Common Data Environments in construction: State-of-the-art and challenges for practical implementation

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Abstract

Purpose – Information management workflow in BIM-based collaboration is based on using a Common Data Environment (CDE). The basic premise of a CDE is exposing all relevant data as a single source of truth and facilitating continuous collaboration between stakeholders. A multitude of tools can be used as a CDE, however, it is not clear how the tools are used or if they fulfil the users' needs. Therefore, this paper investigates current practices of using CDEs for information management during the whole built asset's lifecycle, through a state-of-the-art literature review and an empirical study.

Design/methodology/approach – Literature data is collected according to the PRISMA 2020 guideline for reporting systematic reviews. We include 46 documents in the review and conduct a bibliometric and thematic analysis to identify the main challenges of digital information management. To understand the current practice and the views of the stakeholders using CDEs in their work, we utilised an empirical approach including semi-structured interviews with 15 BIM experts.

Findings – The results indicate that one of the major challenges of CDE adoption is project complexity and using multiple CDEs simultaneously leading to data accountability, transparency and reliability issues. To tackle those challenges the use of novel technologies in CDE development such as blockchain could be further investigated.

Originality/value – The research explores the major challenges in the practical implementation of CDEs for information management. It is the first study on this topic combining a systematic literature review and fieldwork.

KEYWORDS: Building Information Modelling (BIM), Construction Management, Information Systems/Management, Innovation, Project Management, Whole Life Cycle.

1 Introduction

Construction projects involve a large number of stakeholders producing a massive amount of data which naturally creates challenges for information management (Ajam *et al.*, 2010; Charef, 2022). Even thousands of project documents could be generated and exchanged in a single project, including drawings, specifications, correspondence, contracts and many others (Al Qady and Kandil, 2013a; Kiu *et al.*, 2022). Efficient information management is essential in managing projects related to better decision-making, especially in current data-rich environments enabled by technological advancements (Whyte and Levitt, 2011). Building Information Modelling (BIM) is a key information management approach and solution in the Architecture, Engineering, Construction and Operations (AECO) industry and can improve information flows and lead to enhanced building management across the lifecycle (Sacks *et al.*, 2018). Information management workflow in BIM-based collaboration is based on using a Common Data Environment (CDE) (BSI, 2021). AECO projects are organised with a variety of stakeholders that exchange information across various stages of the project lifecycle up to handover and asset operation (Sacks *et al.*, 2018). The purpose of a CDE is to expose all relevant data as a single source of truth and facilitate seamless information exchange and continuous collaboration among stakeholders (BSI, 2021).

The concept of a CDE emerged in BS1192:2007 and was further developed in PAS 1192-2:2013. In 2019 the CDE-based information management workflow received its own international standard, ISO19650 (AEChub, 2022). Since then, an emerging number of tools that can be used as CDEs with a different compliance level with the ISO standard has been developed by various software vendors. In practice, a CDE is usually a cloud-based repository where all stakeholders can store and access project data (Turk *et al.*, 2022). Before the emergence of CDE tools Electronic Document Management Systems (EDMS) were commonly used in AECO. In the early 2010s EDMS were still clearly more used than CDEs as most of the publications focused on their use (Al Qady and Kandil, 2013b; Kähkönen and Rannisto, 2015). This indicates that the widespread use of CDEs started only during the last 10 years.

The 2020 BIM survey (NBS, 2020) identified several tools used by industry practitioners as CDEs, such as Viewpoint/4Projects, Autodesk BIM 360 and Aconex. Moreover, instead of using a purpose-built CDE, professionals are using general-purpose file-based document management systems such as Dropbox (NBS, 2020). There are very few studies investigating the current state of CDE adoption in practice. Kiu et al. (2022) investigated the challenges of EDMS tools in design and construction based on empirical data. The BIM survey (NBS, 2020) identified which tools are used by the practitioners in the design stage but it did not provide any more information about the experiences of the users with the use of CDE tools. It is not clear how the tools are used or if they fulfil the requirements and users' needs. This paper addresses this gap by investigating current practices of using CDEs for information management during the whole built asset's lifecycle, through a state-of-the-art literature review and an empirical study. Notably, this paper focuses on the following research questions (RQ): RQ1) How are CDEs implemented in practice? RQ2) What are the challenges and limitations of CDE-based information management throughout the lifecycle of built assets? Understanding the weaknesses and strengths of current CDE implementations is a promising way for streamlining information management in AECO.

2 Theoretical origins of CDEs

Information is a key element of organisations as information processing is important for reducing task uncertainty (Galbraith, 1974). Expanding this idea between organisations, the information processing view is useful in understanding how different actors interact and make decisions. In the AECO that is organised by projects, Winch (2015) has defined projects as information processing systems. In our current digital economy, information processing becomes less human-centric with minimised human intervention and instead grows increasingly powerful due to digitalisation. New technological solutions and tools have a significant influence on information management practices in project-based industries (Whyte and Levitt, 2011).

CDE is defined in the ISO19650 standard as *"an agreed source of information for any given project or asset for collecting, managing, and disseminating each information container through a managed process*"(BSI, 2021). CDEs include a 'CDE solution' and a 'CDE workflow which organises the flow of information across the whole lifecycle of an asset across four information container states (BIM Dictionary, 2020). ISO19650 (BSI, 2021) describes four states in which each information container can be: work in progress (WIP), shared, published, or archived; the transition from one state to another should be subject to approval and authorisation processes. The 'CDE solution' is usually a server-based or cloud-based technology with database management, transmittal, issue tracking, and related capabilities that support the CDE workflow (BIM Dictionary, 2020).

To more accurately describe what a CDE is beyond the generic definition provided by ISO19650, Bedoiseau et al. (2022) developed a CDE framework analysing four different aspects of CDEs namely Documents, Coordination, Communication and BIM Production. Another study by Das et al. (2021) investigated the aspect of security in collaborative BIM platforms and distinguished three levels of BIM security, considering the security of data, network and systems, data ownership, data sharing, data integrity and information flow. Although both studies investigate how CDEs could be classified, they did not investigate how different CDE solutions available on the market are used in practice. Moreover, there is still confusion between the EDMSs, BIM platforms and CDEs as these terms are often used interchangeably in the studies (Das *et al.*, 2021; Kiu *et al.*, 2022). However, a CDE provides more functionalities than a simple cloud-based repository or an EDMS, as it should facilitate CDE workflows and seamless integration with BIM (Bedoiseau *et al.*, 2022). Basic online file-sharing systems lack crucial elements of a CDE, such as process management, multi-user support, and comprehensive document and model administration (DIN, 2019). Previous works are limited to discussing only EDMS in construction or CDEs for design stages and do not cover the whole lifecycle of a built asset. Therefore, this study aims to offer a comprehensive analysis of CDEs and explain their impact on information management during the whole lifecycle of a built asset.

