

**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 1 Introduction

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

16 The concept of a CDE emerged in BS1192:2007 and was further developed in PAS 1192-2:2013. In 2019 the
17 CDE-based information management workflow received its own international standard, ISO19650 (AeChub,
18 2022). Since then, an emerging number of tools that can be used as CDEs with a different compliance level
19 with the ISO standard has been developed by various software vendors. In practice, a CDE is usually a cloud-
20 based repository where all stakeholders can store and access project data (Turk *et al.*, 2022). Before the
21 emergence of CDE tools Electronic Document Management Systems (EDMS) were commonly used in
22 AECO. In the early 2010s EDMS were still clearly more used than CDEs as most of the publications focused
23 on their use (Al Qady and Kandil, 2013b; Kähkönen and Rannisto, 2015). This indicates that the widespread
24 use of CDEs started only during the last 10 years.

25 The 2020 BIM survey (NBS, 2020) identified several tools used by industry practitioners as CDEs, such as
26 Viewpoint/4Projects, Autodesk BIM 360 and Aconex. Moreover, instead of using a purpose-built CDE,
27 professionals are using general-purpose file-based document management systems such as Dropbox (NBS,

28 2020). There are very few studies investigating the current state of CDE adoption in practice. Kiu et al. (2022)
29 investigated the challenges of EDMS tools in design and construction based on empirical data. The BIM
30 survey (NBS, 2020) identified which tools are used by the practitioners in the design stage but it did not
31 provide any more information about the experiences of the users with the use of CDE tools. It is not clear how
32 the tools are used or if they fulfil the requirements and users' needs. This paper addresses this gap by
33 investigating current practices of using CDEs for information management during the whole built asset's
34 lifecycle, through a state-of-the-art literature review and an empirical study. Notably, this paper focuses on the
35 following research questions (RQ): RQ1) How are CDEs implemented in practice? RQ2) What are the
36 challenges and limitations of CDE-based information management throughout the lifecycle of built assets?
37 Understanding the weaknesses and strengths of current CDE implementations is a promising way for
38 streamlining information management in AECO.

39 **2 Theoretical origins of CDEs**

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

47 CDE is defined in the ISO19650 standard as *"an agreed source of information for any given project or asset*
48 *for collecting, managing, and disseminating each information container through a managed process"* (BSI,
49 2021). CDEs include a 'CDE solution' and a 'CDE workflow which organises the flow of information across
50 the whole lifecycle of an asset across four information container states (BIM Dictionary, 2020). ISO19650
51 (BSI, 2021) describes four states in which each information container can be: work in progress (WIP), shared,
52 published, or archived; the transition from one state to another should be subject to approval and authorisation

53 processes. The 'CDE solution' is usually a server-based or cloud-based technology with database management,
54 transmittal, issue tracking, and related capabilities that support the CDE workflow (BIM Dictionary, 2020).

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

70 **3 Research method**

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

76 As a main analysis method for literature review and interview data we utilised thematic analysis via coding
77 (Braun and Clarke, 2006). Through coding, a researcher can identify themes or patterns in the qualitative data

78 that can be further investigated (Saunders *et al.*, 2019). The publications and interview transcripts were
79 imported to NVivo 2020, and code-related text excerpts related to challenges of CDE adoption and use were

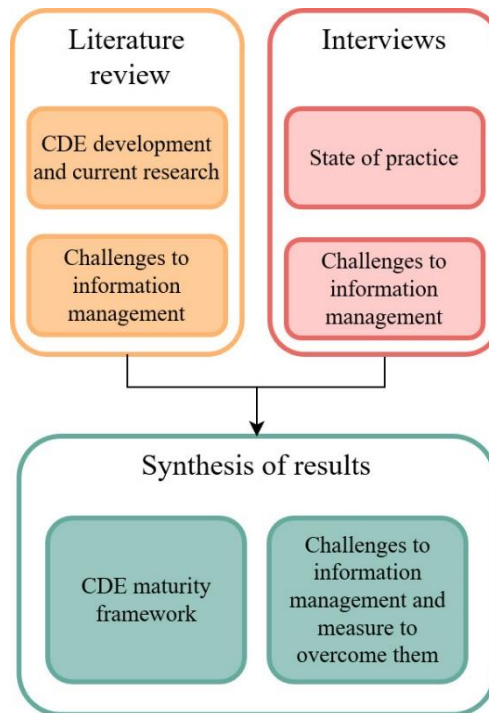


Figure 1 Roadmap of the study.

80 highlighted to recognise their frequency throughout the transcripts. The first coding cycle called initial coding
81 was used to identify preliminary codes. It was followed by focused coding (second cycle) to identify the most
82 frequent or significant initial codes and led to the development of prominent themes in the dataset (Saldaña,
83 2009).

84 **4 Desk research: a systematic review**

85 To understand the state-of-the-art research surrounding CDEs, we conducted an SLR, “a form of secondary
86 study that uses a well-defined methodology to identify, analyse and interpret all available evidence related to a
87 specific research question in a way that is unbiased and (to a degree) repeatable” (Kitchenham and Charters,
88 2007). Advanced search strings using Boolean operators were used on Scopus and WoS databases covering
89 business, economics and engineering subjects for data collection. To find all relevant literature we used the
90 keywords “Common Data Environment”, “document management system” and “single source of truth” which
91 are used interchangeably and combined with “construction”. For the Scopus we used following string:

92 (TITLE-ABS-KEY("Common Data Environment") OR (TITLE-ABS-KEY("document management system")
93 OR TITLE-ABS-KEY("single source of truth"))) AND TITLE-ABS-KEY(construction). Similarly for WoS
94 we searched for TS=("common data environment") OR ((TS=("document management system") OR
95 TS=("single source of truth"))) AND TS=(construction)).

