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COLLABORATIVE DIGITAL PLATFORM FOR INTEGRATED DESIGN AND PRODUCTION PLANNING AND CONTROL: A LITERATURE REVIEW

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Abstract

There is a lack of a cohesive, integrated approach to design and production planning and control, where real-time data can be captured to support various management functions in an interconnected autonomous platform for collaboration. This paper presents a systematic literature review on collaborative digital platforms for BIM-based projects to facilitate synchronous updates of workflows based on real-time project data. The results show that a combined model, including Knowledge Graphs, Common Data Environments, and Digital Twins have potential to support a fully integrated, automated system. Future studies should therefore investigate how to connect these technologies together in an integrated project platform.

Introduction

In recent years, the Architecture, Engineering & Construction (AEC) industry have adopted digitalization to an increasing extent. The evolution of Building Information Management (BIM) over the past decade have pushed the use of digital tools from simply being a way to author digital drawings, to fully developed models containing detailed information on components (Borrmann et al., 2018; Sacks et al., 2018). Multidisciplinary teams are now collaborating in a digital environment thanks to various standards like the IFC format. However, Multi-disciplinary collaboration has many challenges since teams often federate separate models. These challenges must be overcome before AI techniques that manipulate BIM models can be incorporated on a wider scale (Sacks, Girolami, et al., 2020). Collaborative platforms are currently used for information sharing in projects. These collaborative platforms are seen as an overarching solution to improve collaboration by enabling a continuous flow of information and file updates. These functions are supported by scheduling of information deliveries (Borrmann et al., 2018). Hamledari et al. (2017) and Park et al. (2017) state the importance of using the collaborative platform every day throughout a project in order to enable the recording of actual start and completion dates of tasks. By accessing daily reports, a collaborative platform could be used for increased understanding of construction progress through automatic updates and visualization of the BIM-model (Park & Cai, 2017). The current state-of-the-art solutions for Multi-disciplinary BIM models also have several drawbacks that necessitates rework and long cycle times for compiling information (Sacks et al., 2022). Information Delivery Manual (IDM) has been developed by buildingSMART "for all participants in the organization to know which and when different kind of information has to be communicated" (buildingSMART, 2022). By using IDM, the process and information delivery milestones can then be planned. On top of the information delivery planning, traditional planning, scheduling and control approaches, and even 4D BIM involves a complex and stochastic optimization problem while determining the sequence of operations at different stages. However, most of these 4D models generating theoretically optimal solutions, may not be ideal in practice because the uncertainties are not well addressed in dynamic and changeable environments (Jiang et al., 2022). Since schedules need updating during project progression, there's also a need for reliable information transfer during production. Internet-of-Things (IoT) sensors are assumed to be the go-to solution for data transfer, but currently, construction site sensing is limited to large scans and manual updates, which limits BIM capabilities of prediction, since information could be out of date or out of sync with the physical building (Boje et al., 2020). All sensors also have some kind of limitation, be it available bandwidth or lack of algorithms required for semantic point clouds (Rao et al., 2022). Since sensor data capture is almost taken for granted, there is a need to investigate its interoperability and linking capability with BIM data and other digital twin components (Boje et al., 2020; Huang et al., 2023). While limited, the study by (Wang & Rezazadeh Azar, 2019) shows that automatic schedule generation based on existing data is possible. The problem lies in information transfer, where the lack of common formats coupled with manual information inputs hinder full automation for construction simulation (Boje et al., 2020). Since BIM and IoT data is structured differently, they need to be fused together to facilitate interoperability (Huang et al., 2023). This paper presents a literature review on data- and information transfer methods used in BIM. The purpose of this review is to identify different ways of transferring real-time data that could facilitate synchronous updates of workflows in multi-disciplinary projects that support both information delivery and production planning. The following section contain a description on how papers were selected for the study. The results then summarize these papers before they are put into context with the introduction in the discussion section. Finally, the conclusion contains a short summary of the study as well as recommendations for future studies.

Method

Identifying relevant literature

The Population and their problem, Intervention or Issue, Comparative Intervention, Outcomes or themes and

Context (PICOC) framework described in (Booth et al., 2021) have been used to identify key concepts to base the structured literature search on. The full PICOC framework can be seen in Table 1.