3 Research method

This research study uses a combination of two methods to answer the RQs: desk research and fieldwork (Figure 1). In desk research, we conducted a Systematic Literature Review (SLR) to identify the challenges and limitations of current CDE solutions and investigate recent research trends. Simultaneously, we used a qualitative approach to gather empirical data through semi-structured interviews with industry practitioners to complement findings from the literature.

As a main analysis method for literature review and interview data we utilised thematic analysis via coding (Braun and Clarke, 2006). Through coding, a researcher can identify themes or patterns in the qualitative data that can be further investigated (Saunders *et al.*, 2019). The publications and interview transcripts were imported to NVivo 2020, and code-related text excerpts related to challenges of CDE adoption and use were highlighted to recognise their frequency throughout the transcripts. The first coding cycle called initial coding was used to identify preliminary codes. It was followed by focused coding (second cycle) to identify the most frequent or significant initial codes and led to the development of prominent themes in the dataset (Saldaña, 2009).

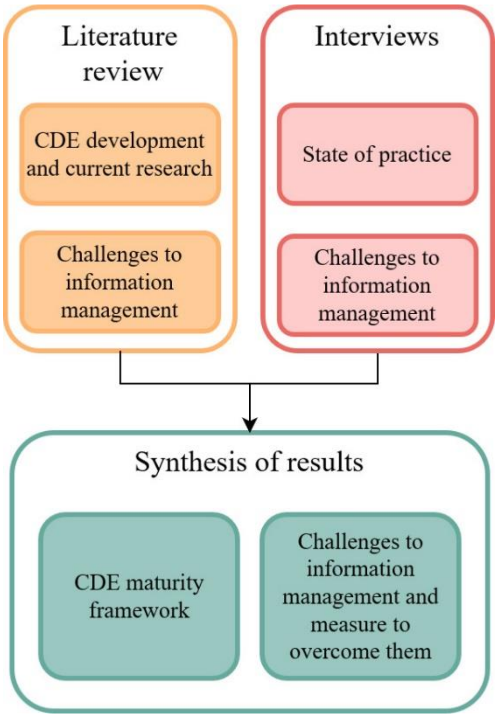

Figure 1 Roadmap of the study.

4 Desk research: a systematic review

To understand the state-of-the-art research surrounding CDEs, we conducted an SLR, “a form of secondary study that uses a well-defined methodology to identify, analyse and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable” (Kitchenham and Charters, 2007). Advanced search strings using Boolean operators were used on Scopus and WoS databases covering business, economics and engineering subjects for data collection. To find all relevant literature we used the keywords “Common Data Environment”, “document management system” and “single source of truth” which are used interchangeably and combined with “construction”. For the Scopus we used following string: (TITLE-ABS-KEY("Common Data Environment") OR (TITLE-ABS-KEY("document management system") OR TITLE-ABS-KEY("single source of truth")) AND TITLE-ABS-KEY(construction). Similarly for WoS we searched for TS=(“common data environment”) OR ((TS=(“document management system”) OR TS=(“single source of truth”)) AND TS=(construction)).

The initial search was conducted in January 2022 and it was repeated in February 2023 to include to most recent literature on CDEs. The number of papers was limited to peer-reviewed journal papers to ensure high quality. Papers published before 2007 were excluded as it was before the ISO19650 publication and definition of CDE terminology. The duplicates were removed and 71 papers were selected for screening following the steps of PRISMA guidelines for systematic reviews (Page *et al.*, 2021). The detailed review process steps are presented in the supplementary material. Finally, 46 documents were selected based on their relevance to CDE.

4.1 Bibliometric analysis

In the first step of bibliometric analysis, we analysed the distribution of publications per year. Till 2020 the number of papers per year was varying slightly between one and four publications. In 2021 this number increased significantly to 14, which was repeated in 2022. This indicates that CDEs gained interest in the research community only in the last two years and a future increase is probable. Furthermore, we compared the number of publications per source. Automation in Construction is the most often chosen journal by the authors followed closely by Buildings and ECAM.

In the next step, we analysed the type of study of the publications. The highest number of papers are literature reviews (14), followed by 11 papers proposing a framework and 10 studies presenting a proof of concept. In 6 studies a prototype of a CDE or similar platform was developed. Furthermore, we investigated which lifecycle phase is the focus of selected studies. 32 publications focus on design or construction phases while only 10 focus on the post-construction phase. Diagrams presenting the results of bibliometric analysis are included in the supplementary material.

4.2 Thematic analysis

Thematic analysis was focused on challenges for information management in construction projects. Selected publications were imported to NVivo Software and related text excerpts were highlighted manually as codes. In the second coding cycle, similar codes were grouped to form 11 themes. The identified challenges, including the total number and relevant references, are summarised in the supplementary material.

4.2.1 Complexity of projects

The fragmented organisational structure of construction projects is difficult to manage in a centralised manner used in current CDEs (Das *et al.*, 2022). Each organisation participating in a project has different hierarchical communication methods and uses different tools leading to challenges in accessing information from external systems (Guo *et al.*, 2021). Managing large projects is generally more challenging than managing smaller ones since large projects tend to be more complicated (Kähkönen and Rannisto, 2015).

The complexity of construction is increasing as technology progresses, with large-scale construction projects reaching unprecedented levels of complexity. Therefore, a greater level of project and information management skills is required (Zhao et al., 2023). The complexity and difficulty of using structured information flows could pose an obstacle to adopting CDEs (Nojedehi *et al.*, 2022). Especially small and medium-size enterprises (SMEs) using simple data repositories might have difficulties with using more sophisticated CDEs (Das et al., 2022). Soman and White (2020) reported that project participants usually have a poor understanding of document control, making it difficult to follow the protocols and fulfil the requirements of structured workflows in complex and not very intuitive CDEs. The information available in the CDE might not be the most updated version due to a long process of authorization and approval, resulting in multiple versions of designs (Soman and Whyte, 2020). Using the work-in-progress (WIP) containers makes it even more challenging to access the latest information, as they can be accessed only by the creators – which encourages isolated working practices (Akponeware and Adamu, 2017).