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

103 4.1 *Bibliometric analysis*

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

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

116 4.2 *Thematic analysis*

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

121 4.2.1 *Complexity of projects*

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

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

139 4.2.2 *Multiple sources of information*

140 Along the project lifecycle, a wide range of systems, tools, and data resources are used simultaneously for
141 information management (Patacas *et al.*, 2020). Stakeholders use unstructured channels for information

142 sharing, such as meetings, reports, or emails that are not recorded in common repositories (Soman and Whyte,
143 2020). Data is distributed in isolated silos and databases are not connected or synchronized (Soman and
144 Whyte, 2020). Only during operation and maintenance (O&M) do stakeholders use tools such as Computer-
145 Aided Facility Management (CAFM) systems, computerized maintenance management systems (CMMS),
146 EDMS or Building Maintenance Systems (BMS) (Patacas *et al.*, 2020). Data is created and manipulated
147 multiple times during the building's lifecycle, resulting in mistakes and omissions as systems are usually not
148 integrated (Becerik-Gerber *et al.*, 2012). Due to the large amount and heterogeneity of data, it is claimed that
149 the adoption and use of single central models or databases is not practical (Patacas *et al.*, 2020). Using
150 multiple software packages, poor information sharing and only partially captured construction process
151 information can lead to data quality issues (Soman and Whyte, 2020). Lack of information transparency and
152 traceability remains a key challenge of current CDEs and EDMSs (Hijazi *et al.*, 2021; Kiu *et al.*, 2022).

153 4.2.3 *Lack of training*

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

162 4.2.4 *Interoperability challenges*

163 Using multiple domain-specific tools and modelling practices in construction projects causes interoperability
164 problems leading to poor data quality (Sacks *et al.*, 2018). Working with CAD tools of different providers
165 necessitates multiple format conversions, potentially resulting in data and information loss (Kurwi *et al.*,
166 2021; Soman and Whyte, 2020). Problems related to data compatibility occur even while working between
167 different versions of the same software (Soman and Whyte, 2020). Another problem related to communication

168 is the lack of a common language, as there are too many developed standards and classification systems,
169 which are costly and time-consuming to implement (Sadrinooshabadi *et al.*, 2021). Open standards, such as
170 ISO16739 Industry Foundation Class (IFC), have been developed to overcome interoperability (Turk *et al.*,
171 2022). However, due to inefficient exporters and importers, conversion between formats always causes
172 information loss, limiting machine readability and lowering data quality for accessibility, completeness and
173 data provenance (Soman and Whyte, 2020). Interoperability problems are key barriers, especially in O&M
174 (Farghaly *et al.*, 2018). Exchanging data between BIM and FM systems is still a one-way process: from
175 design to construction and commissioning phases towards the O&M phase (Nojedehi *et al.*, 2022). However,
176 there is a need for additional data sources, such as CMMS data or service logs, to exchange data back to BIM
177 (Nojedehi *et al.*, 2022).

178 4.2.5 *Manual work*

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

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

193 4.2.6 *Long lifespan of data*

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

205 4.2.7 *Security challenges*

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

218 4.2.8 *Improper use of CDEs*

219 One of the challenges of CDE implementation is the low adoption and improper utilisation of CDE tools in
220 real-world projects. As of 2017, professionals used CDEs more as file storage and sharing platforms rather
221 than true collaborative and managed environments, with email communication being significantly more
222 popular than communicating through a CDE (Akponeware and Adamu, 2017). As of 2021, teams still
223 preferred using emails to exchange information, even if it concerned issues about BIM models (Ciotta *et al.*,
224 2021; Mayer *et al.*, 2021). As of 2020, data exchange using documents and drawings in PDF format was
225 perceived as more intuitive than model-based information sharing (Soman and Whyte, 2020). Using emails
226 rather than CDEs and application programming interfaces (APIs) makes it very difficult to transfer metadata
227 and trace back file versions (Ciotta *et al.*, 2021). Overall, there is a persistent use of unstructured channels and
228 a lack of trust in digital workflows (Soman and Whyte, 2020). There is an urgent need for all actors to employ
229 information exchange platforms as CDEs from the early stages to make the development process auditable
230 (Sadrinooshabadi *et al.*, 2021).

231 4.2.9 High costs

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

239 4.2.10 Other challenges

240 Inadequate requirements definition, ambiguity over the quantity of information required, and inaccurate
241 information requirements for owners are frequent issues in construction projects (Godager *et al.*, 2022).
242 Establishing the information requirements from project inception is important for cooperating more
243 effectively. It is crucial to provide the appropriate information at the appropriate time for the appropriate uses
244 and recipients (Kurwi *et al.*, 2021). Information management in AECO is characterised by a lack of software

245 protocols, non-consistent terminology, taxonomies, and insufficient information leading to project data being
246 disorganised (Godager *et al.*, 2022). The lack of precise standards is one of the reasons why a large number of
247 EDMS and CDE tools are utilised in the industry (Kähkönen and Rannisto, 2015).

248 4.3 *State-of-the-art CDE development*

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

256 Soman and Whyte (2020) investigated the potential of using Artificial Intelligence (AI) and machine learning
257 techniques such as Natural Language Processing (NLP) for construction information. For example, Moon *et al.*
258 (2018) developed a prototype using NLP to analyse the construction market condition based on textual
259 data. However, there are multiple challenges to overcome to make construction information machine-readable
260 due to the low data quality resulting from fragmented and inconsistent information management workflows
261 (Soman and Whyte, 2020).

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

271 **5 Fieldwork: findings and results**

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

282 5.1 CDE platforms comparison

283 During the interviews, participants described various CDE solutions that they are using for managing
284 construction information. BIM 360 by Autodesk was highlighted as a commonly used platform due to its
285 integration with Autodesk's BIM software, real-time collaboration features, and support for managing RFIs
286 and submittals. However, it has limitations such as the absence of suitability codes, which require manual
287 input, leading some users to prefer Aconex for reliability and revision tracking. Interviewee 11 notes that BIM
288 360 is effective for coordination and design management but not as a comprehensive CDE tool, with
289 Viewpoint4Project and Aconex being preferred for managing submittals, document revisions, and sign-offs.
290 Aconex by Oracle offers immutability and advanced version control but faces challenges related to a lack of
291 interoperability with other tools. Other tools such as ProjectWise by Bentley, Asite or Procore were listed in
292 the BIM survey (NBS, 2020) but were not discussed during the interviews. A full comparison of current CDE
293 tools is presented in a recent study by these authors (Jaskula *et al.*, 2023).

294 In light of the challenges and complexity associated with implementing CDEs, stakeholders often opt for
295 simpler tools that are already integrated into their existing workflows. This includes utilizing cloud-based file
296 repositories like Dropbox, Google Drive, or Microsoft SharePoint. According to the BIM Survey 2020, 38%

297 of participants use Dropbox, while 36% use SharePoint as a CDE solution (NBS, 2020). Despite lacking the
298 security measures mandated by ISO19650, as well as object-level access control and interoperability with
299 BIM software, these repositories are widely adopted in the construction industry for their ease of data sharing
300 among stakeholders (Das *et al.*, 2021).