Table 1: PICOC framework

Population and their problem	Population: Schedulers, site managers, designer, supply chain managers, information managers Problems: Production & planning workflow
Intervention and issue	Intervention: Collaborative digital platforms Issue: Transferring project information. Design, planning & control using real-time data transfer
Comparative intervention	Manual real-time planning workflow
Outcomes or themes	Improved understanding of real-time data transfer requirements for 4D BIM-based projects
Context	The construction industry

Using the *PICOC framework,* concepts were identified. The identified concepts were in the next step transformed into search terms used in the literature search. All searches were done for title and abstract. The full list of search terms can be seen in Table 2.

Table 2: Search concepts

Search concepts	Synonyms
C1) Collaborative digital platform	(“collaborative digital platform*” OR “collaborative digital environment*” OR “project platform” OR “collaborat* platform” OR “collaborative digital environment*” OR “CDE” OR “digital twin*” OR “DT” OR “multidisciplin* platform*” OR “multidisciplin* design” OR “multidisciplin* team*”)
C2) Real-time data	(“real-time updat*” OR “live updat*” OR “real-time monitor*” OR “live monitor*” OR “real-time data” OR “live data” OR “real-time information” OR update*)
C3) BIM	(“BIM” OR “building information management” OR “building information model*” OR “BIM technolog*” OR “BIM-project*”)
C4) Construction industry	(“AEC” OR “AEC industry” OR “construction industr*” OR “building industr*” OR building* OR “construction project*” OR “construction sector” OR “building sector” OR “construction production” OR construction)
C5) Planning	(schedul* OR “plan” OR planning OR “production control” OR design OR manag* OR workflow* OR “4D”)
C6) Project information	(“project information” OR information OR “project data*” OR “BIM-data” OR “building information” OR “building data*” OR database)

The main database used for this search was Scopus, since it’s one of the largest databases and features useful search functions, such as combining different searches with Boolean operators. The combined search terms, along with their identified paper counts, are presented in Table 3. In total, 2673 papers were identified through this search process.

Table 3: Search combinations

Combination	Results
C1 AND C3	758
C1 AND C2 AND C3	68
C1 AND C2 AND C4	327
C1 AND C3 AND C5	677
C1 AND C3 AND C6	644
C2 AND C3 AND C6	617
C1 AND C2 AND C3 AND C4 AND C5 AND C6	47

