

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

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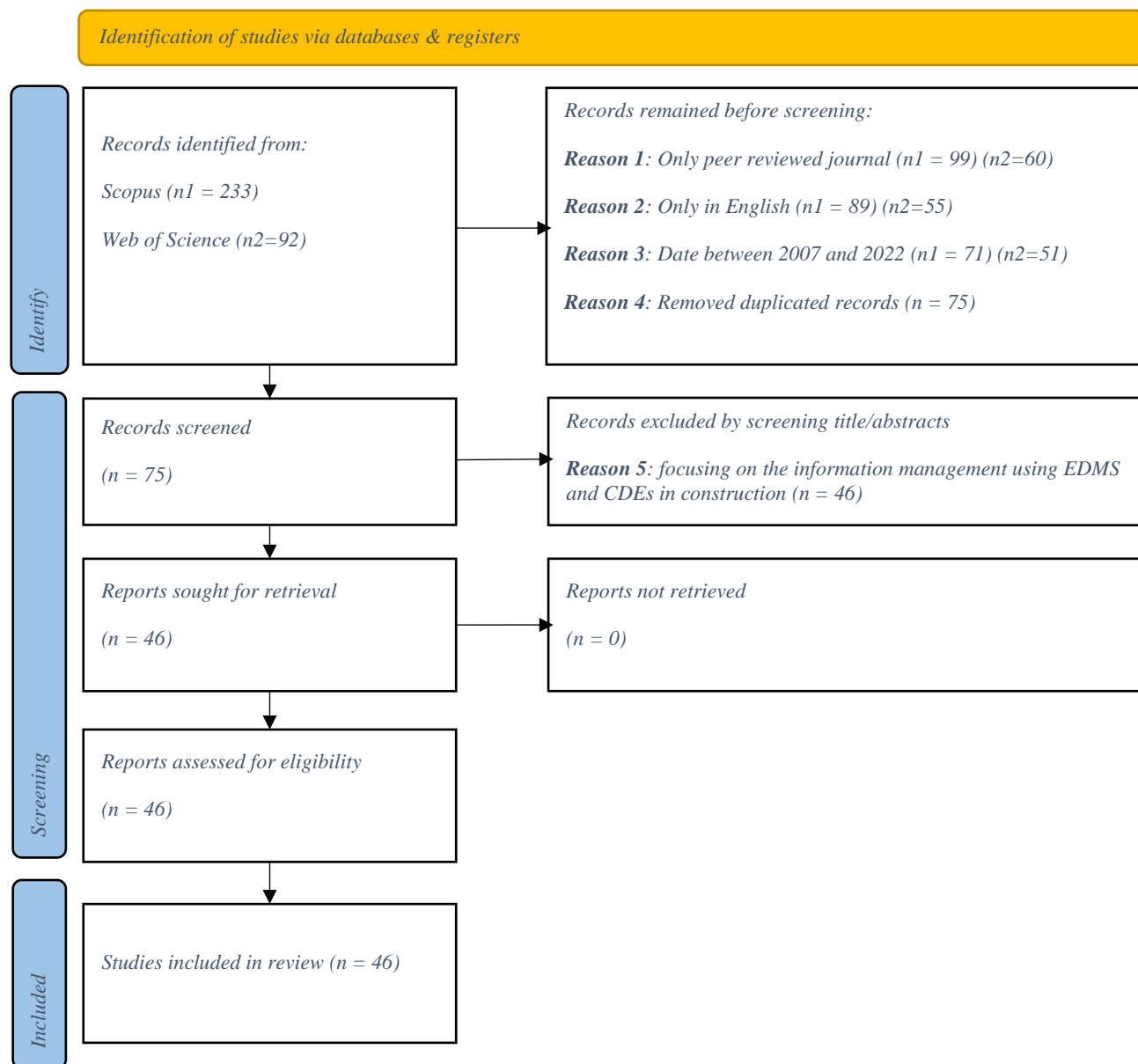
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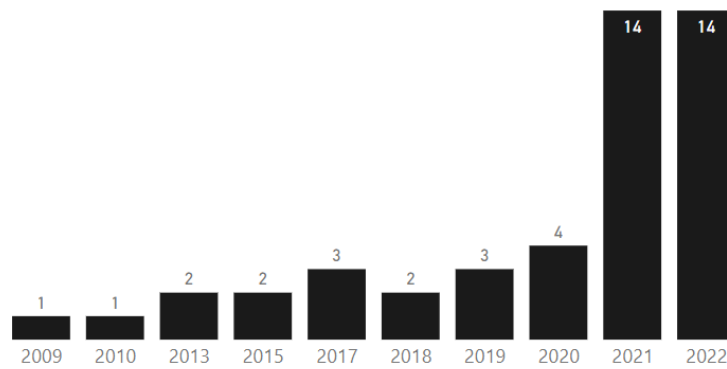
Supplementary material