4.2.2 Multiple sources of information

Along the project lifecycle, a wide range of systems, tools, and data resources are used simultaneously for information management (Patacas *et al.*, 2020). Stakeholders use unstructured channels for information sharing, such as meetings, reports, or emails that are not recorded in common repositories (Soman and Whyte, 2020). Data is distributed in isolated silos and databases are not connected or synchronized (Soman and Whyte, 2020). Only during operation and maintenance (O&M) do stakeholders use tools such as Computer-Aided Facility Management (CAFM) systems, computerized maintenance management systems (CMMS), EDMS or Building Maintenance Systems (BMS) (Patacas *et al.*, 2020). Data is created and manipulated multiple times during the building's lifecycle, resulting in mistakes and omissions as systems are usually not integrated (Becerik-Gerber *et al.*, 2012). Due to the large amount and heterogeneity of data, it is claimed that the adoption and use of single central models or databases is not practical (Patacas *et al.*, 2020). Using multiple software packages, poor information sharing and only partially captured construction process information can lead to data quality issues (Soman and Whyte, 2020). Lack of information transparency and traceability remains a key challenge of current CDEs and EDMSs (Hijazi *et al.*, 2021; Kiu *et al.*, 2022).

4.2.3 Lack of training

Proper implementation of CDEs requires skills for cloud-based systems and BIM software, often lacking in AECO (Akponeware and Adamu, 2017). SMEs especially have limited technical maturity and process capabilities (Adamu *et al.*, 2015). Vidalakis et al. (2019) confirmed that most UK-based SMEs are still struggling with BIM adoption predominantly due to the high implementation cost of BIM-based approaches. Professionals resist change to new systems, particularly when teams have worked in their old ways for long (Taylor, 2017). Kiu et al. (2022) reported that AECO continues to have a poor understanding of EDMSs. Most construction professionals are not technologically proficient and remain comfortable using basic document management tools (Kiu *et al.*, 2022).

4.2.4 Interoperability challenges

Using multiple domain-specific tools and modelling practices in construction projects causes interoperability problems leading to poor data quality (Sacks *et al.*, 2018). Working with CAD tools of different providers necessitates multiple format conversions, potentially resulting in data and information loss (Kurwi *et al.*, 2021; Soman and Whyte, 2020). Problems related to data compatibility occur even while working between different versions of the same software (Soman and Whyte, 2020). Another problem related to communication is the lack of a common language, as there are too many developed standards and classification systems, which are costly and time-consuming to implement (Sadrinooshabadi *et al.*, 2021). Open standards, such as ISO16739 Industry Foundation Class (IFC), have been developed to overcome interoperability (Turk *et al.*, 2022). However, due to inefficient exporters and importers, conversion between formats always causes information loss, limiting machine readability and lowering data quality for accessibility, completeness and data provenance (Soman and Whyte, 2020). Interoperability problems are key barriers, especially in O&M (Farghaly *et al.*, 2018). Exchanging data between BIM and FM systems is still a one-way process: from design to construction and commissioning phases towards the O&M phase (Nojedehi *et al.*, 2022). However, there is a need for additional data sources, such as CMMS data or service logs, to exchange data back to BIM (Nojedehi *et al.*, 2022).

4.2.5 Manual work

Due to the lack of object-based change tracking and version control in contemporary CDEs, changes are still tracked manually on the level of entire file-based BIM models (Esser *et al.*, 2022). The technical and accounting documentation is still produced in PDFs or scanned paperwork, which often requires the signatures of multiple parties (Ciotta *et al.*, 2021). Also, projects using CDE for uploading documents require manual authorisation; document controllers prove if files in the CDE have relevant attributes before being published (Soman and Whyte, 2020). The document control workflow is a very long process with checks and iterative cycles involved at each stage, and it can take over 2–3 weeks for a document to reach its recipient (Soman and Whyte, 2020). All those manual, human-dependent processes in current CDE workflows result in errors, causing delays, redundancy, and loss of documentation (Esser *et al.*, 2022).

The handover process between design, construction and O&M is very unstructured and, therefore, labour-intensive and error-prone, usually left until the end of construction (Patacas *et al.*, 2020). Verification of handover information is complicated; consequently, it is difficult to operate and maintain built assets efficiently, as accurate and reliable data is missing (Patacas *et al.*, 2020). As-built data that needs to be handed over is not always complete and up-to-date, leading to rework by subsequent contractors (Taylor, 2017).

4.2.6 Long lifespan of data

Another significant challenge in the information management of built assets is the length of their lifespan (Patacas *et al.*, 2020). Data generated for built assets can be utilized for up to 40 years post-project inception (Parn and Edwards, 2019). During the asset lifecycle, data is shared between multiple stakeholders, and asset ownership changes can happen several times (Charef, 2022). This poses a risk of missing or outdated data accumulated in CMMS tools during the building lifecycle (Nojedehi *et al.*, 2022). Not only updating the data but also keeping track of data history is problematic in FM (Sadrinooshabadi *et al.*, 2021). The knowledge developed through operational processes, such as lessons learned from failure or reasons for choosing specific maintenance techniques, is a key aspect of O&M. This information generates core expertise needed to teach new employees, thus it must be effectively recovered (Naticchia *et al.*, 2020). Al Qady and Kandil (2013a) emphasised that discourse about knowledge can only be portrayed by the synthesis of the information recorded in all pertinent sources, not just one.

4.2.7 Security challenges

The majority of current EDMSs and CDEs are centralised and entirely controlled by a single authorised party which raises privacy and security concerns about data ownership, change tracking, and unauthorised access to sensitive information; the files may be copied and modified easily, resulting in information integrity loss and potential unauthorised information sharing (Kiu *et al.*, 2022). Project participants themselves can abuse their authorised access to a CDE and tamper with data for their advantage (Das *et al.*, 2022). As project stakeholders are often concerned about losing ownership of their design or having their BIM data manipulated, a lack of trust among project participants is a significant obstacle to BIM-based cooperation; the whole lifecycle of an asset might be endangered through data manipulation (Tao *et al.*, 2021). Possible data breaches can result in the loss of intellectual property on design calculations, construction techniques and specific know-how, which could be misused by competitors (Turk *et al.*, 2022). CDEs hosted on the World Wide Web are exposed to cyber-physical attacks, and the risk of external and internal cyber-attacks increases due to utilizing centralised data networks or cloud services (Parn and Edwards, 2019; Turk *et al.*, 2022).

