of models from different domains into a multimodel container (MMC) while preserving the original data formats (standard or proprietary). At the same time, it can represent the dependencies between the models [19]. It involves the use of multiple models to represent different aspects of the system under study. For example, in a building energy simulation, one model can be used to represent the thermal dynamics of the building envelope, while another model can be used to represent the HVAC system and its control. This makes it easier to focus on specific aspects of the system and to incorporate different types of data. This makes it easier to validate and calibrate the models and update them as new information becomes available. The first version emerged from the Mefisto project [119]. Subsequently, it was continued by buildingSMART as MMC version 2.0 and standardized as BIM LV Container in the DIN SPEC standard 91350 [120].

5.4.2. BIM-LV

The BIM-LV container (BIM-Leistungsverzeichnisse), in its inherent design, provides a digital framework that encapsulates both the geometric and financial aspects of a construction project. With this integrated approach, BIM-LV containers provide a consolidated platform that enables efficient cost management, promotes effective resource planning, and fosters enhanced collaboration among stakeholders throughout the project lifecycle [121].

5.4.3. COINS

The COINS (COINS Open Information Delivery Standard) data exchange standard is designed to facilitate data exchange between different stakeholders [122]. It initially addressed the superficial linking of documents and models [123]. In contrast to the federated MM approach, COINS uses a geometric model as a central reference model from which relevant building data is extended using Semantic Web concepts. Specifically, it uses a common data model and vocabulary to represent and exchange information about buildings and infrastructure projects, including physical characteristics, performance data, and other relevant details. It aims to support the exchange of a wide range of data types and to enable the reuse of this data for asset management and other purposes [124].

The approach of using COINS offers several advantages, the most important of which is the granularity of the data that can be achieved. The transition from a document-oriented to an object-oriented information space improves data retrieval and analysis capabilities. In addition, the use of version control and semantic libraries in this procedures provides dynamic semantic enrichment capabilities that can potentially span multiple lifecycle stages [122]. However, despite these benefits, the practical application of this approach presents certain challenges. In particular, users often find it difficult to integrate additional data sources into the model, indicating a need for improved usability [125]. Furthermore, the system is often centralized around a highly aggregated model, suggesting a need for further development in the distribution and decentralization of data within the system.

5.4.4. ICDD

The ICDD (Information Container for Linked Document Delivery) procedure aims to provide information in a more continuous process [19]. As an advancement from COINS, ICDD provides a bridge or linking methodology between previously structured files in incompatible data formats. It facilitates linking and storing non-RDF data formats such as images, point clouds, and geometry [28]. Instead of creating a dump folder, a web-based distributed construction project ecosystem can use ICDD to link semantic construction data to non-RDF, document-based project information.

ICDD is described in the ISO 21597 standard, which consists of two parts. Part 1 defines the container structure and the general link concept by specifying a container ontology, the corresponding data types and object properties, and a link set ontology with the corresponding data types and properties. The second part defines the ICDD folder structure, where additional link types are defined and extended link sets are represented.

An ICDD container can be thought of as a package used to ship a library of linked files to store a particular version or state of a complex project. Although it allows references to external resources, the standard focuses on the description of the files within the container and assumes that their maintenance is more frequent when all referenced files are contained in the ICDD folder. In this case, this is a more efficient and accessible method of querying the project data stored in the container [126].

One limitation, however, is that the use of ICDD as an exchange and data structure is only an intermediate step in overcoming the challenges of file-based data exchange and establishing an access system for granular data [28]. This is somewhat in contrast to a platform approach, where information access is already possible at a granular data level but usually in a proprietary format. There are also differences in the implementation effort. Compared to alternative approaches, ICDD requires more effort, mainly due to its early stage of development. As a result, MMC is already used in commercial software applications, whereas ICDD is not yet widely used.

5.4.5. *Categorization within the proposed framework*

The information container approach encapsulates disparate sources from file systems, making it inherently file-based. The file remains in its original form, supporting different models to function independently within their respective domains. Containers are typically designed for local use, meaning that the user can manage and securely store the entire data set within their local system. Therefore, we classified information container approaches such as MM and BIM-LV as file-based, stored locally (see Fig. 3, orange category). However, the approach also interfaces with cloud technology, as containers can be shared through cloud platforms. In addition, the information container approach, especially when incorporating standards such as COINS and ICDD, exhibits characteristics of the Web-of-data modality. This is evidenced by the linking of different types of files, which improves interoperability and exchange. While these connections do not fully align with Semantic Web principles, within a networked system, information containers can improve data accessibility and integration by emulating some aspects of the Web-of-data classification. Overall, we see open source approaches like COINS and ICDD as file-based and stored in the cloud or Web-of-data (see Fig. 3, orange category).

5.5. *Traditional software*

In the context of construction data management, file-based computing is a common approach that uses traditional software such as PDF or Excel to store, analyze and share information [127]. For example, PDF documents are often used to store project drawings, specifications, and other documents in a read-only format that preserves the integrity of the original document. However, PDF files are not easily manipulated or integrated with other data sources, limiting their usefulness for data management.