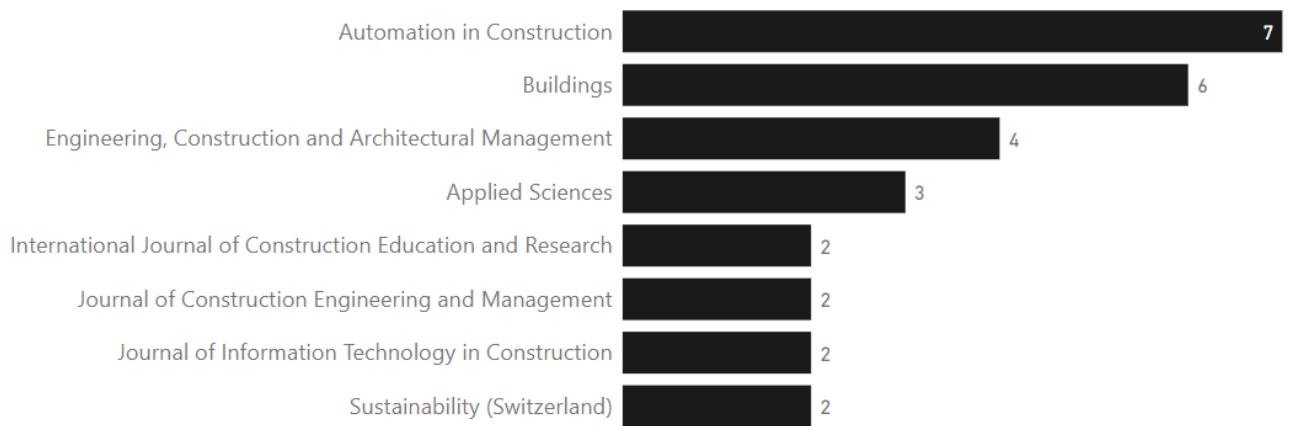
Appendix 1 Steps of the systematic literature review.

Appendix 2 Search strings.

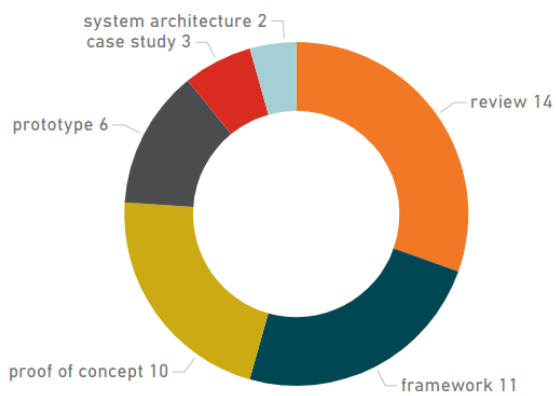
Scopus	TITLE-ABS-KEY("Common Data Environment") OR ((TITLE-ABS-KEY("document management system") OR TITLE-ABS-KEY("single source of truth") AND TITLE-ABS-KEY(construction))
Web of Science (WoS)	TS=("common data environment") OR ((TS=("document management system") OR TS=("single source of truth")) AND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



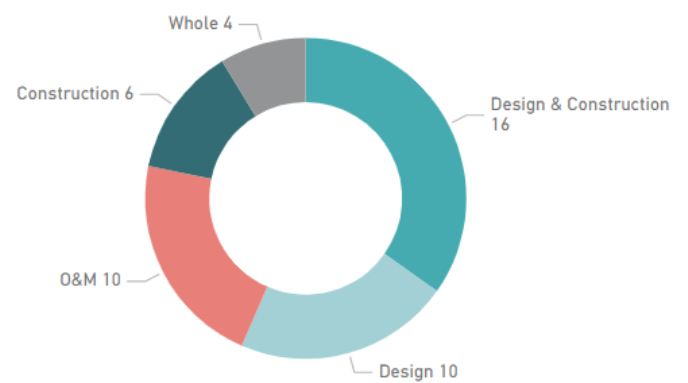
Appendix 3 Number of publications per year.



Appendix 4 Number of publications per source.



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; Nojedehe <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; Nojedehe <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; Nojedehe <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; Nojedehe <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,

		Gášparík, <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-Kiełbasa, 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)

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)

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

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>

Low digitalisation	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>
	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>
Manual processes	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>
	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>

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