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

314 5.2 *Identified challenges*

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

318 5.2.1 *Using multiple data sources*

319 All interviewees working in construction and FM commonly agreed that the main problem of information
320 management is the simultaneous use of multiple information sources unconnected to each other. During the
321 design phase, solutions like Autodesk 360 or BIM Collab are used for managing BIM data, while

322 Viewpoint4Project or Aconex might be used for storing documents and drawings for signing off. During
323 O&M a different set of tools is used, including CAFM systems such as Concept Evolution, Autodesk Ops, and
324 BMS such as Cylon. Lack of compatibility of design CDEs with other systems, such as later-stage CDEs and
325 CAFM systems forces businesses to utilise specialised software to transfer data between the systems
326 (Interviewee 3). For the handover of information between construction and O&M phases, tools like
327 Springboard, gliderBIM or BIM 360 Glue are used. Some interviewees also mentioned using simple cloud-
328 based repositories such as Microsoft SharePoint for a manual gathering of handover information. The wide
329 variety of tools used in each phase causes massive data integrity problems.

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

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

342 5.2.2 Lack of skills and knowledge about standards

343 One of the biggest challenges in CDE implementation is to *“make people understand what the different parts*
344 *are for”* as it is very complicated and *“people did not have the training to use the BIM common data*
345 *environment”* (Interviewee 2). Starting a project involving multiple small companies requires a lot of effort
346 and time for intensive training, as *“a lot of subcontractors when we start talking about information*
347 *management, it's like over their head very hard”* (Interviewee 8). Getting suppliers and designers *“to actually*

348 *submit information correctly (and) comply with standards*” is challenging (Interviewee 11). Interviewee 9
349 argued that especially architects are not complying with standards.

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

357 5.2.3 *Low digitisation*

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

371 5.2.4 *Manual processes*

372 Many processes during the project lifecycle are still done manually, starting from document revision during
373 design, through manual handover to FM systems and maintenance tasks in O&M. Involving human work

374 takes a lot of time and is prone to mistakes and omissions. Revisions and sign-off of documents created by
375 designers are usually done manually before those are uploaded to the CDE, primarily to make sure that the
376 name conventions, the status quo revision codes, and the technical content, are correct. Facility managers
377 often manually adjust the temperature or the schedule on the BMS and stop and start the air handling unit,
378 although it could be done automatically using data from IoT sensors. Facility managers often have “*to be the*
379 *link between all the bits*” (Interviewee 13).

380 5.2.5 Handover issues

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

398 Interviewee 8 had doubts about using COBie, describing it as a “*wasted process*” which requires converting
399 the information into an Excel sheet as an intermediary file. Interview 9 reported that using software from the

400 same vendor, such as Autodesk, makes the handover of the information from design and construction to
401 CAFM systems much faster. Transferring even thousands of assets with a serious amount of data attached to
402 them can be achieved in a matter of minutes through BIM 360 Glue if both systems are Autodesk products.
403 However, as Interviewee 9 mentioned, the handover process can be a struggle as some clients do not like to
404 use a proper CAFM system at all. In general, most of the companies are using a different kind of software for
405 FM than Autodesk and nobody should be forced to transfer to a specific vendor – therefore the problem of
406 unstructured handover remains.

407 5.2.6 *Traceability of data*

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

417 5.2.7 *Understanding information*

418 In large-scale projects, it is sometimes difficult to understand large amounts of information or find the specific
419 information one is looking for. Some CDE software is “*bombarding*” stakeholders with notifications but
420 without complete information necessary for understanding the data. Interviewee 4 explained that especially
421 clients have little understanding of the consequences of some design decisions. The information level in the
422 models is often not high enough to understand the data. Interviewee 14 expressed concerns about splitting the
423 information depending on the purpose, as none of the tools can currently do that and detail the information as
424 they work. Interviewee 15 said that there is a growing need to hire people who can understand and use data

425 which is usually in numerical or non-readable form. Although the information about the asset is available, it is
426 often not used, as facility managers do not have the skills to utilise it.

427 5.2.8 *Monopoly of software companies*

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

434 5.2.9 *Lack of interoperability*

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

444 5.2.10 *Other challenges*

445 One of the barriers to exchanging digital information is the construction professionals' fear that their data
446 could be stolen or manipulated. Using third-party sensors for sending information through Wi-Fi poses risks
447 of data leakage or manipulation, which could seriously damage an asset's operation. Construction companies
448 are not trusting the big software vendors to secure their data on their servers and in effect “*there's so much*

449 *good technology out there but a user or company wouldn't trust anything like this if it's not a trustworthy*
450 *organization behind”* (Interviewee 4).

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

465 **6 Discussion**

466 *6.1 Synthesis of results*

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

471 Based on the outcomes of the literature review and semi-structured interviews we identified the challenges of
472 using CDEs and synthesised the results in Figure 2. The frequency for each of the challenges was calculated
473 based on the maximum result for each of the methods. The maximum frequency for literature review was

474 assigned to “complexity of projects” which was mentioned by 25 publications. In the interviews, the most
475 frequently mentioned challenge was “multiple sources of information” with 93% of respondents mentioning
476 it.