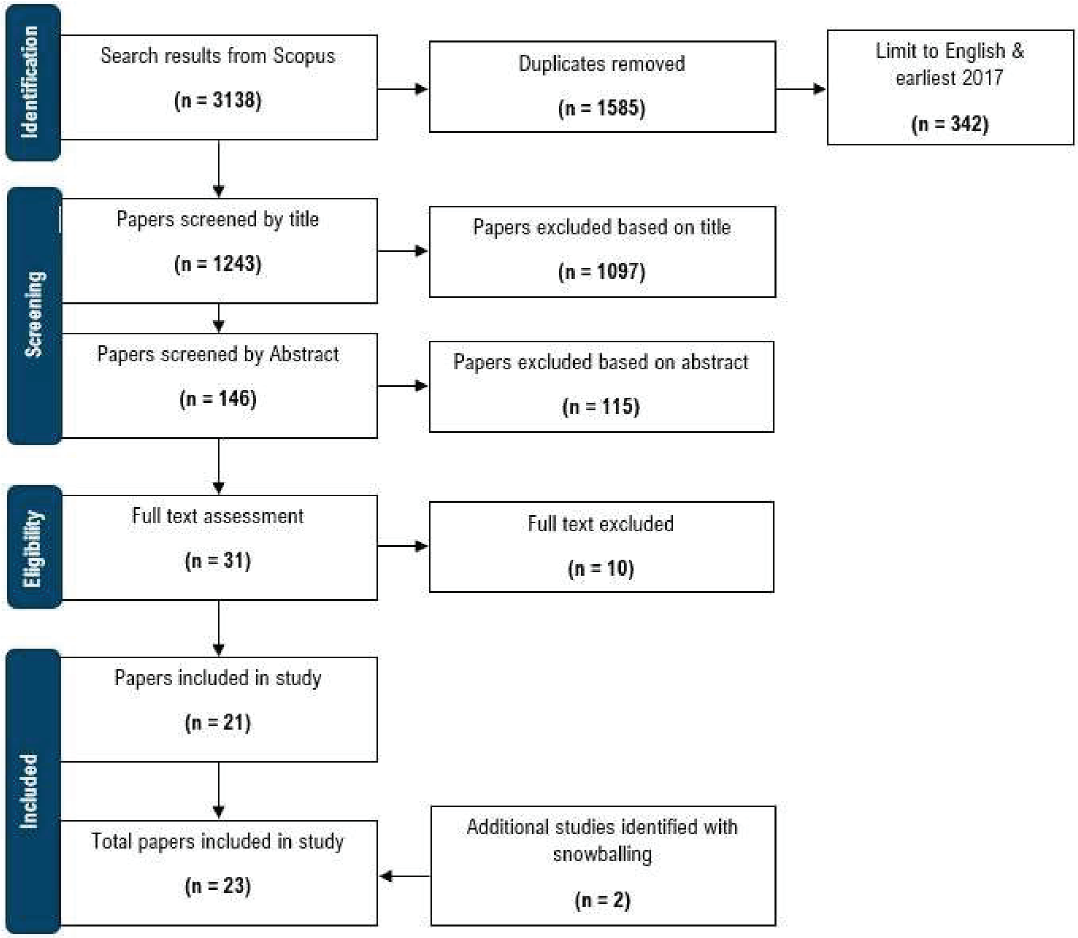

Figure 1: Paper selection process

Paper selection process

The 2673 papers identified in the search process were narrowed down through a series of screenings based on the following inclusion and exclusion criteria:

Inclusion:

- Papers that discuss data transfer based on real-time-data in BIM or the AEC industry.

Exclusion:

- Papers that don't discuss real-time-data for data transfer in BIM.
- Papers that focus more on related topics than the data transfer itself.

All the search results were saved into a list on Scopus, with the websites list functions automatically removed any duplicates from the searches, leaving 1382 papers in the list. This list was then limited to English language from 2017 and onwards. This left 1052 papers for the screening process. The title screening then eliminated 937 papers, among which many focused on different topics or fields, leaving 115 for the abstract screening. After the abstract screening was complete, 25 papers were left for full-text assessment. At this stage, two papers were excluded due to not having their main focus on the relevant topics. Along with the three papers that were not accessible for full-text, this took the number of full-text papers included to 20. Finally, two more papers were identified through snowballing, bringing the final count to 22.The full paper selection process is demonstrated in Figure 1. The results of this literature study have been synthesized in an aggregative way, which combines the findings of multiple studies in order to identify multiple themes (Booth et al., 2021).

Results/Analysis

Paper distribution/descriptive analysis

The twenty-three identified papers (which can be found in table 4) all focus on one of three solutions: Knowledge Graphs (Graphs)(8), Digital Twins (DT)(10) or Common Data Environments (CDE)(10), with most researchers seeing these solutions as tools that can aid in create integrated collaborative platforms.

Table 4: Selected papers

Author (year)	Focus Topic			Title
	Graph	DT	CDE	
Huang et al. (2023)	X	X		BIM and IoT data fusion: The data process model perspective
Ryzhakova et al. (2022)		X		Construction Project Management with Digital Twin Information System
Seidenschnur et al. (2022)			X	A common data environment for HVAC design and engineering
Jiang et al. (2022)		X		Digital twin-enabled real-time synchronization for planning, scheduling, and execution in precast on-site assembly
Sacks et al. (2022)	X		X	Toward artificially intelligent cloud-based building information modelling for collaborative multidisciplinary design
Yang et al. (2021)	X	X		Ifc-based 4d construction management information model of prefabricated buildings and its application in graph database
Lee et al. (2021)		X		Integrated digital twin and blockchain framework to support accountable information sharing in construction projects
Karlapudi et al. (2021)			X	An explanatory use case for the implementation of Information Container for linked Document Delivery in Common Data Environments
Dong et al. (2021)	X			Realizing, Twinning, and Applying IFC-based 4D Construction Management Information Model of Prefabricated Buildings
Boje et al. (2021)			X	A 4D BIM System Architecture for the Semantic Web
Sacks, Brilakis, et al. (2020)		X		Construction with digital twin information systems
Sacks, Girolami, et al. (2020)	X			Building Information Modelling, Artificial Intelligence and Construction Tech
Boje et al. (2020)		X		Towards a semantic Construction Digital Twin: Directions for future research
Simeone et al. (2020)	X		X	Reasoning in Common Data Environments Re-thinking CDEs to enhance collaboration in BIM processes
Bucher and Hall (2020)			X	Common data environment within the AEC ecosystem: Moving collaborative platforms beyond the open versus closed dichotomy
Fitriawijaya et al. (2019)			X	A blockchain approach to supply chain management in a BIM-enabled environment
Hamledari et al. (2018)	X			IFC-Based Development of As-Built and As-Is BIMs Using Construction and Facility Inspection Data: Site-to-BIM Data Transfer Automation
Klemt-Albert et al. (2018)			X	Utilising the potential of standardised bim models by a fundamental transformation of collaboration processes
Roith et al. (2017)	X			Supporting the building design process with graph-based methods using centrally coordinated federated databases
Preidel et al. (2017)			X	Data retrieval from building information models based on visual programming
Park et al. (2017)		X	X	Database-Supported and Web-Based Visualization for Daily 4D BIM
Son et al. (2017)		X		Automated Schedule Updates Using As-Built Data and a 4D Building Information Model
Hamledari et al. (2017)		X		Automated Schedule and Progress Updating of IFC-Based 4D BIMs

