Identification of Common Data Environment Functions During Construction Phase of BIM-based Projects

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Abstract
The utilization of building information modeling (BIM) has been rapidly increasing in the last decade as it stimulates project constructability, quality, efficiency, and success. A well-structured and organized information system is the major requirement to ensure adequate collection, management and dissemination of documentation and the central BIM-model for the whole project team. This consistent source of information, called as the common data environment (CDE), carries an important role to achieve a centralized information system in the BIM-based construction projects. Despite the general perception, common data environments (CDEs) should not be considered only as a digital storage and sharing space. A CDE system, set up at the beginning of the project according to the international standards, can support the successful project management by providing instant insights related to the project performance and eliminating non-value adding activities (e.g., rework, defect). Although the CDE is an ultimate necessity for a data-driven construction project management, the literature remains quite incapable of revealing the functions of the CDE system. The aim of this study is to identify and categorize the CDE functions used in the construction phase of BIM-based projects. In the first step, possible CDE functions were derived from a literature review and online sources. In the second step, semi-structured focused interviews were conducted with five subject matter experts who use the CDE system efficiently in the international BIM-based construction projects. This methodology allows to link aspects of different perspectives and achieve meaningful and reliable outputs. The results will provide valuable information about the CDE functions in the BIM-based construction projects to practitioners and researchers. Further, this research can create awareness about the CDEs and encourage the use of CDEs in the BIM projects.

Keywords: Building information modeling, common data environment, information management, construction industry

1 Introduction
The construction industry requires the involvement of multiple parties including owners, engineers, contractors, designers, subcontractors, and material suppliers (Skibniewski & Ghosh 2009). Multi-party involvement and dynamic nature of the construction industry makes projects intractable to manage. Over the course of many years, the industry has been criticized for its underperforming performance measurements and project process monitoring (Kagioglou et al 2001). The underlying reason is mainly traditional means of communication techniques such as face-to-face meetings, exchange of documents in paper forms (Stewart 2007). The distance between headquarters and construction sites further obstructs the precise and on-time information transfer which are critical features for the project success (Deng et al 2001). Even in

a small-sized construction project, the amount of produced and interchanged data is enormous (Deng et al 2001) and excessive dispersed information make the management practices complicated (Skibniewski & Ghosh 2009).

Communication, coordination, decision-making, and knowledge-management, the four key management skills, are significant for the construction projects (Al Nahyan et al 2019). Previous studies show that communication problems and data loss, might cause poor project performance, particularly in complicated construction projects (Ozturk 2020). According to the yearly report of PlanGrid and FMI, 30% of construction data is lost from early stages of the project through the turnover stage and 52% of all reworks are caused by poor data and miscommunication (Schott 2018). These statistics prove the need for a centralized communication network and information repository for collection, exchange, and management of generated data throughout the project life cycle.

Common data environment (CDE) is a centralized information repository where project participants manage processes and exchange information within their authorization frameworks. The CDE is defined as *"agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process*" in ISO 19650-1 which is the transformed version of the British BS 1192 Standard. Creating a uniform framework to ensure data consistency is crucial due to the nonoptimal nature of information sharing (Vidal & Möller 2007). On this point, international standards (e.g., ISO 19650 series) give a basis for this uniform framework execution. Despite the general perception, CDEs should not be only regarded as a digital information storage and exchange platform. Stransky (2020) indicated that the CDE is more than just being a storage and a way of sharing data, by facilitating functions like BIM project management, status and workflow management, monitoring construction site progress. CDE can present a perception for the current status of the project by providing accurate information at the required time from anywhere while streamlining the communication, coordination and management among all stakeholders. Moreover, the efficient use of CDE can promote not only the project management skills and collaboration among project participants but also increase the productivity and project value by reducing non-value adding activities such as delays, quality losses and cost overruns.