Excel spreadsheets are often used to track project schedules, budgets, and other project information because they provide powerful analysis tools. However, manual data entry into spreadsheets can lead to errors, and large and complex spreadsheets can be difficult to manage. However, using these local databases to share files with traditional software is a well-established and widely used approach to managing construction data.

Despite its widespread use, the file-based approach to data processing has limitations. For example, data can be spread across multiple files, making it difficult to manage and integrate with other sources. It also lacks version control, which can lead to errors and inconsistencies. As a result, alternative approaches such as database management systems and cloud-based platforms have emerged to address these limitations and improve the efficiency and effectiveness of construction data management.

5.5.1. *Categorization within the proposed framework*

The current approach is classified as file-based because it relies on individual files to store, edit, and share data. These files exist as independent entities and are manually edited for each operation, such as data entry, analysis, or transfer. Furthermore, depending on where the data is stored and how accessible it is, the approach can be classified as local and cloud. In a local environment, these files are stored on local or mobile devices, allowing quick access to the data, but with limitations such as the risk of data loss due to hardware failure and limited storage capacity. In the cloud, these files are stored on remote servers managed by third parties, improving access to data from any location. However, it also presents a number of challenges, such as potential security risks and data privacy and ownership issues. Overall, we see traditional software such as PDF's and Excel as file-based and stored locally or in the cloud (see Fig. 3, yellow category).

6. The connection between data management concepts

The structured categorization used in this study allows the mapping of the specific technological frameworks to more general data management concepts. As highlighted in Section 2.2, accurately characterizing data management concepts is a significant challenge due to their multifaceted nature, continuous evolution, and varying implementation and adaptation in the industry. This complexity is further compounded by inconsistencies in concept usage across projects and organizations, making it even more difficult to establish definitive correlations [128]. Therefore, a primary objective of this study was to foster a more detailed understanding of these complex interrelationships, taking into account their dynamic and varied implementations of construction data management. The framework proposed in this paper can help to develop a more comprehensive understanding by highlighting the interconnectedness or differences of different concepts and technologies. We present two exemplary scenarios that demonstrate the applicability of our proposed framework.

6.1. *Example 1: Multiple technological approaches for an identical concept*

The concept of Building Information Modeling (BIM) can be considered as a representative case how a data management concept can transcend the boundaries of a single technology. Rather, it manifests itself as a synthesis of various technological strategies, embodying the intersection of multiple approaches. For example, a potential strategy to implement BIM involves a local storage paradigm that uses a combination of closed and open schema data. This model synchronizes across different internal servers by using information containers, as shown in Intersection A in our conceptual framework (see Fig. 4). Another feasible strategy could be to adopt a cloud-based approach (see Intersection B in Fig. 4). This approach could be based on a closed schema, an open schema, or even an open source framework, thus branching into three different technological possibilities.

Despite the different technological components of these two alternatives, both can be classified within the BIM data management concept. This illustrates the adaptable, but at the same time confusing nature of the BIM concept, which embraces different technological methodologies.

6.2. *Example 2: Similar technological approaches for different concepts*

The concept of CDEs can be technically implemented through cloud-based infrastructures using information containers, open source frameworks, or both closed and open schema strategies (see Intersection C in Fig. 4).

Comparing this technical implementation of a CDE with the previously discussed implementation of a cloud-based BIM (see intersection B in Fig. 4), the framework shows how different concepts refer to almost identical approaches in technological terms. This observation