4.2.8 Improper use of CDEs

One of the challenges of CDE implementation is the low adoption and improper utilisation of CDE tools in real-world projects. As of 2017, professionals used CDEs more as file storage and sharing platforms rather than true collaborative and managed environments, with email communication being significantly more popular than communicating through a CDE (Akponeware and Adamu, 2017). As of 2021, teams still preferred using emails to exchange information, even if it concerned issues about BIM models (Ciotta *et al.*, 2021; Mayer *et al.*, 2021). As of 2020, data exchange using documents and drawings in PDF format was perceived as more intuitive than model-based information sharing (Soman and Whyte, 2020). Using emails rather than CDEs and application programming interfaces (APIs) makes it very difficult to transfer metadata and trace back file versions (Ciotta *et al.*, 2021). Overall, there is a persistent use of unstructured channels and a lack of trust in digital workflows (Soman and Whyte, 2020). There is an urgent need for all actors to employ information exchange platforms as CDEs from the early stages to make the development process auditable (Sadrinooshabadi *et al.*, 2021).

4.2.9 High costs

Another significant challenge associated with CDE is its high implementation cost, a considerable barrier, especially for SMEs (Das *et al.*, 2022). Using CDE tools improves quality and effectiveness, however, it also increases costs compared to standard 2D CAD tools (Mayer *et al.*, 2021). Many companies do not understand the benefits of CDEs in their projects and still consider investing in implementing a new system as high risk (Sadrinooshabadi *et al.*, 2021). For SMEs, licence fees could be a substantial amount of money. This might be the major reason AECO continues to use traditional document management techniques rather than investing in more expensive long-term EDMS (Kiu *et al.*, 2022).

4.2.10 Other challenges

Inadequate requirements definition, ambiguity over the quantity of information required, and inaccurate information requirements for owners are frequent issues in construction projects (Godager *et al.*, 2022). Establishing the information requirements from project inception is important for cooperating more effectively. It is crucial to provide the appropriate information at the appropriate time for the appropriate uses and recipients (Kurwi *et al.*, 2021). Information management in AECO is characterised by a lack of software protocols, non-consistent terminology, taxonomies, and insufficient information leading to project data being disorganised (Godager *et al.*, 2022). The lack of precise standards is one of the reasons why a large number of EDMS and CDE tools are utilised in the industry (Kähkönen and Rannisto, 2015).

4.3 State-of-the-art CDE development

There have recently been many approaches to using different technologies for developing a CDE in the academic literature. In the supplementary material, we list the technological solutions for CDEs and references mentioning them. Promising ideas are using an SQL Server as a base for a CDE and investigating linked data and semantic web technologies for CDE development, to solve interoperability issues. Farhghaly et al. (2018) developed a taxonomy representing required data for the effective application of BIM for AM, whereas Mugumya et al. (2019) proposed the use of linked building data and augmented reality to visualise information in CDE.

Soman and Whyte (2020) investigated the potential of using Artificial Intelligence (AI) and machine learning techniques such as Natural Language Processing (NLP) for construction information. For example, Moon *et al.* (2018) developed a prototype using NLP to analyse the construction market condition based on textual data. However, there are multiple challenges to overcome to make construction information machine-readable due to the low data quality resulting from fragmented and inconsistent information management workflows (Soman and Whyte, 2020).

A recent research direction focuses on the possible implementation of blockchain in AECO. Parn and Edwards (2019) suggest blockchain for storing sensitive digital infrastructure data with high security and privacy requirements. Blockchain resistance to cyber-attacks would fortify the security of built assets managed digitally in CDEs (Parn and Edwards, 2019). Ciotta et al. (2021) proposed to integrate blockchain into information flows used in various CDEs and to use smart contracts to reduce human errors and increase the reliability and transparency of decision-making processes. Studies by Das *et al.* (2022), Tao *et al.* (2021) and Hijazi *et al.* (2021) suggest tracking significant events in the blockchain to create verifiable and reliable evidence and improve the immutability and transparency of the information flow. Moreover, blockchain has the potential to legally certify construction site documents to prevent litigation issues (Ciotta *et al.*, 2021).

5 Fieldwork: findings and results

For the semi-structured interviews, we sought only experts applying BIM tools and BIM methodology including methods described in the ISO19650 standard on a daily basis, as they have the best knowledge about the practical implementation of CDEs in practice. Such target interviewees were project managers, BIM managers, and general contractors as well as facility managers, as insights about information management in all phases of assets' lifecycles were searched for. The interviewees were first asked to describe what is the level of BIM adoption and how they deal with information management in their projects. Further, they were asked to elaborate on information management challenges they experienced while using CDEs. In total, fifteen professionals were interviewed from different companies, positions and years of experience (data in the supplementary material). The interviews took place between November 2021 and April 2022. Each interview took between 40 and 80 min, and the recordings were transcribed and verified subsequently.

5.1 CDE platforms comparison

During the interviews, participants described various CDE solutions that they are using for managing construction information. BIM 360 by Autodesk was highlighted as a commonly used platform due to its integration with Autodesk's BIM software, real-time collaboration features, and support for managing RFIs and submittals. However, it has limitations such as the absence of suitability codes, which require manual input, leading some users to prefer Aconex for reliability and revision tracking. Interviewee 11 notes that BIM 360 is effective for coordination and design management but not as a comprehensive CDE tool, with Viewpoint4Project and Aconex being preferred for managing submittals, document revisions, and sign-offs. Aconex by Oracle offers immutability and advanced version control but faces challenges related to a lack of interoperability with other tools. Other tools such as ProjectWise by Bentley, Asite or Procore were listed in the BIM survey (NBS, 2020) but were not discussed during the interviews. A full comparison of current CDE tools is presented in a recent study by these authors (Jaskula *et al.*, 2023).