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

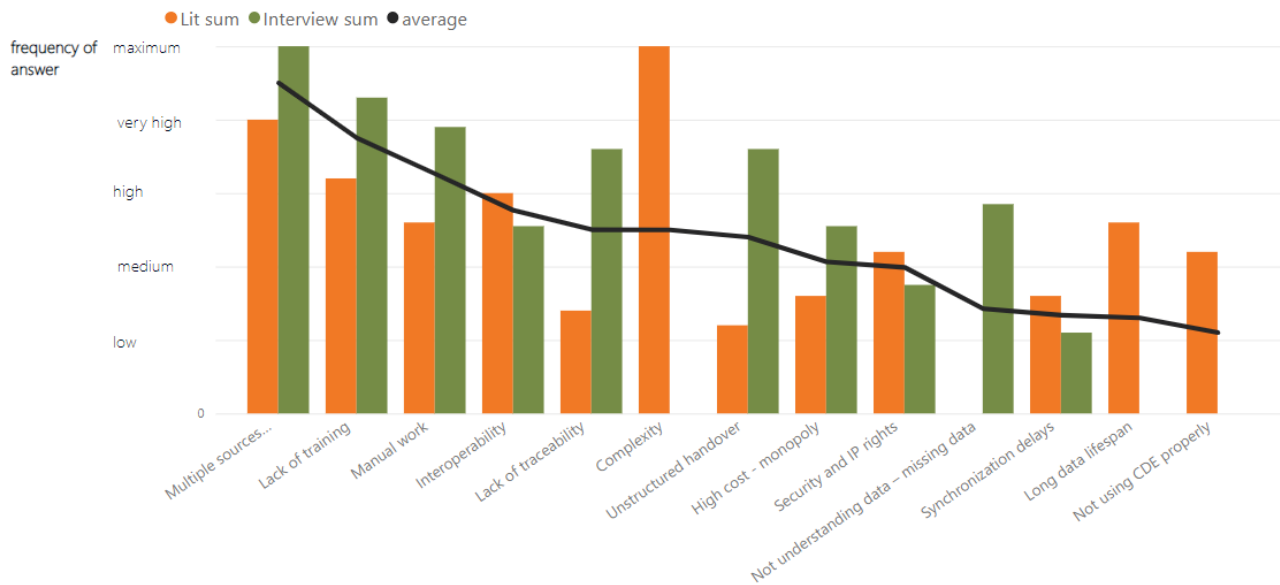


Figure 2 Synthesis of results from literature review and interviews.

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.

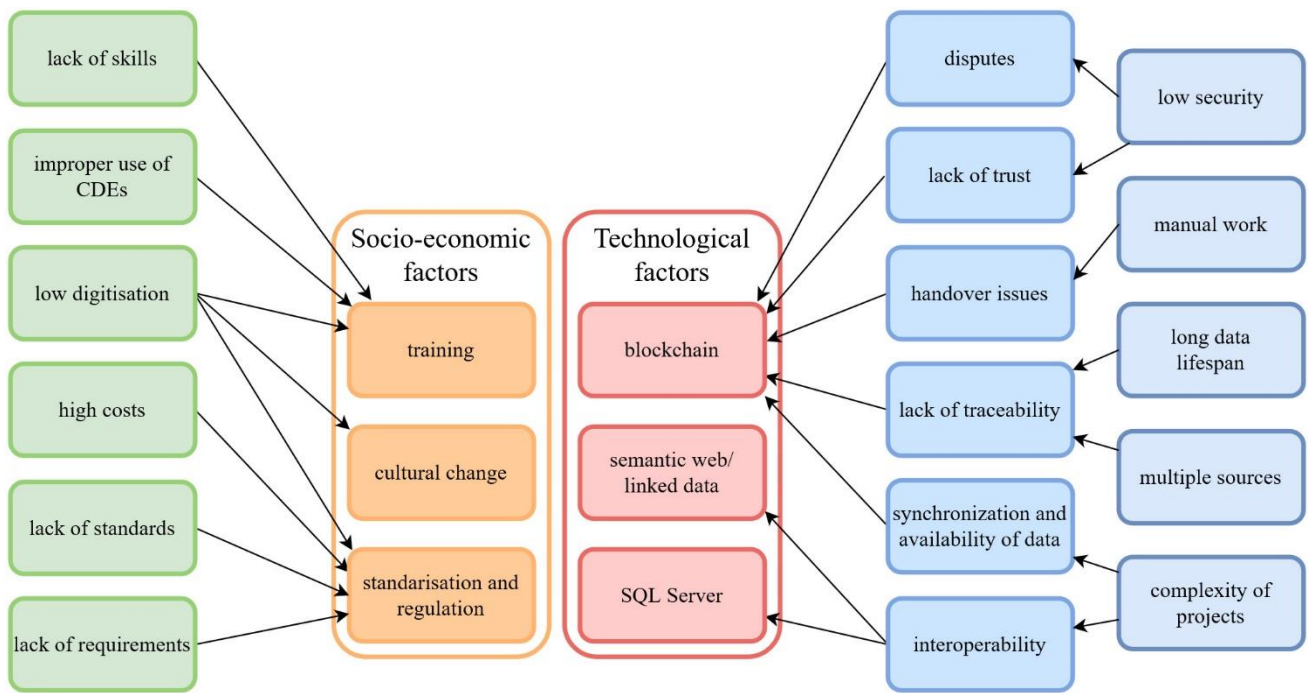


Figure 3 Challenges identified in the study with corresponding means to overcome them.

509 6.3 Limitations and future directions

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

515 The findings of this study suggest that current approaches to information management based on CDEs face
 516 many challenges in practice and still need much improvement. The idea of a CDE being a single source of
 517 truth is difficult to implement in practice when multiple sources of information are used simultaneously.
 518 Fragmentation and inconsistency lead to low machine readability of construction information and limit the use
 519 of AI techniques such as NLP (Soman and Whyte, 2020). Recent research by Corneli *et al.* (2023) shows the
 520 potential of using NLP and virtual assistants for querying BIM models in graph-based CDEs. Therefore, there
 521 is a high demand to find a new solution integrating the information between various sources and provide more
 522 trust in digital workflows (Soman and Whyte, 2020). One such solution suggested in the literature could be

523 blockchain technology, providing an immutable, secure and transparent record of transactions between
524 different applications. Providing such records could provide a more accountable information source which
525 could be then used as a source for AI integration. However, the use of AI is still facing many challenges such
526 as low accuracy and complexity of data (Corneli *et al.*, 2023). Blockchain is still in its infancy and more
527 research needs to be conducted to ascertain whether both blockchain and AI might be beneficial and feasible
528 solutions to be integrated with current CDE-based workflows.

529 *6.4 Implications for research, practice and society*

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

544 **7 Conclusions**

545 A CDE is a base of information management in current a BIM-based collaboration process. There are multiple
546 tools and software that can be used as CDEs and there is a lack of studies on the actual adoption of CDE
547 workflows in practice. This study aimed to identify the current state-of-the-art of CDE development, its
548 limitations and problems. To the best knowledge of the authors, this is the first study combining desk review

549 and fieldwork on the adoption and use of CDEs in practice. The findings of this study provide a
550 comprehensive analysis of practical challenges surrounding CDE implementation and clarify the fundamental
551 components and characteristics that define current practice in construction data management. A CDE enables
552 successful BIM implementation and is one of the key components for broader digital transformation in the
553 construction industry. The knowledge about the current application of CDEs in construction projects may
554 impart vital information and can aid the industry in developing more innovative solutions.