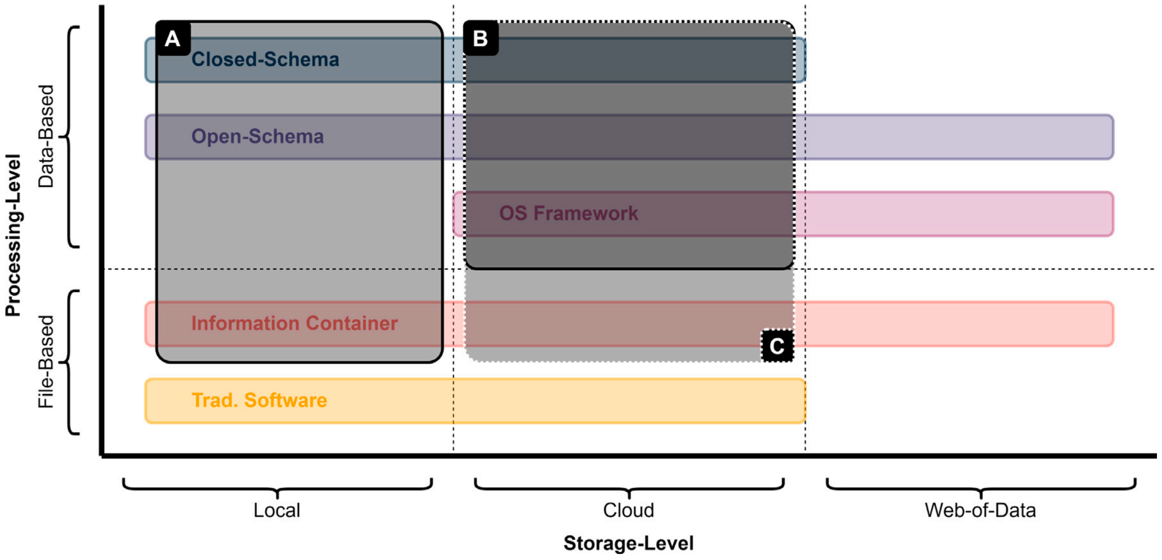


Fig. 4. The framework can help categorize data management concepts as a combination of the identified categories to improve the understanding of data management approaches in construction informatics, e.g for different implementations of the BIM concept (A/B), or similar implementation of two concepts, such as BIM (B) and CDE (C).

vividly illustrates the potential overlap of data management concepts and further explains the complexities and ambiguities that make its understanding difficult. Without specific reference to the underlying technology, perplexing questions arise, such as whether a BIM implementation uses a CDE or whether the CDE represents a new approach to BIM. The use of the framework clarifies that from a data processing and storage perspective, they perform identical functionality.

7. Integrating Web3 technologies into the classification

Web3 systems can have a transformative influence on the facets of data storage, data access and ownership mechanism, and data management. In particular, decentralized networks within such systems embody the potential to displace traditional, more centralized paradigms. In the current scientific discourse, Web3 technologies are often separated from conventional data management strategies and lack an integrative perspective (see Section 2.2.4), despite their intrinsic nature as data management systems [129]. Consequently, discussing the concepts of Web3 in the proposed framework can help to evaluate these technologies in relation to existing data management approaches. For a structured approach, we use the Web3 technology stack of the Web3 Foundation [69] as a base for the classification pictured in Fig. 5.

For the scope of this paper, while the various layers of the architecture are important when examined in depth, we figured that focusing primarily on Layer 1 (L1) technologies (see Figure Fig. 5) serves the purpose of a high-level comparison with the other existing data management approaches examined.

In essence, these L1 technologies function in a manner that promote broad access and interconnectivity of data across various nodes within the network, in addition to providing mechanisms for data processing. Specifically, in the context of blockchain, each block in the chain encapsulates a unique set of data points, mostly transactions, that are individually accessible and verifiable across the network of nodes. Similarly, some decentralized data protocols (DDPs), especially decentralized storage networks (DSNs), handle structured data points, such as key value pairs that can be accessed, updated, and manipulated individually. Therefore, all technology components included in the Web3 technology stack as shown in Fig. 5 align within the Web-of-data category.

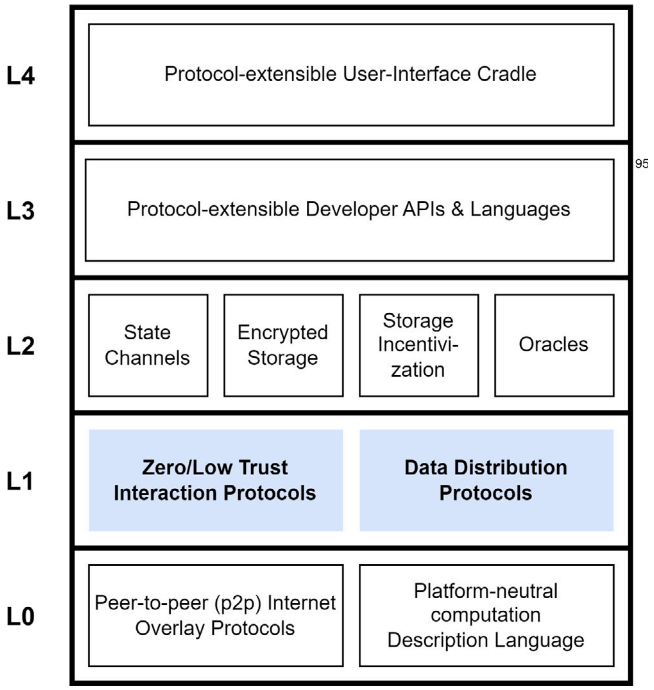


Fig. 5. Web3 Technology Stack, adopted from the Web3 Foundation [69]. In this paper, we focus primarily on the fundamental Layer 1 (L1) Web3 technologies of zero/low trust interaction protocols (also known as blockchain) and data distribution protocols, which are highlighted in blue.