In light of the challenges and complexity associated with implementing CDEs, stakeholders often opt for simpler tools that are already integrated into their existing workflows. This includes utilizing cloud-based file repositories like Dropbox, Google Drive, or Microsoft SharePoint. According to the BIM Survey 2020, 38% of participants use Dropbox, while 36% use SharePoint as a CDE solution (NBS, 2020). Despite lacking the security measures mandated by ISO19650, as well as object-level access control and interoperability with

BIM software, these repositories are widely adopted in the construction industry for their ease of data sharing among stakeholders (Das *et al.*, 2021).

Interviewees involved in the O&M phase noted that similar to previous stages, they rely on multiple information sources and different tools compared to those used during design and construction. Design CDEs are unsuitable for O&M data management due to the distinct characteristics and requirements of asset management data. Interviewee 13 mentioned using BMS software called Cylon, while Interviewee 15 referred to using CAFM software called Concept Evolution. Interviewee 15 also mentioned testing Autodesk's newly developed CAFM tool, BIM 360 Ops but found it inadequate for managing building operation data compared to established CAFM tools. To facilitate information handover between design and construction CDEs and CAFM systems, interviewees mentioned tools like Springboard, gliderBIM, and Autodesk BIM 360 Glue. However, gathering data through Springboard remains primarily manual due to integration challenges with CDEs like Aconex, as mentioned by Interviewee 3. Autodesk's BIM 360 Glue enables a direct connection between BIM 360 used in design and construction and BIM 360 Ops used in the O&M phase, resulting in reduced handover time, as reported by Interviewees 13 and 9. However, Interviewee 9 noted that some clients lack a proper CAFM system, leading to manual information gathering in SharePoint.

5.2 Identified challenges

Interviewees were asked to elaborate on information management challenges across the project lifecycle. The most frequently mentioned challenges, concerning the respondents' lifecycle phase expertise are summarised in Table I. In the following sections, each of the challenges will be described in more detail.

5.2.1 Using multiple data sources

All interviewees working in construction and FM commonly agreed that the main problem of information management is the simultaneous use of multiple information sources unconnected to each other. During the design phase, solutions like Autodesk 360 or BIM Collab are used for managing BIM data, while Viewpoint4Project or Aconex might be used for storing documents and drawings for signing off. During O&M a different set of tools is used, including CAFM systems such as Concept Evolution, Autodesk Ops, and

BMS such as Cylon. Lack of compatibility of design CDEs with other systems, such as later-stage CDEs and CAFM systems forces businesses to utilise specialised software to transfer data between the systems (Interviewee 3). For the handover of information between construction and O&M phases, tools like Springboard, gliderBIM or BIM 360 Glue are used. Some interviewees also mentioned using simple cloud-based repositories such as Microsoft SharePoint for a manual gathering of handover information. The wide variety of tools used in each phase causes massive data integrity problems.

Even within O&M, there are integrity issues as tools such as BMS, CAFM or IoT software *"all function by themselves"* (Interviewee 13). Interviewee 8 stated that *"there's no (single) common data environment. We have 'common' common data environments like a few of them and they need to interact"* and further *"I don't believe in a single CDE. I believe in CDEs that all rotate and are linked to each other".* It is not possible to manage all information in one tool as *"there isn't one platform out there that does everything that you would like to do"* (Interviewee 9). Interviewee 7 added: *"you often need to connect a sort of different platforms or different software that complement each other"*. Interviewee 14 further explained that their company was also unsuccessful in finding a platform that met all their needs.

Although some design CDE software vendors like Autodesk tried to develop a tool to manage data in O&M, they were unsuccessful according to Interviewee 15. Accordingly, Autodesk started to develop CAFM tools too late compared to other software vendors and their BIM 360 Ops is "*quite a clever toy, but just a toy"* (Interviewee 15).

5.2.2 Lack of skills and knowledge about standards

One of the biggest challenges in CDE implementation is to *"make people understand what the different parts are for"* as it is very complicated and *"people did not have the training to use the BIM common data environment"* (Interviewee 2). Starting a project involving multiple small companies requires a lot of effort and time for intensive training, as "*a lot of subcontractors when we start talking about information management, it's like over their head very hard"* (Interviewee 8). Getting suppliers and designers *"to actually submit information correctly (and) comply with standards"* is challenging (Interviewee 11). Interviewee 9 argued that especially architects are not complying with standards.

In the beginning *"you spend more time talking on the phone or in teams showing them how to upload a document"* (Interviewee 9). Especially clients usually lack skills, as Interviewee 4 and Interviewee 9 stated: "*They (...) don't have the technology to even use a CAFM system, they're back in the days of using a clipboard and a pen and paper."* Interviewee 15 explained further that customers *"want an in-house capability, but they don't even have a CAFM system in the first place".* Additionally, they also explained that there is a high demand for people with new skill sets – such as data scientists, managers and analysts, who can help FM update the information digitally.

5.2.3 Low digitisation

Another significant issue facing the industry is low digitisation and slow technology adoption. AECO professionals are used to working with 2D CAD drawings and often do not understand that BIM is not only about building 3D models and creating drawings but also contains information supporting information and project management. Interviewee 4 stated that *"introduction to new technology or new ways of thinking is all about changing management".* Companies prefer using old methods than learning new ones as *"people prefer the bad to the unknown"* (Interviewee 1). As Interviewee 10 stated *"there is a heavy underutilisation of the BIM tools and a lot of companies who claim they use BIM is only using a very small part of it".* Especially SMEs struggle with technology adoption, as they often find investing in training and purchasing new software too costly. Contrariwise, *"big companies have more money and more time to invest in training and obviously more projects to apply those things"* (Interviewee 3). While it is quite common that companies in design and construction have a strategy for BIM implementation, FM companies usually do not – possibly due to low demand for BIM adoption from clients. Interviewee 15 explained that clients are mostly unaware of software possibilities.

5.2.4 Manual processes

Many processes during the project lifecycle are still done manually, starting from document revision during design, through manual handover to FM systems and maintenance tasks in O&M. Involving human work takes a lot of time and is prone to mistakes and omissions. Revisions and sign-off of documents created by designers are usually done manually before those are uploaded to the CDE, primarily to make sure that the name conventions, the status quo revision codes, and the technical content, are correct. Facility managers often manually adjust the temperature or the schedule on the BMS and stop and start the air handling unit, although it could be done automatically using data from IoT sensors. Facility managers often have *"to be the link between all the bits* (Interviewee 13).