Knowledge Graphs

According to the found literature, Knowledge graphs seems like a promising solution for storing IFC information, since they share the same format that IFC files has (Dong et al., 2021). They are also more suitable than relational databases, since they are more intuitive than other alternatives and the algorithm lays a foundation for analyzing IFC based information (Yang et al., 2021). An automatic algorithm is also necessary when attempting to reveal the complicated inner relationships of an IFC file, since IFC models are not sufficient in digital interoperation (Boje et al., 2021; Dong et al., 2021). However, when working with IFC, if new data structures are created that don't conform to the IFC specifications, an IFC-based as-built BIM model will not be useable in downstream applications (Hamledari et al., 2018). Graphs can also aid in automatic calculation of start and finishing times (among other scheduling tasks), which is better than manually typing functions in excel sheets (Yang et al., 2021). Through a graph, users can also clearly understand relationships and hierarchies in a BIM model (Dong et al., 2021; Roith et al., 2017), as well as retrieve any information they need via the graph's edge (Yang et al., 2021). Efficient ontology-based tools would allow for robust semantic knowledge-driven data storage, which could then be exploited by AI technologies (Boje et al., 2020). Graphs would then be able to use those advanced AI techniques and are also a natural format for representing links between objects (Sacks et al., 2022). Semantic linking across sub-graphs can also provide an added layer of information, which in turn enables the use of functions which require more meaningful representation of buildings (Sacks et al., 2022). These sub-graphs are also a good substitute for exact geometry since they contain spatial relationships that are required for the machine learning AI tools (Sacks et al., 2022). A flexible data structure is also needed in order to handle a wide range of data format in order to achieve loss-free data (Bucher & Hall, 2020). Graph databases could serve as foundations for Digital Twins (Dong et al., 2021), since graph-based data is generated by uploading BIM data directly into the graph database, which in turn allows for updating of models in response to changes (Sacks et al., 2022).

Digital Twins

Some researchers suggest that a Digital Twin (DT) system could be a solution for automatic data transfer from construction sites to BIM models. The main benefits of DT systems are traceable and reliable transactions that allows for sharing of project information without the need to store data, as well as enabling compliance checks based on as-planned and as-built models which allows for fast decision-making (Lee et al., 2021). Semantic definitions then allow for item-level mapping and categorization (Jiang et al., 2022). A more complex, integrated DT system should also be able to adapt scheduling automatically according to site changes and inform managers of potential disruptions and their causes (Boje et al., 2020). Point-cloud as-built models created with IoT scanners can be used for this purpose, and any deviations detected can then be used to automatically generate new schedules (Son et al., 2017). Automatic schedule updates seem to be a promising solution, since it can be made accurate enough and doesn't require much computation power (Hamledari et al., 2017). However, there are some problems that needs addressing before DT can be used as a reliable tool for automatic updates. One of which is that the BIM development of DTs is very low and the generally low level of IFC adoption in nD modelling (Boje et al., 2020). Just adopting IFC into a project won't automatically solve the problem either, since the poor readability of IFC files makes them difficult to update and modify (Dong et al., 2021). 4D models are also often kept separate from 3D as-planned models, which could cause further disruptions when attempting automation of updates (Boje et al., 2020). This lack of interoperability and automation in BIM makes constructing a comprehensive DT a challenge, since it requires a real-time connection to the physical twin (Boje et al., 2020; Sacks, Brilakis, et al., 2020; Sacks, Girolami, et al., 2020). Ryzhakova et al. (2022) suggests a big data system as a solution for various calculation and processing problems, but it still doesn't solve the integration of different automated systems, which is necessary for constructing DTs. Data is available in abundance, but the lack of reliable linked data limit the possibilities of properly utilizing automated performance monitoring and control technologies (Sacks, Girolami, et al., 2020). Huang et al. (2023) identified two routes for fusing IoT and BIM data; the relational route that enhances situational awareness, and the semantic route, which focus on context-based BIM data for information inference. Finally, different projects also have different demands, and in order to support this the DT platform needs to be adaptable enough to fit the needs of each specific project (Boje et al., 2020).