The categorization of the processing modes for DDPs then again depends on the specific technologies used. We can distinguish between distributed file systems (DFS), such as the InterPlanetary File System (IPFS) [130], and decentralized storage networks (DSNs), such as Ceramic [131] (see Fig. 6). The former is classified as file-based at the storage level because it focuses on storing, retrieving, and distributing entire files rather than individual data points. In contrast, DSNs provide a mechanism for storing and synchronizing structured data within a network, and are therefore data-based. Overall, DDP can be classified as Web-of-data with both DFS as file-based technologies and DSN as data-based technology (see Fig. 6, DSN and DFS summarized as DDPs). Since blockchain usually stores synchronized structured transactional data across the network, we categorize blockchain technology exclusively

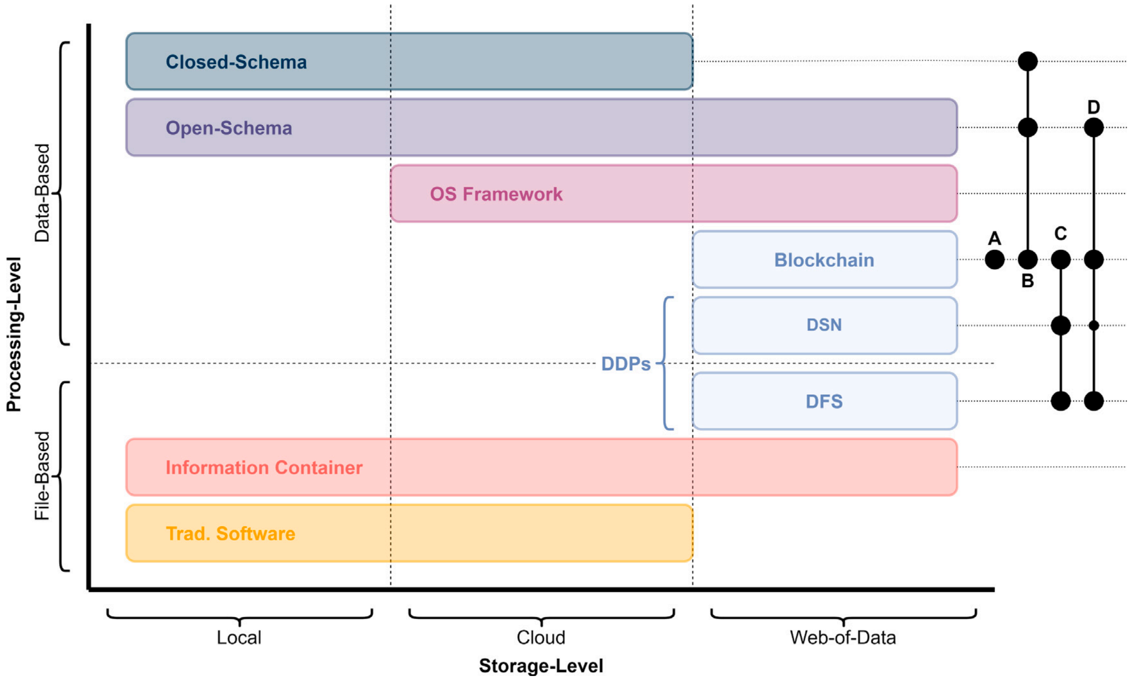


Fig. 6. Integrating the two Web3 technologies blockchain and decentralized data protocols (DDP) into the established framework of current data management approaches in construction informatics. The isolated use of blockchain and DDP (A/C) and the interactions with existing data management approaches (B/D) is discussed in the text.

data-based as processing level in the Web-of-data storage level (see Fig. 6, Blockchain).

Given these classifications at the storage and processing levels, we can discuss the interactions of Web3 technologies with data management approaches already investigated in construction, such as open schema, OS frameworks, and information containers (see Fig. 6). In the following, we highlight the focus of existing studies on blockchain and DDPs in a construction informatics context.

7.1. Studies about blockchain with other data management approaches

Looking at the evolution of blockchain technology research, we see that the initial studies took a largely isolated approach (see Fig. 6, Point A). Before exploring the interactions with existing data management methods, studies focused on the inherent properties of this technology, such as transparency, immutability, and new ownership mechanism, with the aim of building a robust and trusted system [132–134].

A case illustrating the standalone use of blockchain, untethered from conventional data management (see Fig. 6, Point A), includes a study of a blockchain framework for quality-related information [135] and a method for transparent payments [83].

The overlap considerations with existing methodologies, such as open schema [136], were only made after understanding how this technology could complement and contribute to data management. As an example of this, one of the major critiques of linked data, namely the true decentralization through ownership mechanisms, can be addressed. Blockchain technology may facilitate the implementation of such enhancements as well as versioning challenges, which does not depend on a central platform [84]. Interaction B in Fig. 6 summarizes studies such as the integration of blockchain with BIM (open and closed schema) in the context of smart cities [137], or addressing issues related to information redundancy that could potentially arise from such an integration [138].

7.2. Studies of DDP with other data management approaches

The second technology of interest, DDPs, has received comparatively less research attention than blockchain. If research investigates the use of DDPs, it is done primarily in combination with blockchain technology [86] (see Interaction C in Fig. 6). More specifically, initial research has explored how these novel data storage methods could be beneficial in addressing challenges such as privacy, fine-grained access control, and the single point of failure inherent in current storage systems [81,139]. In fact, recent studies are increasingly considering the integration of a DDP with blockchain technology. These studies propose, for example, the use of IPFS for a CDE in collaborative design [54,140].