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

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572

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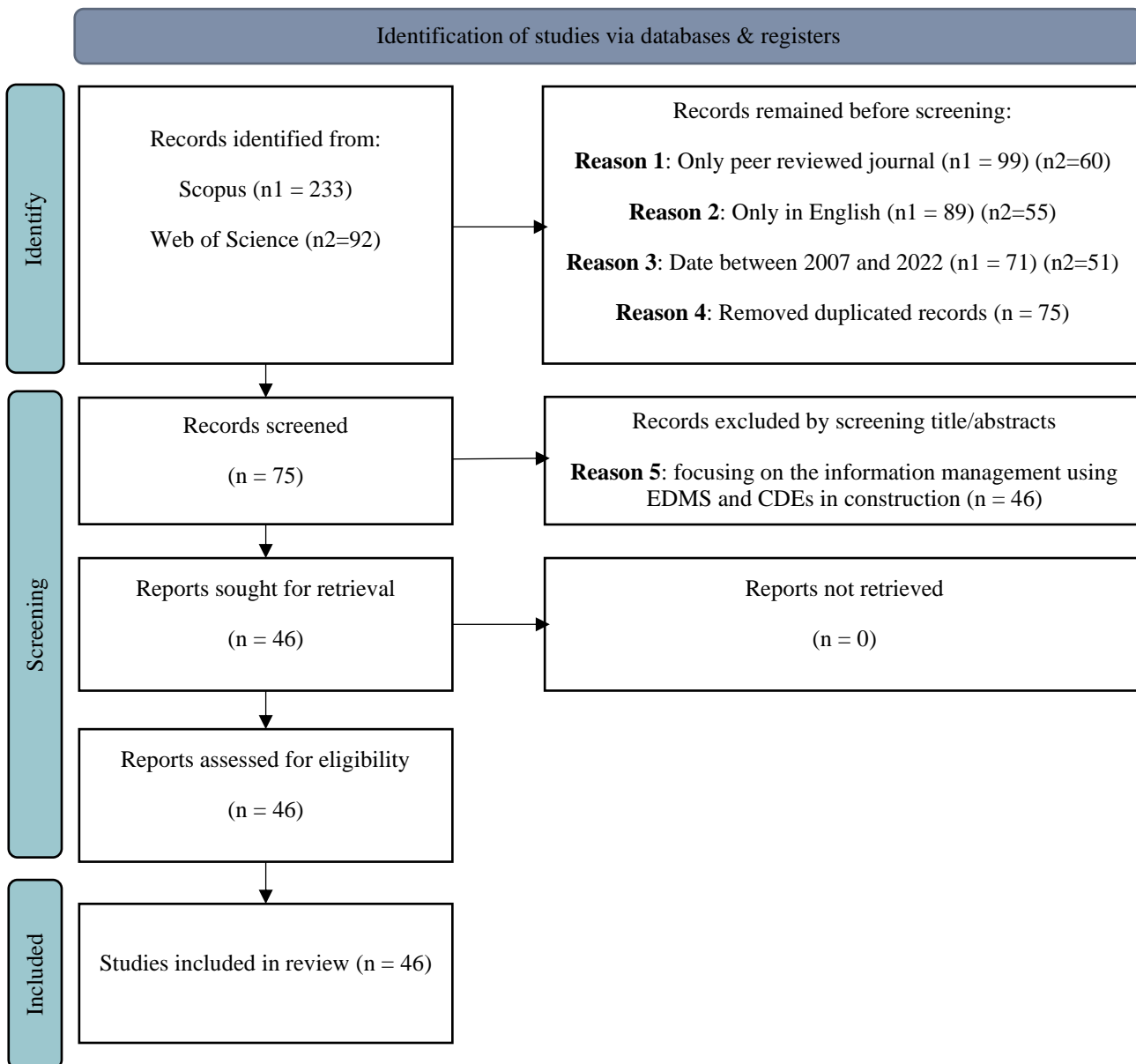
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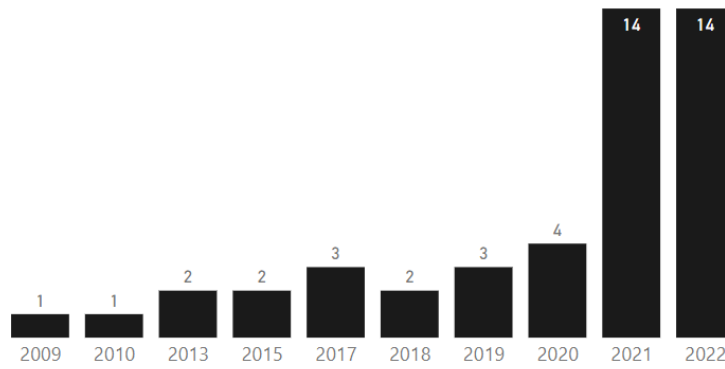


Appendix 1 Steps of the systematic literature review.

Appendix 2 Search strings.

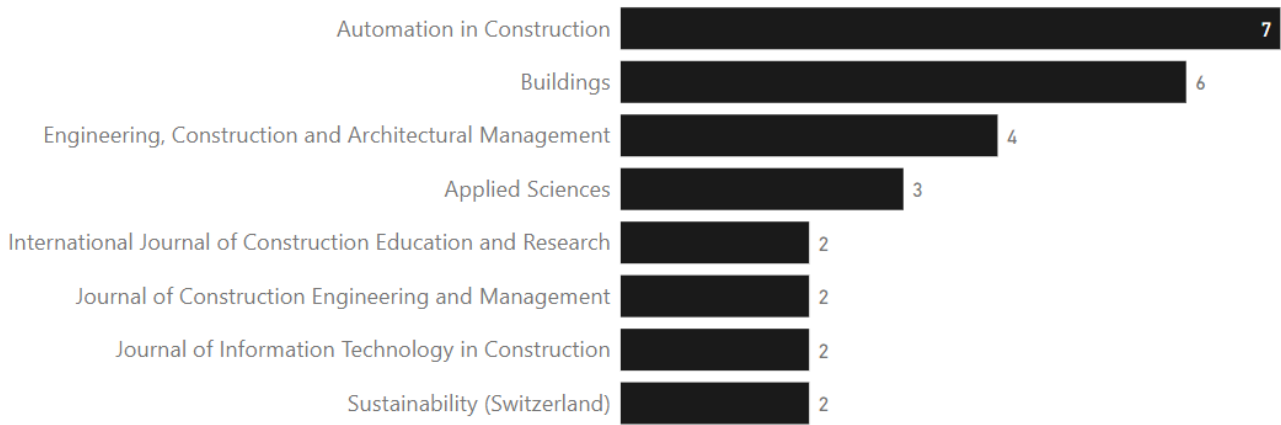
Scopus	TITLE-ABS-KEY("Common Data Environment") OR ((TITLE-ABS-KEY("document management system") OR TITLE-ABS-KEY("single source of truth") AND TITLE-ABS-KEY(construction))
Web of Science (WoS)	TS=("common data environment") OR ((TS=("document management system") OR TS=("single source of truth")) AND TS=(construction))