Common Data Environments

A Common Data Environment (CDE), is by ISO 19650 defines as: "an agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process" (ISO 19650-1). Bucher and Hall (2020) states that a CDE involves all actors in a project, which enhances collaborative performance, and the current evolution of CDEs have resulted in an increased interoperability in construction. A CDE can allow for continuous integration, since it can be created in such a way that if an individual part of the system fails, it can be tested and fixed without touching the code for any other parts (Seidenschnur et al., 2022). It also enables an advanced level of information retrieval due to its integration with semantic data and interconnected information structures (Klemt-Albert et al., 2018). If files are updated directly into a shared database will also enable web-viewing of BIM models for all project participants, eliminating the need for manual file uploads (Park et al., 2017). It's therefore necessary to integrate workflow management that substitute analogue communication into a CDE in order to facilitate this level of collaboration and documentation (Fitriawijaya et al., 2019; Klemt-Albert et al., 2018). History and ownership of each part of a model must also be recorded when using discipline specific models instead of a combined shared model (Klemt-Albert et al., 2018). Viewing the CDE only as a two-dimensional platform will limit potential development, hence three-dimensional CDEs that also serve as storage for data and enables enterprise level exchange should be the goal when setting up future CDEs (Bucher & Hall, 2020). A risk when designing a CDE is to design it for "the perfect scenario", where the BIM model contains all the necessary data (Seidenschnur et al., 2022). However, it's likely that BIM models don't contain all the required data for such a complete model, so the CDE must be designed with this in mind (Seidenschnur et al., 2022). Seidenschnur et al. (2022) also gives an example of this problem, where they state that IFC parsing from BIM tools like Revit is error prone when representing HVAC systems and say that there's a need for open format CDEs that can properly represent flow systems. This could be because relationships between entities in IFC-based information is complicated, which leads to poor readability (Dong et al., 2021; Yang et al., 2021).

One solution to this problem could be ontologies (Boje et al., 2020), where natural language questions could be translated into SPARQL queries, making semantic queries possible, which in turn could be used to verify knowledge representation in ontologies when using the link generation capabilities of CDEs (Karlapudi et al., 2021). The reason that query languages have not been used much in the past is that the textual programming languages have been a major obstacle for architects and engineers (Preidel et al., 2017). Another problem with query languages is that many front-end tools rely on the ".json" format for visualization, which makes semantic RDF/OWL ontology models difficult to explore in detail (Boje et al., 2021). Visual programming is easier for non-programmers to learn and understand and have therefore become more popular in the AEC industry in recent years (Preidel et al., 2017). Visual programming allows for filtering and exporting datasets in different formats, which enables reconstruction of entity relations, making it suitable for CDEs (Simeone et al., 2020). The main problem with visual languages is that it's difficult to properly represent queries for more complex control schemes, such as iterative loops and error handling (Preidel et al., 2017).