In this context, blockchain should not be seen primarily as a storage utility. Rather, its role is to facilitate governance and access mechanisms within these systems. This can be achieved, for example, by using wallets with specific private keys for individual participants or by integrating decentralized identities.

Furthermore, some initial contributions have been made in the context of existing data management approaches such as open schema together with both DDPs and blockchain [140,141] as pictured in interaction D (see Fig. 6). However, here we find that the focus is mainly on the use of DFS such as IPFS, while other DSNs have hardly been explored [129], therefore, also represented by a smaller circle in interaction D.

Additional interactions involving DDPs, the OS framework, and the information container are not delineated in Fig. 6. This omission is due to the fact that to the best of our knowledge, there are no comprehensive studies investigating these specific combinations.

Using the established framework, we show that the early work has the potential to provide improved solutions to the prevailing data management challenges by combining them with blockchain and DDP as an integrated Web3 approach [80], although they are often perceived as disconnected from traditional construction data management methodologies.

8. Discussion

8.1. Recent trends observable in data management

Overall, a trend in two directions is noticeable: data-based processing levels and a Web-of-data storage level. Within our framework, this means that we are progressing towards the upper right quadrant. This becomes even more evident when further evaluating the literature reviewed for this paper, narrowed down to contributions since 2019. The filtered set of 99 contributions was initially plotted on the basis of their publication dates, citation counts, and interrelationships. The resulting visualization is presented in Fig. 7(a). By isolating the 20 most cited and interrelated contributions and thematically clustering them into our established framework (see Fig. 7(b)), the emerging pattern indeed suggests a direction of research efforts towards the upper right quadrant.

Furthermore, we observe that these efforts rarely deal with isolated categories. Instead, they exist within overlapped domains. This finding strengthens our analysis that the advancement of Web3 technology aligns with new paradigm perspectives and shows the current research trajectory in the field. Furthermore, our identified overlap with the Web3 construct supports the usefulness of our framework in clarifying the current state. This will serve as a foundation for a further discussion as we dive into the details of these aspects.

8.2. Data management trends in the context of the three challenges

Research has made significant progress in addressing the two challenges described in Section 2.1. In summary, an information-rich and interoperable AEC information environment requires three key elements. The environment must give controlled access to all project information for any trade, facilitate scalable extraction from unstructured sources with related information linkage, and enable data-driven insights. However, despite the progress made, there are still obstacles that require additional investigation and resolutions. As shown in Section 8.1, the framework helps identify emerging trends in data management practices to address these ongoing challenges.

8.2.1. From file-based to data-based

Data aggregation and maintenance can be challenging when using file-based approaches, leading to coordination and versioning issues when dealing with multiple trade-specific files. To address these issues, a data-centric approach can be adopted using open-schema standards that adhere to Semantic Web principles. For example, replacing IFC with ifcOWL demonstrates the potential of such an approach.

8.2.2. From local and cloud towards Web-of-data

As shown in Fig. 4 and discussed in Section 8.1, our framework indicates a trend in the use of Web-of-data methodologies. However, most current research focuses on cloud storage as an improvement from local storage, with only a limited amount exploring Web-of-data storage mechanisms [142]. It is essential to highlight recent notable research advances in this area, including the implementation of the Solid Ecosystem [143] and the federated data infrastructure [144,145].

However, our analysis also shows that many current solutions maintain centralized components [146], including data storage and the use of access protocols based on cloud-based infrastructures [147,148]. Consequently, these solutions face obstacles in managing dynamic data ownership, intricate access architectures, and sophisticated decentralized sharing mechanisms. Centralized data repositories, if standardized, can inadvertently result in the relinquishment of data sovereignty and establish vendor lock-in [149].

To our knowledge, only the LBDServer mentioned and its ecosystem envisioned propose a solution in this regard [150]. It employs linked data to facilitate interoperability and tackles the issue of data silos despite having federated storage. This is achieved by describing the database of a construction project as a network of resources, both accessible to the public and contingent on authorization [151,152]. The SOLID ecosystem can serve as an authentication mechanism to address the shortcomings of centralized platforms [153]. For example, a WebID method could eliminate the need for an external identity provider to operate as a go-between [154]. As a result, all stakeholders can arrange the data they generate on their individual servers, while the ecosystem makes it possible to connect to external data.

Within our analytical framework, we expand on this illustration to examine the possible advantages of decentralized methodologies that utilize Web3 technologies to improve data owners' autonomy and ensure data accessibility. Additionally, the framework illuminates the differentiation between linked data and Web3 technologies. The former pertains to approaches in data processing, while Web3 technologies prioritize decentralization, authentication, and data transactions in a trusted and permissionless setting.