As the BIM system has started to become a necessity for Industry 4.0, the research on these collaborative work platforms increased. Preidel & Borrmann (2016) identified the challenges and needs of BIM-based collaboration and proposed an approach that streamlines the integration among the CDE and presented software products. Brucher & Hall (2020) investigated the interoperability between tools within a single CDE, CDE within a project or firm, and collaborative and digital twin platforms. Further, Brucher & Hall (2020) proposed a three-dimensional CDE operating within an ecosystem for interoperable CDE development. Senthivel et al (2020) examined how the information container for linked document delivery (ICDD) can be presented across the three CDE frameworks, selected as DIN SPEC 91391-2, OpenCDE-API, and W3C Connected Data Platform. Some studies show that CDE is not just a data and document repository (Simone et al, 2020; Akob et al, 2018; Losev, 2020). One of these works conducted by Simone et al (2020), proposed a conceptual framework that facilitates the presentation of CDE from the point of BIM-oriented processes by integrating its repository function with a knowledge-based system. Additionally, Simone et al (2020) stated that the effective collaboration in the architecture, engineering and construction (AEC) industry is still not sufficiently supported by the CDE. In the other study performed by Akob et al (2018), presented the use and key benefits of CDE, which is Bentley's ProjectWise, for the design, construction, operation, and asset management processes of the Pan Borneo Highway. Similarly, Losev (2020) examined the CDE from the building lifecycle management perspective and clarified the concepts such as the common knowledge environment (CKE) which arise from the changes of building information models during the project lifecycle.

A few studies only focused on clarifying and categorizing the functions of CDE. One of them conducted by Radl & Kaise (2019), demonstrated the actual state of CDE document structure of highway projects in Czech Republic. According to the research conducted by Radl & Kaise (2019), the documents were created, signed, and exchanged in paper form, then they were transferred to the digital platform in highway projects of Czech Republic. The initial paper-based method does not fully meet the requirements of the digitalization, and indeed hinders the primary purpose of working in CDE. Thus, the research performed by Radl & Kaise (2019) is quite incapable to reveal the full potential of the CDE systems. A more recent study performed by Stransky (2020), conducted qualitative research on four common data environments, which are Dalux Tender, Viewpoint for Projects, Trimble Connect and Bentley ProjectWise in terms of their abilities for supporting procurement processes of subcontractors. The study of Stransky (2020) mainly relied on the online sources, questionnaires and slightingly supported by the literature background. In addition, the interviewees information, interview questions and durations were not clarified which are important features to collect valid data on the subject domain. Indeed, the expert-based research methods work more effectively when those experts are believed to have sufficient observation and knowledge regarding the technology of interest, but in the study conducted by Stransky (2020), it is doubtful how well the research questions fit the data collection approach. Another study performed by Klemt-Albert et al (2018), presented an approach about the implementation of standardized collaboration process, data, and issue management into a CDE. Klemt-Albert et al (2018) classified the content and processes within a CDE as models, comprehensive information, documents, drawings, workflows, collaborative communication. The classification developed by Klemt-Albert et al (2018) is based on the applicable functions such as import/exporting, versioning, querying, locking and sharing and the research is mainly focused on the integrated workflows and collaborative information management within the CDE concept.

The successful implementation and utilization of the CDE system can be achieved by starting to work in this environment from the early beginnings of the project. The project stakeholders can work on this collaborative environment throughout the project lifecycle. There are several dominant features of CDEs are: the collaboration and interoperability in design; bidding, tendering in pre-construction; communication and collaboration during construction; facility management during operation and management; knowledge management throughout all these phases. However, there is no comprehensive research which explains the full potential of the current CDE systems used during the project lifecycle. In this context, this study aims to identify and categorize the CDE functions that are utilized during the construction phase of the BIM-based construction projects from the main contractors' point of view. For this purpose, a literature review and semi-structured focused interviews with five industry professionals were conducted. Besides, online sources such as websites of CDE software were investigated. 53 functions were determined considering the triangulation results of literature review, interviews, and online resources. The identified functions were grouped into 12 management domains based on their dominant attributes. Accordingly, the findings of this study allow practitioners and researchers to have an overall insight to the abilities and capabilities of the CDEs.