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Appendix 3 Number of publications per year.

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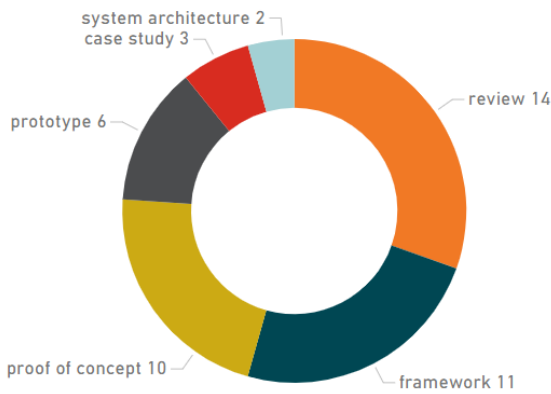


Appendix 4 Number of publications per source.

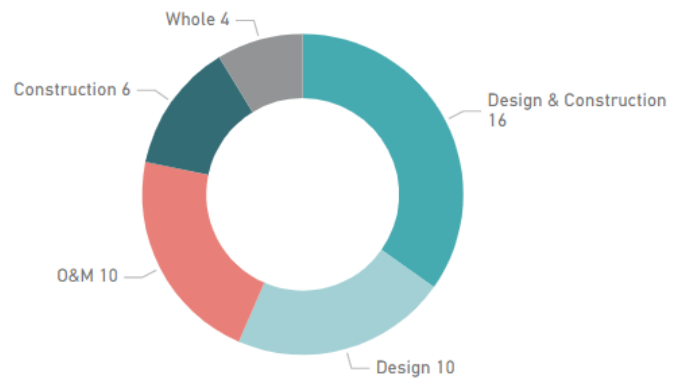
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Appendix 5 Number of publications per type of study.



Appendix 6 Number of publications per lifecycle phase.

Challenge	Number of sources	References
Complexity of projects	25	(Ajam <i>et al.</i> , 2010; Al Qady and Kandil, 2013; Charef, 2022; Das <i>et al.</i> , 2022; Esser <i>et al.</i> , 2022; Godager <i>et al.</i> , 2022; Guo <i>et al.</i> , 2021; Hijazi <i>et al.</i> , 2021, 2022, 2023; Kähkönen and Rannisto, 2015; Kiu <i>et al.</i> , 2022; Moon <i>et al.</i> , 2018; Mugumya <i>et al.</i> , 2019; Naticchia <i>et al.</i> , 2020; Nojedehi <i>et al.</i> , 2022; Philips-Ryder <i>et al.</i> , 2013; Roman <i>et al.</i> , 2022; Sadrinooshabadi <i>et al.</i> , 2021; Shehab <i>et al.</i> , 2009; Soman and Whyte, 2020; Tao <i>et al.</i> , 2021; Taylor, 2017; Zanni <i>et al.</i> , 2020; Zhao <i>et al.</i> , 2023)
Synchronization and availability of data	8	(Adamu <i>et al.</i> , 2015; Akponeware and Adamu, 2017; Charef, 2022; Esser <i>et al.</i> , 2022; Soman and Whyte, 2020)
Multiple sources of information	20	(Ajam <i>et al.</i> , 2010; Akponeware and Adamu, 2017; Al Qady and Kandil, 2013; Esser <i>et al.</i> , 2022; Farghaly <i>et al.</i> , 2018; Hijazi <i>et al.</i> , 2021, 2023; Jang <i>et al.</i> , 2021; Kähkönen and Rannisto, 2015; Kiu <i>et al.</i> , 2022; Moon <i>et al.</i> , 2018; Mugumya <i>et al.</i> , 2019; Naticchia <i>et al.</i> , 2020; Nojedehi <i>et al.</i> , 2022; Patacas <i>et al.</i> , 2020; Soman and Whyte, 2020; Taylor, 2017; Turk <i>et al.</i> , 2022; Zanni <i>et al.</i> , 2020; Zhao <i>et al.</i> , 2023; Zima and Mitera-Kielbasa, 2021)
Lack of traceability	7	(Ajam <i>et al.</i> , 2010; Hijazi <i>et al.</i> , 2021, 2023; Kiu <i>et al.</i> , 2022; Kurwi <i>et al.</i> , 2021; Soman and Whyte, 2020; Zima and Mitera-Kielbasa, 2021)
Lack of skills	16	(Adamu <i>et al.</i> , 2015; Ajam <i>et al.</i> , 2010; Akponeware and Adamu, 2017; Comiskey <i>et al.</i> , 2017; Godager <i>et al.</i> , 2022; Guo <i>et al.</i> , 2021; Hijazi <i>et al.</i> , 2021; Kähkönen and Rannisto, 2015; Kiu <i>et al.</i> , 2022; Kurwi <i>et al.</i> , 2021; Mayer, Funtík, Erdélyi, <i>et al.</i> , 2021; Moon <i>et al.</i> , 2018; Mzyece <i>et al.</i> , 2019; Philips-Ryder <i>et al.</i> , 2013; Sadrinooshabadi <i>et al.</i> , 2021; Taylor, 2017)
Interoperability	15	(Ajam <i>et al.</i> , 2010; Al Qady and Kandil, 2013; Esser <i>et al.</i> , 2022; Farghaly <i>et al.</i> , 2018; Godager <i>et al.</i> , 2022; Guo <i>et al.</i> , 2021; Kähkönen and Rannisto, 2015; Kurwi <i>et al.</i> , 2021; Naticchia <i>et al.</i> , 2020; Nojedehi <i>et al.</i> , 2022; Patacas <i>et al.</i> , 2020; Sadrinooshabadi <i>et al.</i> , 2021; Seidenschnur <i>et al.</i> , 2022; Soman and Whyte, 2020; Turk <i>et al.</i> , 2022)
Long data lifespan	13	(Al Qady and Kandil, 2013; Charef, 2022; Das <i>et al.</i> , 2022; Godager <i>et al.</i> , 2022; Naticchia <i>et al.</i> , 2020; Nojedehi <i>et al.</i> , 2022; Parn and Edwards, 2019; Patacas <i>et al.</i> , 2020; Roman <i>et al.</i> , 2022; Sadrinooshabadi <i>et al.</i> , 2021; Turk <i>et al.</i> , 2022; Zhao <i>et al.</i> , 2023; Zima and Mitera-Kielbasa, 2021)
Manual work	13	(Ajam <i>et al.</i> , 2010; Ciotta <i>et al.</i> , 2021; Esser <i>et al.</i> , 2022; Farghaly <i>et al.</i> , 2018; Hijazi <i>et al.</i> , 2022; Mayer, Funtík, Erdélyi, <i>et al.</i> , 2021; Naticchia <i>et al.</i> , 2020; Patacas <i>et al.</i> , 2020; Sadrinooshabadi <i>et al.</i> , 2021; Seidenschnur <i>et al.</i> , 2022; Shehab <i>et al.</i> , 2009; Soman and Whyte, 2020; Taylor, 2017)
Unstructured handover	6	(Ajam <i>et al.</i> , 2010; Farghaly <i>et al.</i> , 2018; Godager <i>et al.</i> , 2022; Kurwi <i>et al.</i> , 2021; Sadrinooshabadi <i>et al.</i> , 2021; Zima and Mitera-Kielbasa, 2021)
Security and protection of IP rights	11	(Adamu <i>et al.</i> , 2015; Akponeware and Adamu, 2017; Comiskey <i>et al.</i> , 2017; Das <i>et al.</i> , 2022; Hijazi <i>et al.</i> , 2021; Kiu <i>et al.</i> , 2022; Parn and Edwards, 2019; Tao <i>et al.</i> , 2021; Turk <i>et al.</i> , 2022; Zhao <i>et al.</i> , 2023; Zima and Mitera-Kielbasa, 2021)
Lack of trust	4	(Hijazi <i>et al.</i> , 2021; Soman and Whyte, 2020; Tao <i>et al.</i> , 2021; Taylor, 2017)
Disputes	4	(Das <i>et al.</i> , 2022; Hijazi <i>et al.</i> , 2021, 2023; Philips-Ryder <i>et al.</i> , 2013)
Not using CDE properly	11	(Akponeware and Adamu, 2017; Ciotta <i>et al.</i> , 2021; Comiskey <i>et al.</i> , 2017; Kähkönen and Rannisto, 2015; Kiu <i>et al.</i> , 2022; Mayer, Funtík,