8.2.3. The potential of Web3

Our analysis indicates that Web3 could be a disruptive solution to the inherent systemic data management constraints. The general movement towards decentralized data management approaches also supports the notion that Web3 technologies can be integrated with conventional construction data management practices. The framework identifies opportunities to connect conventional methods and the decentralization capabilities provided by Web3. It accentuates the necessity for additional exploration to objectively investigate the potential of such collaborations in various construction-related scenarios. Although incorporating Web3 concepts for improving individual use cases and streamlining processes could prove advantageous, it does not suffice to address systemic limitations. This paper does not comprehensively demonstrate this issue, its purpose is to encourage further consideration.

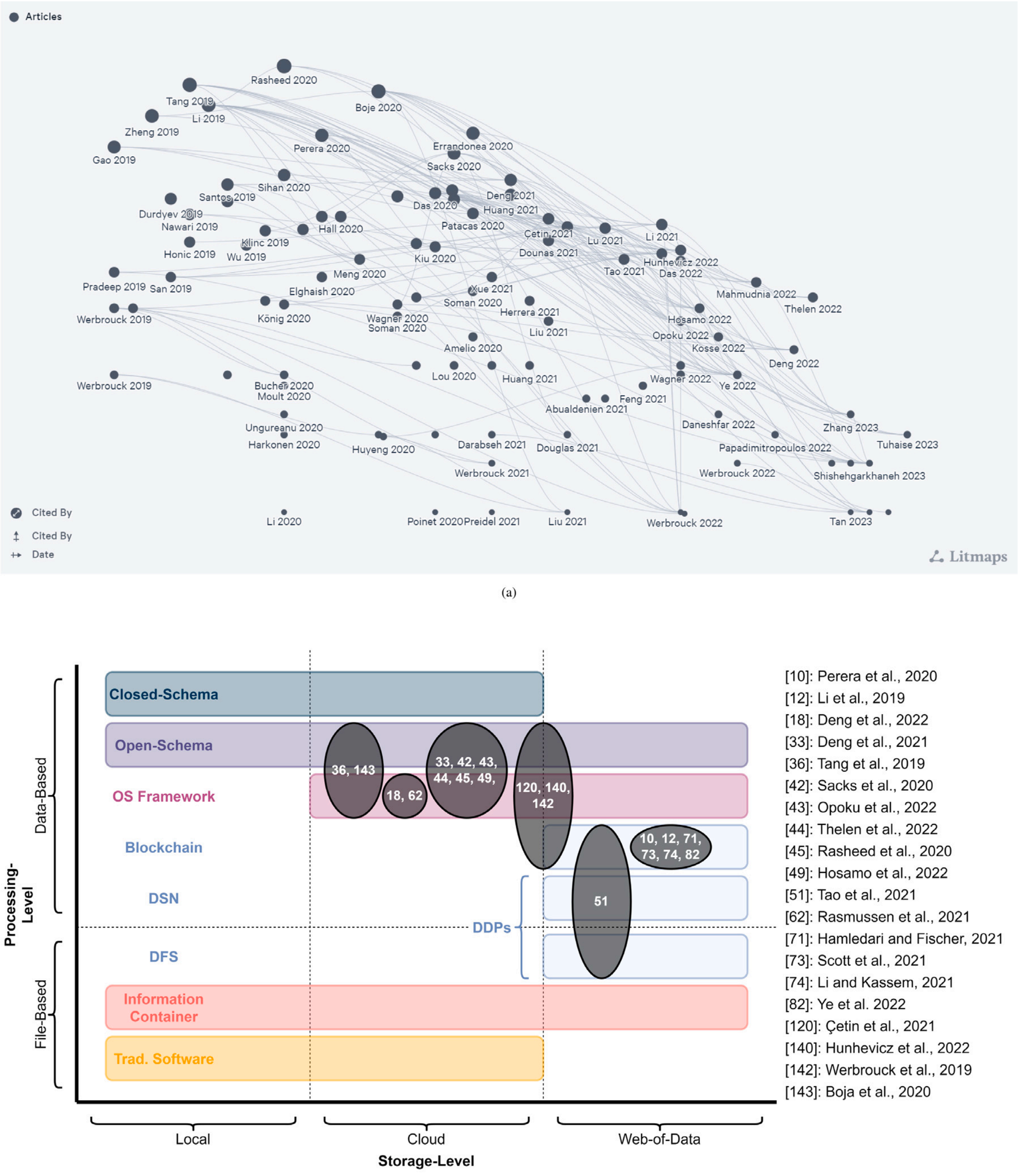
Web3 has the potential to manage an extended data lifecycle in situations where trusted data and data provenance are necessary. One possible approach is to use provenance mechanisms such as blockchain timestamping to ensure this. Despite the fact that the resulting cryptographic hash is data-based, the framework effectively demonstrates its independence from the source files' data management dimensions (file or data-based, as well as storage). This also holds true for blockchain-based logic through smart contracts. In decentralized Web-of-data approaches, participants should be incentivized to share data via a non-centralized mechanism, avoiding monopolies. Blockchain-based incentive systems have the potential to promote stakeholder participation in a shared data environment in the long run [155].