Discussion

The purpose of this study was to identify potential ways of using real-time data with managerial functions that could support integrated design and production planning and control. Knowledge graphs, DTs and CDEs all show potential as solutions for this purpose. However, there are many obstacles that must be overcome for any of these tools to be an efficient solution. Many of these problems are intertwined with one another, meaning one problem stems from another. The main problems that need solving are:

- Teams federate separate models (Sacks, Girolami, et al., 2020)
- Rework and long cycle times are common (Sacks et al., 2022)
- Dynamic and changeable project environments (Jiang et al., 2022)
- Lack of reliable information transfer (Boje et al., 2020)
- Lack of automatically updated schedules (Wang & Rezazadeh Azar, 2019)
- IoT sensing is limited, leading to out-of-sync models (Boje et al., 2020)
- Lack of common formats (Boje et al., 2020)
- Manual information inputs (Boje et al., 2020)

Digital Twins for automatic data transfers

In order to enable automatic updates of schedules it is necessary to have access to reliable information transfers of data in common formats that is accepted and understandable by downstream applications. DTs can allow for the automatic data transfer needed and they can also enable the compliance checks needed for automatic schedule updates (Lee et al., 2021). In order to automate these checks, actual as-built data is required. IoT scanners could be used to create point-clouds to create an as-built model (Son et al., 2017). However, many projects using DTs do not have a high level of BIM and IFC development (Boje et al., 2020), which could be a result of IFCs poor readability, which makes them difficult to update (Dong et al., 2021). Since graphs share the same format as IFCs (Dong et al., 2021), they seem like a promising solution to this problem. Using DTs, where information is gathered with the aid of automated data capturing tools and then translated into graph formats in order to perform the compliance checks needed for automated schedule updates could therefore be a potential solution. The data fusion solution suggested by Huang et al. (2023), where two technological routes (relational and semantic) are fused together, could then aid in creating a more comprehensive DT. Another benefit of using graphs, is that they could also aid in the actual schedule calculations needed for the automatic updates (Yang et al., 2021), eliminating the need for manual inputs. The solution proposed by (Sacks et al., 2022), where BIM data is uploaded directly into a graph database therefore looks like a promising solution. Using a combination of DTs and graphs would allow for updates of as-built models based on changes, which solves the problem of information and models being out of sync.

CDEs enable information sharing

While being able to automate updates of models and schedules is an achievement, it is important to consider that project teams often federate many different models across various disciplines. For the automated processes to work in such an environment, there needs to be a reliable way of transferring and sharing all the information. CDEs allow for good information sharing, since all actors in the project can be involved (Bucher & Hall, 2020). Integrating the CDE with semantic data also allows for advanced information retrieval (Klemt-Albert et al., 2018), but as Seidenschnur et al. (2022) states, it is likely that the models does not contain all the data necessary for a complete, shared model and the CDE must therefore be designed with this in mind. Open data formats that support ontologies could be a solution to this problem, since queries could then be used to verify the data according to the ontologies (Karlapudi et al., 2021). This in turn requires existing links between data. Fortunately, CDEs could be capable of generating such links (Karlapudi et al., 2021).

Graphs as connectors

The results from the literature review indicates that it should be possible to create a project ecosystem based on various DT, graph and CDE technology. Graphs in particular appears to be a key piece in solving the puzzle, since they could be a part of the solution for most of the problems. Many of the problems stems from the need of open formats and reliable, readable data. Using graphs as the common way of storing data, like the "Cloud-BIM" approach suggested by Sacks et al. (2022), could therefore enable an interconnected project platform that can be adapted and modified as needed. Graphs could then be seen as an enabler for a digital project ecosystem by connecting a CDE with DTs and their IoT devices, IFCs and semantic queries. However, involving queries in construction projects creates a new problem, which is that their languages are complicated and therefore difficult for architects and engineers to understand (Preidel et al., 2017). While visual programming is easier for them to understand (Preidel et al., 2017) and is suitable for CDEs (Simeone et al., 2020), as Preidel et al. (2017) states, it is difficult to properly represent complex query language with visual programming. Future studies should therefore focus on how visual programming could be used in tandem with query languages within a CDE. Since the goal of using the proposed technology ecosystem is to improve collaboration, future studies on how to support integrated design and production planning and control within a connected project ecosystem should also be considered in order to be able to assess if such a system is actually a valuable solution.

Conclusion

The systematic literature review indicates that in order to support integrated design and production planning and control within a connected project ecosystem and allow for automatic updates of schedules, using a combination of DT, graphs and a CDE could be a good solution. Graphs in particular seem very useful for linking together various formats. While some testing with graphs have already been performed, more studies are needed on how to manage graphs using software and methods more familiar to architects and engineers.

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