		Gašparík, <i>et al.</i> , 2021; Mugumya <i>et al.</i> , 2019; Sadrinooshabadi <i>et al.</i> , 2021; Soman and Whyte, 2020; Taylor, 2017; Zanni <i>et al.</i> , 2020)
High cost	8	(Adamu <i>et al.</i> , 2015; Bedoiseau <i>et al.</i> , 2022; Das <i>et al.</i> , 2022; Guo <i>et al.</i> , 2021; Kiu <i>et al.</i> , 2022; Mayer, Funtík, Erdélyi, <i>et al.</i> , 2021; Naticchia <i>et al.</i> , 2020; Sadrinooshabadi <i>et al.</i> , 2021)
Lack of requirements	6	(Ajam <i>et al.</i> , 2010; Farghaly <i>et al.</i> , 2018; Godager <i>et al.</i> , 2022; Kurwi <i>et al.</i> , 2021; Sadrinooshabadi <i>et al.</i> , 2021; Zima and Mitera-Kielbasa, 2021)
Lack of standards	4	(Godager <i>et al.</i> , 2022; Kähkönen and Rannisto, 2015; Kurwi <i>et al.</i> , 2021; Philips-Ryder <i>et al.</i> , 2013)

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Appendix 8 Technological solutions used in the literature for CDE development.

Technology	Number of sources	References
Blockchain	9	(Ciotta <i>et al.</i> , 2021; Das <i>et al.</i> , 2022; Hijazi <i>et al.</i> , 2021, 2022, 2023; Kiu <i>et al.</i> , 2022; Parn and Edwards, 2019; Tao <i>et al.</i> , 2021; Zhao <i>et al.</i> , 2023)
Linked data/ semantic web	5	(Al Qady and Kandil, 2013; Esser <i>et al.</i> , 2022; Farghaly <i>et al.</i> , 2018; Mugumya <i>et al.</i> , 2019; Nojedehe <i>et al.</i> , 2022)
Cloud technology	4	(Adamu <i>et al.</i> , 2015; Akponeware and Adamu, 2017; Mzyece <i>et al.</i> , 2019; Naticchia <i>et al.</i> , 2020)
SQL server	4	(Baraibar <i>et al.</i> , 2022; Daniotti <i>et al.</i> , 2021; Nieto-Julián <i>et al.</i> , 2021; Patacas <i>et al.</i> , 2020)

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Appendix 9 Semi-structured interviews participants' data.

Interviewee	Position	Company profile	Years of experience	Country	BIM expertise	Used CDE tools	Design & Con.	O&M
1	Consultant	Standards, regulations, BIM implementation	20+	UK	expert		y	y
2	BIM Manager/ researcher	Project management, research	15+	UK	expert	BIM 360, Aconex, Sharepoint	y	n
3	BIM Manager	Project management, architectural practice	5+	UK	expert	BIM 360, Aconex	y	n
4	Consultant	MEP, HVAC planning	15+	Sweden	very good		y	y
5	Blockchain developer, researcher	Blockchain applications development	<5	UK	not applicable		na	na
6	Consultant/ researcher	Implementation of IT in construction	30+	Denmark	very good		y	y
7	Consultant	Smart buildings, sustainable construction, General Contractor	30+	Sweden	very good		y	n
8	BIM Manager	Project management, General Contractor	20+	Ireland	expert	Autodesk Glue, Viewpoint	y	n

9	Construction manager	Digital management, design management	10+	Ireland	expert	BIM 360, Autodesk Glue, Viewpoint	y	n
10	Consultant/researcher	Implementation of IT in construction	20+	Sweden, Denmark	very good		y	n
11	BIM Manager	Project management, architectural practice	5+	UK	expert	BIM 360, Aconex	y	n
12	Consultant/researcher	Asset management from the owner side for infrastructure projects	10+	Estonia	very good		n	y
13	Facility Manager	Facility management of public assets	5+	Ireland	expert	Autodesk Glue, Cylon	n	y
14	Department manager	Digital construction in project management, General Contractor	15+	Sweden	expert		y	n
15	Development director	Facility management	20+	UK	expert	BIM 360 Ops, Concept Evolution CAFM	n	y
TOTAL							11	6

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Appendix 10 Quotations supporting identified themes.