5.2.5 Handover issues

After the building is completed, the data generated during the design and construction phases must be handed over to the FM systems. This process often includes a manual transition of information about all assets (from BIM-based CDEs to CAFM systems) used by facility managers. Although some professionals are using additional tools specifically designed to facilitate the handover such as Springboard or eDocs, they still require a manual transfer of information to those tools. If the databases are not integrated well, the handover process might take months or years as some single subcontractors might finish their work that early and need to hand over their information at that time. Uploading a massive amount of information (e.g. BIM files) to a new system requires a reorganisation of the whole data, which is time-consuming and complicated. It might become even more complicated if clients are not using a proper CAFM but instead storing their data in simple cloud storage. Moreover, handed-over data is often not complete or accurate. Sometimes also the suppliers do not fill in the information as accurately and fully as they should. Additionally, too much information is also creating problems, as facility managers do not need all of the data created in previous phases. Interviewee 6 described the handover as the weak link in a chain: *"If you have a chain of the whole thing, this is where it's weak because the consultant company they are rushing out to the next project and consulting company the same and nobody wants to define and make all the deliveries and so on".* Interviewee 15 compared the lifecycle to a golden thread, which *"still gets broken between the design-construction process and handover to operations."*

Interviewee 8 had doubts about using COBie, describing it as a *"wasted process"* which requires converting the information into an Excel sheet as an intermediary file. Interview 9 reported that using software from the same vendor, such as Autodesk, makes the handover of the information from design and construction to CAFM systems much faster. Transferring even thousands of assets with a serious amount of data attached to them can be achieved in a matter of minutes through BIM 360 Glue if both systems are Autodesk products. However, as Interviewee 9 mentioned, the handover process can be a struggle as some clients do not like to use a proper CAFM system at all. In general, most of the companies are using a different kind of software for FM than Autodesk and nobody should be forced to transfer to a specific vendor – therefore the problem of unstructured handover remains.

5.2.6 Traceability of data

Losing track of information is a common problem while transferring data between different systems. Understanding which data is the most current can be challenging when using multiple sources of information, as there might be several copies of each file per platform. Interviewee 3 stated that in construction *"so many parties are involved that the information is just getting lost all the time".* In large-scale projects, it is even more complicated to trace information, as the amount of data and stakeholders is significantly larger. *"There are so many different types of transactions happening during a project which are impossible to monitor"* (Interviewee 4). Interviewee 8 mentioned that there are unseen and never-tracked things and people will never really get lessons learned or fully understand the project's total cost. Interviewee 15 elaborated more about the lifecycle as a golden thread which gets repeatedly broken and causes a lack of trust in data.

5.2.7 Understanding information

In large-scale projects, it is sometimes difficult to understand large amounts of information or find the specific information one is looking for. Some CDE software is *"bombarding"* stakeholders with notifications but without complete information necessary for understanding the data. Interviewee 4 explained that especially clients have little understanding of the consequences of some design decisions. The information level in the models is often not high enough to understand the data. Interviewee 14 expressed concerns about splitting the information depending on the purpose, as none of the tools can currently do that and detail the information as they work. Interviewee 15 said that there is a growing need to hire people who can understand and use data which is usually in numerical or non-readable form. Although the information about the asset is available, it is often not used, as facility managers do not have the skills to utilise it.

5.2.8 Monopoly of software companies

Almost half of the interviewees raised concerns about the strong monopolisation of the industry by a few large software companies, making it too expensive especially for SMEs. Interviewee 13 said "*Autodesk doesn't have many people who are to the same level as they are on the market. They're not. They don't have any true competitors that I'm aware of anyway."* Interviewee 4 added, *"You have to pay for it, whatever it costs 'cause, that's the industry standard and that's what the client requires. So you have to pay for it".* Interviewee 11 had concerns about companies taking advantage of the situation on the market.

5.2.9 Lack of interoperability

Lack of interoperability is one of the most pressing issues in collaboration and data exchange in construction projects. Most of the software used in construction is not compatible with other vendors' tools – e.g., Aconex does not work with any other software. *"You have to download the information and upload it into your system, so it's very manual"* (Interviewee 3). Especially the CAFM is very closed as *"they try to get full information and then all these apps, smart app, small cheap apps and data that don't fit it"* (Interviewee 6). Although there are *"a lot of initiatives going on in the industry trying to standardize communication, technologies and formats, it doesn't seem to work"* (Interviewee 4). The problem with using open standards such as the IFC is that *"when you export Revit to IFC it just turns the model into something that's not workable"* (Interviewee 9).

5.2.10 Other challenges

One of the barriers to exchanging digital information is the construction professionals' fear that their data could be stolen or manipulated. Using third-party sensors for sending information through Wi-Fi poses risks of data leakage or manipulation, which could seriously damage an asset's operation. Construction companies are not trusting the big software vendors to secure their data on their servers and in effect "*there's so much good technology out there but a user or company wouldn't trust anything like this if it's not a trustworthy organization behind"* (Interviewee 4).

Although CDEs allow the collection of a massive amount of information and data during the whole building lifecycle, the users are often not using it, as they do not trust the data accuracy. *"If you don't trust data, nobody uses it (…) and I think that one of the biggest challenges we have is that data we have inside these models can't be trusted"* (Interviewee 6). Interviewee 12 admitted, *"we don't see the value behind the information that we already have to make decisions afterwards".* A growing amount of information means that more powerful computers will be needed to store and process the data and finding computational resources might be a serious problem soon. Keeping the information updated is also another big challenge, especially during O&M. Interviewee 6 reported about their CAFM that *"within a half a year the system didn't have any value because the changes in the real world compared to the FM already was so huge that the data in the FM system wasn't trustworthy*". The model updates in FM are usually not regulated and the responsibility and timeliness of the updates are not specified. Centralising all the information in one place was described as an unnatural solution that gives the leading party "super user rights" with the power to change or delete data. As Interviewee 1 explained, *"One of the things about a CDE is that everyone has to follow the rules and if one party, particularly the lead party doesn't follow the rules, then there is no trust".*

6 Discussion

6.1 Synthesis of results

This study aimed to investigate the state of practice and challenges surrounding CDE implementation. The contribution to knowledge compared to other studies on the use of information management platforms is providing a state-of-the-art review of literature combined with evidence collected through fieldwork. The outcomes provide an understanding of the most recent developments of CDE and their practical challenges.