8.3. Next research steps

As noted in Section 8.1, we observe a trend in our framework towards the data-based processing mode and the Web-of-data storage mode, which is also relevant for future research by identifying potential paths for future exploration and development. For example, a possible next research step could be to merge approaches, such as Speckle or ifcOWL, with emerging technical data infrastructures, such as blockchain and decentralized data protocols. In addition, more research is needed in the following areas.

8.3.1. Framework validation and extension

First, we need to examine the framework in more detail. We introduced various data management technologies and their potential interrelationships. However, we did not comprehensively evaluate their benefits or drawbacks while contextualizing the technologies with each other. There is the possibility that not all connections are practically viable, which future research could demonstrate. For example, merging linked data with Web3 technologies could yield certain advantages. While previous Web3 research has focused on blockchain technology, another critical aspect of Web3, decentralized data distribution protocols, has yet to be substantially explored. Their integration with current machine readability and inference technologies could be advantageous. Further research is necessary to explore the integration of various technologies and verify their effectiveness in improving data management processes within the construction sector.



(a)

(b)

Fig. 7. Analysis of recent research trends in data processing and storage. (a) maps 99 post-2019 contributions by date and impact, while (b) clusters the top 20 within our framework, hinting at a research trajectory towards integrating emerging technologies.

8.3.2. *Implications of decentralized approaches to construction informatics*

The growing use of technological approaches has far-reaching implications that require thorough analysis. For example, there is a need to better understand the advantages and limitations of decentralization as it pertains to the technological landscape in the construction sector. The implications of the novel ownership and control of individual data sets and the potential for new service-based business models remain unclear [145]. Furthermore, decentralization raises complex questions about incentives to share in the context of distributed storage. A paradigm shift may occur where intrinsic motivation through incentive systems drives data sharing and collaboration. To achieve this goal, it is essential to grasp the ways of creating data systems that combine established methods with modern Web3 technologies while acknowledging their potential consequences on the wider ecosystem.

8.3.3. *Addressing technical challenges*

Third, it is important to acknowledge the complexity of combining different technologies. This is particularly challenging given the constantly evolving landscape of new standards and implementations. For example, selecting a suitable DLT and associated data protocols can be difficult given the many options available [75]. Therefore, it is crucial to evaluate the strengths and weaknesses of these technologies before they are implemented. Additionally, existing technologies such as linked data continuously improve and must be considered when building prototypes. To address these challenges, future research should focus on implementations of specific use cases to demonstrate and test prototypes in a construction context.

9. Conclusion

This paper introduces a pioneering framework for data management in construction informatics, integrating emerging Web3 technologies. To our knowledge, there is currently no comprehensive framework for data management practices in construction informatics. The proposed framework can organize data management procedures and minimizes uncertainty surrounding their understanding, including the incorporation of Web3 technologies. Furthermore, the framework enables the recognition of current research trends that lean towards data-based and Web-of-data approaches in alignment with the principles of Web3.

Our research is significant because it shows that Web3 has the potential to transform data management practices, bringing improved data authenticity, new access, and ownership models. The deployment of Web3 technologies alongside, for example, Building Information Modeling (BIM), creates opportunities for more sophisticated and distributed data management systems in the construction sector. In addition, our study indicates that Web3 is compatible with existing data structures in the construction industry. It is thus feasible to replace individual system components with decentralized technologies in order to integrate, for instance, novel ownership mechanisms. This could potentially result in enhanced data availability and more active stakeholder involvement.

It also contributes to the academic discourse on data management by proposing a novel integration of Web3 technologies with established construction informatics frameworks. The conceptualization of data flows and data governance within Web3 paradigms is extending the boundaries of traditional data management theories.

However, our study is not without limitations. The rapidly evolving landscape of Web3 technologies and the complexities of integrating them with existing data management strategies present challenges beyond the scope of this paper. To advance this field of research, future contributions should focus on the empirical validation of the framework through small-scale practical implementations and projects. In addition, further research is needed to validate the framework and the proposed developments. Another similar study could be helpful at a later stage.

Our research has practical implications that are relevant to the construction industry, providing tangible benefits beyond academic discourse. The implementation of Web3 technologies has the potential to greatly improve data transparency and collaboration, resulting in more efficient and effective project management. It is recommended that practitioners integrate Web3 technologies in a gradual manner, proceeding from the implementation of pilot projects designed to effectively measure impact and scalability.

CRediT authorship contribution statement

David F. Bucher: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Jens J. Hunhevicz:** Writing – review & editing, Validation, Resources, Investigation, Conceptualization. **Ranjith K. Soman:** Writing – review & editing, Validation, Resources. **Pieter Pauwels:** Writing – review & editing, Validation, Resources . **Daniel M. Hall:** Writing – review & editing, Validation, Resources, Supervision, Conceptualization.

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.