Code	Interviewee	Quotation
Using multiple data sources	13	<i>“the BMS functions by itself. The CAFM system functions by itself. Any IoT sensors that you bring into the building, they all function by themselves, so (...) that is not compliant, you can't get any actions out of it. So it's something that is common across the industry”</i>
	1	<i>“and then we also get this nonsense about multiple CDEs”</i>
	8	<i>“there's no (single) common data environment. We have common common data environments like a few of them and they need to interact”, “I don't believe in a single CDE. I believe in common data environments that all rotate and are linked to each other”.</i>
	9	<i>“there isn't one platform out there that does everything that you would like to do”</i>
	7	<i>“you often need to connect a sort of different platforms or different software that complement each other”.</i>
	14	<i>“there is no tool that works for our different purposes and that is understandable from the different type of processes and systems that our specialists are using (...) They couldn't handle all the type of data and they couldn't handle it as flexible as we wanted”.</i>
	15	<i>“Autodesk turned up in 2013, 2014, said we can do that. They probably could but with the investment they would have to make to catch up... they were already a decade and a half too late. So when they came up with BIM Ops... from what we see it's like a toy, you know, it's rubbish and it's not comprehensive enough for what we need. Quite a clever toy, but just a toy”.</i>
Lack of skills and using standards	2	One of the biggest challenges in CDE implementation is to <i>“make people understand what the different parts are for”</i> as it is very complicated and <i>“people did not have the training to use the BIM common data environment”</i>

	8	<i>“a lot of subcontractors when we start talking about information management, it's like over their head very hard”</i>
	9	<i>“Architectural firms tend to have their own opinion on how to name documents and how this fits buildings even though you provide a naming convention and a zoning strategy, they still have their own perception of how holdings should be named and you're there fighting with them at the very start until the time that they just concede”</i> <i>“They don't understand fully what a CAFM system does for them, and some FM providers (...) 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.”</i>
	15	<i>customers “want an in-house capability, but they don't even have a CAFM system in the first place. They work from Excel, they're so under-resourced, it's quite staggering. We see a lot of customers like that”</i>
Low digitalisation	1	<i>“people prefer the bad to the unknown”</i>
	10	<i>“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”.</i>
	3	<i>“big companies have more money and more time to invest in training and obviously more projects to apply those things”</i>
	15	<i>“It's really interesting that customers are not really woken up to the detail that's available for them. They seem distinctly unaware that there's more that we could do to not just receive information into our CAFM system and maintain it in there, but actually, also maintain the digital model either graphically in terms of the asset data or in terms of the kind of non-graphical data.”</i>
Manual processes	13	<i>Facility managers often have “to be the link between all the bits. You have to move from the BMS to the CAFM system, to the IoT sensor dashboard platforms, and to the AHU controllers. They have to know how each works and find the difference”</i>
Handover issues	6	<i>“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 want to define and make all the deliveries and so on”.</i>
	15	<i>“still gets broken between the design-construction process and handover to operations. It's still a gap, there is no connection between.”</i>
Traceability of data	3	<i>“so many parties are involved that the information is just getting lost all the time”.</i>
	4	<i>“There are so many different types of transactions happening during a project which are impossible to monitor”</i>
	15	<i>“This golden thread gets broken when the building's finished and the first FM contractor arrives but it actually then breaks repeatedly because the FM contractor, the people, and the company come and go, and every time they go, they take a lot of data with them, unknowingly. They take data knowledge away, or people retire and they take data knowledge when they retire and I don't think the data is capable of suffering so many attacks (...) it gets some holes in it and then gets more holes in it and eventually is no data left that anyone trusts”.</i>
Understanding information	4	<i>“The client actually has very little detail knowledge or construction knowledge about what happens if we remove something like sensors or whatever. If we change them to a cheaper one, the whole system could fail. which is very common today that this happened, but the client doesn't have that knowledge through the whole process”</i>

	14	<i>“To really understand everything and to exactly come with your expectations and your learnings from other projects (...) if you would have that full picture of all the combined data, I think everyone would take more right decision and real decision.”</i>
Monopoly of software companies	13	<i>“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.”</i>
	4	<i>“You have to pay for it, whatever it cost 'cause, that's the industry standard and that's what the client requires. So you have to pay for it”.</i>
	11	<i>“people are willing to pay for it, but also the industry is kind of taking advantage of that and the pricing for all these sorts of things is going up and up. And at the end of the day, everyone's gonna eat, so they're gonna take advantage of it if they can”.</i>
Lack of interoperability	3	<i>“You have to download the information and upload it into your system, so it's very manual”</i>
	6	<i>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”</i>
	4	<i>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”</i>
	9	<i>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”</i>
Low security	4	<i>“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”</i>
Centralisation of data	1	<i>“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”.</i>
Computational burden	12	<i>“we don't have so powerful computers that are able to process the information and to store data, so it's more of technical type of obstacle that at the moment it's not a problem. But I see that if everything goes into the BIM there will be problem”</i>
Lack of trust to data accuracy	6	<i>If you don't trust data, nobody uses it, nobody dares to use it, and I think that one of the biggest challenges we have is that data we have inside these models can't be trusted”</i>
	12	<i>“We just throw everything away that we collected and we start assessing some conditions. (...) so we don't see the value behind the information that we already have to make decisions afterwards”.</i>
Outdated information	6	<i>“within a half a year the system didn't have any value because the changes in the real world compared to the facility management already was so huge that the data in the FM system wasn't trustworthy”.</i>