Based on the outcomes of the literature review and semi-structured interviews we identified the challenges of using CDEs and synthesised the results in Figure 2. The frequency for each of the challenges was calculated based on the maximum result for each of the methods. The maximum frequency for literature review was assigned to "complexity of projects" which was mentioned by 25 publications. In the interviews, the most frequently mentioned challenge was "multiple sources of information" with 93% of respondents mentioning it.

The complexity of projects resulting from a massive amount of data, fragmentation of the industry and unique nature of projects was the most frequent challenge mentioned in the literature, however, it was not mentioned by the interviewees. Lack of skills and training was one of the most often mentioned problems by interviewees and is also widely recognised in the literature. Both the literature review and the interview responses highlighted the multiplicity of simultaneously used CDEs and the use of unstructured channels of communication outside of the CDE workflow. This indicates that currently used CDE solutions are still not entirely in line with ISO19650, as a single source of truth is not provided. This leads to a lack of trust to data accuracy and causes problems with data traceability, integrity and accountability, as different CDEs are usually not communicating with each other, and it is nearly impossible to track the transactions between them. The lack of traceability was highlighted much more by the interviewees than by the literature, similar to the problem of manual work. Especially the problem with the handover of project data from construction to the O&M phase was highlighted by the interviewees. They described it as the weakest link in the chain of information management workflow. The handover process is usually still manual and therefore inefficient and prone to mistakes. Even using tools such as Springboard for collecting handover information requires manual data gathering and integration into the new systems.

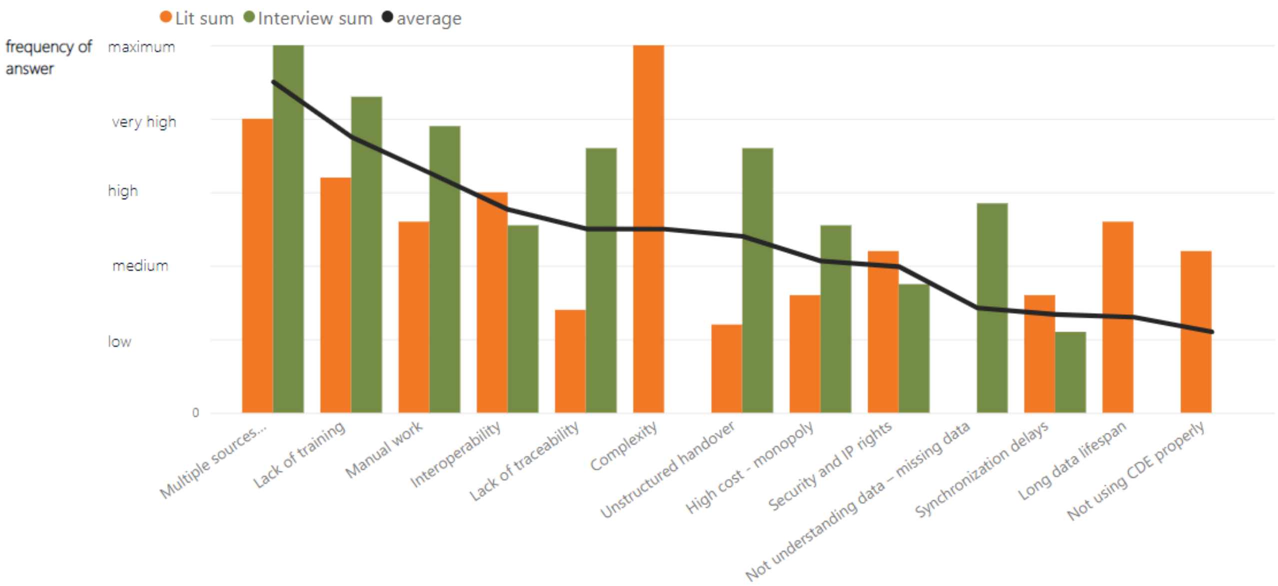

Figure 2 Synthesis of results from literature review and interviews.

6.2 Practical recommendations

In Figure 3 we mapped all identified challenges and matched them with possible measures to overcome them. We distinguished two types of measures of action: socio-economic measures including cultural change, training and standardisation and regulation and technological measures including the introduction of novel technologies such as blockchain, AI, semantic webs or SQL servers. Blockchain technology was often advocated by researchers as a way to overcome the lack of traceability and trust and low security in CDE platforms. Challenges such as “lack of skills”, “low digitisation”, and “improper use of CDEs” were ranked very high in the literature and by interviewees. However, implementing new technologies will rather not improve the situation in this area. Socio-economic measures such as more training or cultural and behavioural changes must be introduced to overcome these challenges. “Lack of standards” and “lack of requirements” also require social measures to improve the situation, as new regulations need to be introduced by regulating bodies and governments. The high cost of tools is a result of the free market and policies of individual software vendors. It is difficult to change this situation but could be possibly improved by introducing other, more affordable and open-source solutions to the market. The example of a CDE tool developed by the French government to support SMEs in France (Bedoiseau *et al.*, 2022) is showing that governments can influence the market.