2 Methodology

The research methodology of this study includes three steps which are review of the literature, investigation of the online sources addressing CDEs for BIM projects and semi-structured focused interviews with the subject matter experts (SMEs). A literature review based on the "common data environment" and "information management" keywords were conducted to see the current state of the subject matter using Scopus Database. Webinars given by the industry professionals addressing the digitalization of the construction industry and online sources such as websites of software providers (e.g., Bentley, Autodesk, Oracle) were also investigated. In the second step, semi-structured focused interviews, the essential point of this research, were conducted online with five industry experts who have at least 4 years of experience in the BIM-based construction projects (Table 1). Interviewees are managers or consultants who work for the digitalization of the construction industry, who have experience in complex projects in various countries such as UAE, Turkey, Kuwait, Azerbaijan any many others. Semi-structured focused interviews with SMEs allows to examine the CDE system from the viewpoint of both consultants and system users.

An interview framework was prepared which consist of 12 questions divided into 4 main topics that are a general overview to information management, CDE systems, key performance indicators (KPIs) and the relations between CDE and KPIs. Explanatory interview questions were preferred to get experts' overall opinion about the CDE systems and additional, specific functions which are not mentioned in the literature, online sources, and webinars. The interview durations were approximately forty-five minutes to ninety minutes. Only one interviewee delivered the answers to the interview questions in written format. In the last step, the findings from various sources (i.e., literature, interviews, and online sources) were triangulated to identify the managerial functions of the CDE and categorized based on their key attributes.

Table 1. Profile of interview participants

Profession	Education	Title	Experience in construction industry	Experience in BIM-based projects	Interview Durations
Electrical electronics engineer	B.Sc. M.B.A.	Digital Transformation Expert	10	10	55 min
Mechanical engineer	B.Sc. M.B.A.	BIM Consultant	25	14	45 min
Architect	B.Sc. M.Sc.	Global BIM Manager	18	18	90 min
Civil Engineer	B.Sc.	Digital Transformation Expert	9	4	90 min
Mechanical engineer	B.Sc.	BIM Manager	14	14	Answers delivered in written format

3 Classification of CDE functions based on managerial attributes

According to the triangulation results of the literature, interviews, and online sources, 53 general functions of CDEs related to the construction processes were identified and grouped under 12 main management domains based on their dominant attributes. The functions and relevant categorizations are provided in Table 2.

3.1 Contract Management

Several change orders may occur in the construction projects. The reasons of change orders (i.e., variation order) can be inaccurate drawings, specifications in design or contract, inadequate budgets and schedules, unforeseen events and obstructions, change in worker or material conditions. These changes on the contracts must be approved by related parties which can be time-consuming and require patience. A formalized approach should be adopted while managing change orders to prevent failure of the project or costly delays occurrences. Similarly, claims, extension of time request processes should be executed to prevent disagreements in an efficient way. Digitalization in the AEC industry helps to reduce the time and expenditures wasted for variation orders. Fast and accurate changes in the contract may even led your project moving forward by mitigating the time wasted for inadequate or error-prone implementations. In addition, progress claim request (claims for payment) and progress payments processes can be reviewed and approved according to the specified rules explained in the contract documents. Monitoring cost changes in the contracts may help contractors to forecast the aspect of alterations on the overall project budget and progress payments.