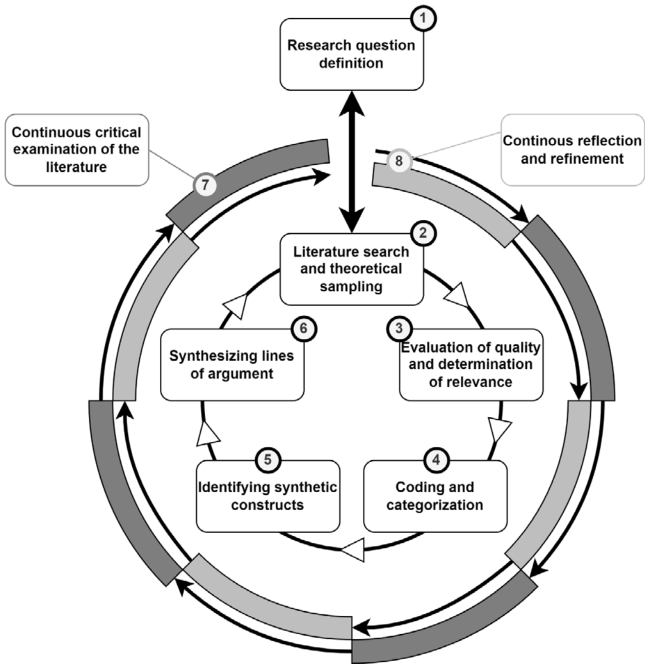


Fig. A.8. Detailed overview of the iterative and recursive process of critical interpretive synthesis (CIS) used in this study.

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Appendix

As described in the corresponding Section 3, our methodology is based on the *critical interpretative synthesis* (CIS) process. In the following, we outline the specific steps of the process that are in line with the diagram in Fig. A.8.

1 — Research question definition: As a first step, we laid the groundwork for exploring the target area by defining two broad research questions. As mentioned above, these questions were preliminary and underwent several revisions during the development of this paper. However, they proved useful for an initial literature review. After several iterations, we concluded with the research question found in Section 2.3.

2 — Literature search and theoretical sampling: In response to the research question, we performed a literature search to identify relevant studies. However, the selection of studies to be included was not necessarily predetermined. Instead, a process of theoretical sampling was used. This means that the criteria for selecting the studies to be included in the review evolved as the authors' understanding developed.

As a starting point, academic search engines such as Scopus and arXiv were used to identify articles and research papers that met the initial requirements. Here, the scope encompassed a wide range of sources relevant to data management practices in construction informatics. We also searched the archives of standards bodies such as BuildingSmart to identify relevant national and international standards. In addition, we conducted a Google search to capture industry viewpoints and non-academic articles that offer practical insights and industry viewpoints.

The rationale behind this diverse selection was to gather a wide array of perspectives and approaches to data management. By combining academic research with industry standards and practical experience, our aim was to develop a well-rounded and nuanced understanding that accurately reflects the current state and emerging trends in construction informatics.

3 — Evaluation of quality and determination of relevance: As noted above, the quality of a study in the context of a CIS was not assessed on the basis of specific methodological features or results derived from sources, as is typical in traditional systematic reviews. Instead, the assessment was based on their relevance and likely contribution to the theoretical development of the framework. We therefore included as many different perspectives as possible in order to develop and evaluate a comprehensive understanding of the approaches and their interrelationships.

4 — Coding and categorization: We developed then initial codes based on recurring ideas or themes in the literature. Similar to Point 2, this step was iterative and interpretive, meaning that the codes were revised as more literature was reviewed and the authors' understanding deepened. We focused primarily on overarching approaches and technical methodologies, rather than specific technical details, processes, or use cases.

5 — Identifying synthetic constructs: In Step 5, we aimed for a new synthetic understanding or theory based on constructs representing overarching interpretations or concepts that emerged from the iterative process of reviewing and coding the literature. Specifically, we identified thematic categories, such as differences in data storage (Section 4.1) and processing level (Section 4.2), which we subsequently referred to as dimensions. Furthermore, we identified different technical approaches (Section 5), which subsequently helped to formulate an initial framework integrating emerging technologies and concepts.

6 — Synthesizing lines of argument: In the final iterative step, we develop an overarching narrative that synthesized the constructs into a coherent framework identifying differences and connections between the thematic clusters as presented in (Section 5). Although the narrative is grounded in the reviewed literature, it proposes a new interpretation for the comprehensive understanding of data management approaches in the construction industry.

7 — Continuous critical examination of the literature: As discussed above, a distinctive feature of the CIS is its critical engagement with existing research traditions, theoretical assumptions, and contexts. Its consistent use within the steps allows the authors to improve their understanding and contextualization of the research findings.

8 — Continuous reflection and refinement: As an important feature of the iterative nature of the CIS, we applied a continuous process of reflection and refinement to the research question, sampling, categories and synthesis through several iterations. This ensured that the emerging framework was coherent, comprehensive, and informative.

Data availability

No data was used for the research described in the article.

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