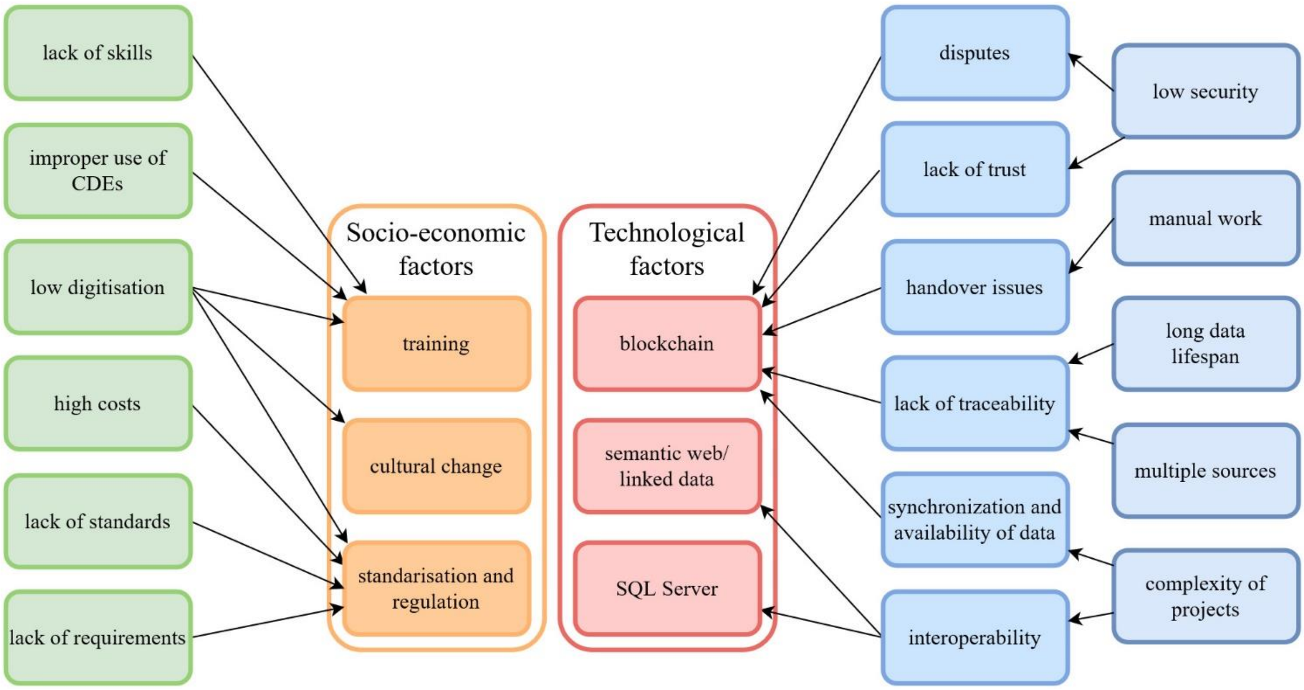

Figure 3 Challenges identified in the study with corresponding means to overcome them.

6.3 Limitations and future directions

To identify the challenges surrounding the implementation of CDEs in practice in a most comprehensive way, a mixed method approach was utilised and a synthesis of the two datasets was conducted. The results of the literature review were validated through semi-structured interviews. However, due to the limited number of interviewees, it still does not represent the whole industry which could be improved by conducting an industry survey on a large scale.

The findings of this study suggest that current approaches to information management based on CDEs face many challenges in practice and still need much improvement. The idea of a CDE being a single source of truth is difficult to implement in practice when multiple sources of information are used simultaneously. Fragmentation and inconsistency lead to low machine readability of construction information and limit the use of AI techniques such as NLP (Soman and Whyte, 2020). Recent research by Corneli *et al.* (2023) shows the potential of using NLP and virtual assistants for querying BIM models in graph-based CDEs. Therefore, there is a high demand to find a new solution integrating the information between various sources and provide more trust in digital workflows (Soman and Whyte, 2020). One such solution suggested in the literature could be blockchain technology, providing an immutable, secure and transparent record of transactions between different applications. Providing such records could provide a more accountable information source which could be then used as a source for AI integration. However, the use of AI is still facing many challenges such as low accuracy and complexity of data (Corneli *et al.*, 2023). Blockchain is still in its infancy and more research needs to be conducted to ascertain whether both blockchain and AI might be beneficial and feasible solutions to be integrated with current CDE-based workflows.

6.4 Implications for research, practice and society

The results of this study may have the following implications for researchers, practitioners and society. First of all, this study identified knowledge gaps such as a lack of integrated approach to information management along the lifecycle of a built asset. Fragmentation of processes and workflows could be addressed by both technological solutions as well as the introduction of new policies and guidelines. Furthermore, this review highlights emerging trends and technologies related to CDEs. Researchers can use this information to explore innovative areas of study, such as the integration of artificial intelligence, linked data and blockchain or a combination of them for developing new solutions for CDEs. Furthermore, this review assesses the barriers and facilitators of CDE adoption in the industry. Practitioners can use this information to navigate challenges and develop strategies for successful implementation. This knowledge can inform their practices and improve project outcomes. Companies can gain a competitive advantage by staying up-to-date with the latest research on CDEs and applying relevant findings to their projects. The adoption of CDEs can enhance transparency and accountability in construction projects, which can be of interest to various stakeholders, including homeowners, investors, and regulatory bodies. It serves as a valuable resource for both researchers and practitioners seeking to better understand and leverage CDEs in the construction sector.

7 Conclusions

A CDE is a base of information management in current a BIM-based collaboration process. There are multiple tools and software that can be used as CDEs and there is a lack of studies on the actual adoption of CDE workflows in practice. This study aimed to identify the current state-of-the-art of CDE development, its limitations and problems. To the best knowledge of the authors, this is the first study combining desk review and fieldwork on the adoption and use of CDEs in practice. The findings of this study provide a comprehensive analysis of practical challenges surrounding CDE implementation and clarify the fundamental components and characteristics that define current practice in construction data management. A CDE enables successful BIM implementation and is one of the key components for broader digital transformation in the construction industry. The knowledge about the current application of CDEs in construction projects may impart vital information and can aid the industry in developing more innovative solutions.

The results show that the implementation of CDEs as advised in ISO19650 is difficult to be implemented in practice. The evidence gathered from both the SLR and fieldwork proved that in most cases there is no single source of truth for information in projects but instead a myriad of tools and sources that are used simultaneously along the built assets' lifecycle. This leads to a lack of traceability of information stored in multiple places simultaneously and a lack of transparency. Developing one single tool that could work as a CDE along the whole lifecycle of a built asset is most probably not possible, as in each of the lifecycle phases the tool must fulfil many different requirements. This leads to the conclusion that to achieve the goal of a single source of truth, solutions to integrate data between multiple CDEs must be investigated. One promising direction would be to investigate novel technologies such as blockchain, which would enable data integrity, and improve accountability and traceability of the information flow. Other directions include the integration of AI techniques to analyse information and linked data to provide better interoperability.

8 Acknowledgements

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10 Supplementary material

https://drive.google.com/file/d/1Nac_aS_ZFgi_9Jw8TL5wdO6Dd86xSQLZ/view?usp=sharing