Table 2. CDE functions and categorization based on managerial attributes

Management Domains	CDE functions
Contract Management	Review & management of contracts Extension of time (EOT) requests Change request & orders (variation order) Claims Progress Payment protocols Bidding & tendering & offers
Design Management	Review of design documentation BIM model coordination & 3D views Model version control & comparisons Shop drawings Design collaboration
Document Management	Work-in-progress, Shared, Published, Archive stages Storage, monitoring, management and access for all kinds of documents Document version control Advanced & standardized forms Authorization permits
Communication Management	Standardized collaboration processes Mail/messaging Notifications Transmittals
Deliverable Management	Submittals RFIs
Workflow Management	Review/Approval processes Manage, resolve, report Issue & Markups Responsibility & role assignments Task assignments
QA/QC Management	Access to standards, guidelines, specifications Method of statement submission (MS) Work inspection reports (WIR) Test plans (including hold & witness point) Non-conformance reports (NCR) Verification & Validation (V&V) processes
HSE Management	Accident, incident, near miss investigation reports Corrective, prohibitor activity assignment & inspection Permit to work (PTW) HSE training, PPE delivery tracking forms Return to work authorization Environmental impact assessments Notice of improvement & prohibition
Procurement Management	Demand management Procurement order monitoring Supplies flow monitoring Inventory control & material withdraw Managing supplier contracts
Project Performance Management	Proactive progress monitoring Progress reporting Real-time analytics & dashboards KPI monitoring Accountability assessments by audit trails
Handover Management	Import & export COBie data As-built BIM models
Knowledge Management	Records of the project information for the future projects Accumulating, storing, sharing existing knowledge

3.2 Design Management

In this study, the CDE functions categorized under design management indicate the functions to facilitate design management during the construction stage. Project participants can review the accurate design documents related to the implementation at any time in a CDE environment. Shop drawings can be generated, reviewed, approved, and distributed through the necessary departments using CDE. The CDE can provide model version control and comparisons which further prevents the implementation defects and reworks. Keeping the BIM models updated during the construction process is critical for the latter phases of project lifecycle. Working in a CDE streamlines the BIM model coordination by connecting teams, models, project data and supporting interoperable data formats such as industry foundation classes (IFC). Reviewing the 3D drawings regardless of their native software preferences is possible using suitable CDE software.

3.3 Document Management

The execution of construction projects requires numerous data and information transmittal among project participants. Paper-based ways of communication and information storage are time-consuming, and they may cause error-prone activities that directly reduce the project productivity. Data and document losses may arise due to the manual exchange and conservation which causes delays and additional costs. Instead of traditional ways of document storage, digitalized and centralized document repositories are crucial for reducing such non-value adding activities during construction process. Secured storage, monitoring, management of all kinds of documents, such as PDFs, spreadsheets, DWGs, and their version controls can be effectively and efficiently accomplished by the usage of the CDEs. In fact, CDEs help project participants to create, upload, update or revise any kind of documents, such as drawings, RFIs, specifications by staying loyal to the predefined document management protocols. The phases and collaboration levels of data interaction consists of four phases, work in progress, shared, published and archive, as specified in ISO 19650-1. Work in progress module enables the task teams working only within the team and the produced documents cannot be seen by other parties. After the check, review and approval process, the documents can be shared among the project team. The information/documentation is reviewed and authorized for the use in later phases of construction in the published module. All documents and audit trails are recorded and stored in the archive module. Security and visibility of these documents can be controlled with the authorization permits. In accordance, advanced and standardized forms of documents prevent the complexity. Moreover, automatized processes such as automatic cover letter production may accelerate the document development.

3.4 Communication Management

Inefficient and poor communication among project stakeholders cause several reworks throughout the project delivery process. Straightforward and standardized communication is one of the key pillars in construction management which facilitates the productivity by reducing the time wasted for searching information among numerous e-mails. The CDE enhances the efficient collaboration by providing a centralized communication network without using traditional ways of communication such as phone calls, e-mails, and paper-based processes. Advanced communication among stakeholders can reduce the RFI submissions nearly 50% ranging the e-mail and messaging processes that help to prevent the e-mail accumulation and notifications for the tasks or project participants and to fulfill the project requirements on time (Oracle, 2021). The transmittals are a form of communication in the CDEs which contributes to the audit trails and facilitates staying loyal to the planned schedule.

3.5 Deliverable Management

Deliverable management refers to the internal deliverables (i.e., submittals and request for information (RFIs)) which should be delivered to the related project teams in the construction stage. Appointing parties should manage the submittals derived from the appointed parties to obtain each aspect of the project information. However, submittal processes in paper form may take a long time and lead to errors in construction which further causes rework and delays. Probability of reworks and delays can be eliminated by the usage of automated, digital submittal logs within the CDEs. Similarly, on time responses to the RFIs are critical for preventing costly delays, reworks, conflicts, and disagreements. In fact, using one digital platform with the participation of all stakeholders to create and manage RFIs is essential for achieving the projects on time, budget, and quality.

3.6 Workflow Management

One of the key factors for streamlining the workflows is straightforward coordination among project participants. Generally, data and systems are in separate localizations which may cause repetitive data entries. Collaborative, standardized, integrated, and automated workflow management to coordinate tasks and deliver information between participants and systems can improve efficiency, consistency, and responsiveness. Particularly, change orders and RFIs require a set of review, approval actions by responsible parties. The execution of review and approval processes in a digital platform reduces the non-value adding activities such as paper-based deliveries and wet signature-based approvals. On the other hand, issue management through CDEs, can help to integrate different systems and can be supported by the markups. For example, an issue related to the design can be stated directly in the BIM model with markups then related notifications can be sent to the responsible parties automatically. Responsibility, role, and task assignments ensure the transparency of duties and project participants can monitor their progress and their next actions with the deadlines.

3.7 Quality Assurance/Quality Control (QA/QC) Management

QA/QC department is responsible for the execution of required processes to prevent defects and inspection of products or productions to detect and remove the defects if they exist. These processes are standardized by the regulatory norms such as ISO 9001 and require plenty of review, approval, check, test, and validation processes before, during and after the implementation to ensure compliance with contract terms and conditions. Efficient management of quality assurance and control processes facilitate to meet contract, standard requirements, client needs and satisfaction while reducing the reworks which causes delays and additional costs to the project. The CDE enables a streamlined transmission among subcontractors, suppliers and controllers which supports the execution of efficient quality management. Participants can easily access the standards, guidelines, specifications and submit and review the method of statements (MS) related to the procedure of an activity. Work inspections and test plans, including hold point and witness point steps, can be executed properly. Non-conformance reports (NCR) can be generated, supported by the attachments (e.g., measurements, photographs, test reports) and transmitted to responsible parties in a standardized way. Verification and validation processes can be streamlined among the designer, client, and contractor. Improving the QA/QC efficiency, by the help of a collaborative work environment, re-works and contractual incompatibilities can be reduced while the quality of the construction works increases.

3.8 Health, Safety and Environment (HSE) Management

The efficient monitoring and management of HSE processes are possible within the CDE scope. Using a centralized environment to manage HSE processes among project participants may accelerate the response and close off time while reducing the risks and ensuring safety in the project. Accident, incident and near miss investigations can be conducted and supported by the attachments such as pictures from construction site that provide detailed information about the dangerous situations. The HSE department can derive the information related to breaches and risks by allowing improvement and prohibition notices. Afterwards, corrective and prohibitor activities can be assigned to the responsible parties which enables auditable, real-time action tracking. HSE performance analysis can be performed in terms of performances of stakeholders, incident trends such as accident location, time, occupation, and root causes such as deficiencies, mistakes. The HSE performance analysis facilitates to fulfill the regulatory requirements. Advanced analytics helps HSE officers to deeply understand the incident trends, root causes and accelerates taking action before something happens on the project site. This feature reduces risks and prevents further incidents. Permit to work documents, safety walk inspections, return to work authorizations and forms of HSE training and personal protective equipment (PPE) delivery forms can be followed through a digitalized and standardized process. Additionally, environmental data including waste, air, fuel, energy can be maintained to reveal their aspects by generating reports in CDEs.

3.9 Procurement Management

The procurement processes are time-sensitive activities in construction due to numerous purchases of various materials, equipment and machinery services from different vendors or suppliers. For this reason, procurement processes should be monitored accurately to prevent any delays and deficiencies in production. Executing the procurement processes and managing the supplier contracts in CDEs mitigate the misunderstandings among buyers and suppliers while improving the procurement decisions and makes the effective procurement process tracking possible from planning to material withdrawals. Procurement demands and orders can be managed during all the stages and approvals can be recorded in a collaborative environment. Supplies flow can be monitored including logistics and material acceptances. Hence, accurate, reliable and up to date information in the digital data repository allows to see the real-time situation from inventory controls to material withdraws from warehouses.

3.10 Project Performance Management

The project performance drivers can directly focus on the status and outputs of the construction project by the advanced and real-time analytics in CDEs, instead of wasting time for collecting data from the various departments individually. Key performance indicators (KPIs) are important to facilitate the performance measurements. The accurate recordings of information in the CDE facilitates and increases the reliability of the KPI assessments. The KPIs can be specialized based on the firm or project needs. Tracking any kind of performance indicators becomes possible within the CDE boundaries. Quick access to the real-time and trustworthy project status is crucial for enabling accurate decision-making. The progress monitoring function is utilized by different departments and can be customized by their needs. For example, the real-time dashboards can be related to the QA/QC department which highlights the current status of work inspection reports, NCRs based on their work disciplines, classifications and average times taken to fix defects. Similarly, administrative departments dashboards can clarify the project work status, workloads, completion percentages, schedule performance index (SPI), budget variances, cost performance index (CPI), rework costs as well as HSE issues such as accident-free days and many other aspects. Automatized reporting function helps to save time on the project while providing standardization. Accountability assessments by audit trails may help to detect deficiencies in the processes or stakeholder capabilities. Thus, records of audit trails help decision-makers to take the necessary actions against the mitigation of these deficiencies. Accordingly, the data-driven management approach increases the company's value and may facilitate the company's competitive advantage.

3.11 Handover Management

The handover phase is the final stage of the construction works and delivery of the assets to the client. The client takes over the asset and relevant information from the contractor. Traditionally, the information related to the building consists of numerous documents and drawings in the paper format. These papers are in a part of a building, and it is hard to find the exact document when information related to a part of building, or an object is required. In the BIM-based projects, instead of paper-based document delivery, the contractor delivers the as-built BIM model and construction operations building information exchange (COBie) data to the client. These assets and information in the CDEs can be used in the facility management actions by the owner.

3.12 Knowledge Management

Knowledge management (KM) refers to creating, sharing, using, and managing the accumulated knowledge held within the organization (Girard & Girard 2015). However, without having standardized and digitized information repository, it is hard to query the information such as common defects and errors, successful resolving actions that occurred during the previous construction projects. Gaining knowledge and obtaining lessons-learnt cases could be achieved by only keeping the records of previous project information. Accumulation and storage of the knowledge in CDEs enables the knowledge sharing among the firm boundaries. Hence, access to accumulated knowledge via CDE may increase the present and even future projects performances.

4 Discussion

In this research, the classification of CDE functions were made based on the general management processes performed in a construction project. All phases in a construction project (e.g., design, construction, facility management) are interrelated. Therefore, it is also possible to consider a function under two or more management domains. For example, any kind of documents and processes have a review, approval protocols. Instead of adding every single review, approval functions, such as method of statement approval or RFI review, all the reviews and approvals related to the processes, are placed under workflow management. Change order management is a process which affects multiple parties involved and the aspects such as design, cost and scheduling, contracts, and quality. In fact, change orders are placed under contract management as change orders may require contractual changes including updated cost and scheduling. The cost and schedule management domains may also be inserted to Table 2; however, no such distinction has been made because all functions influence overall project cost and schedule. Instead, cost and schedule management issues are placed under project performance management (PPM) domain. Likewise, progress and KPI monitoring, progress reporting and real-time analytics under the PPM domain comprises all the aspects such as HSE, quality or document management statuses. However, the functions are placed under the most matching management domain instead of multiple placings to prevent information congestion and confusion. This way of categorization ensures to mitigate the data repetition. Consequently, this study achieved the proposed objective by giving clarified CDE function categorizations.

5 Conclusion

This research identifies and categorizes the CDE functions during the construction stage of a BIM-based project throughout literature review, semi-structured focused interviews and online sources. By triangulating the outputs of these different sources, 53 functions were identified. These 53 functions were categorized under 12 main domains which are management of contract, design, document, communication, deliverable, workflow, QA/QC, HSE, procurement, project performance, handover, and knowledge. The findings of this study will provide an overall insight about the CDE abilities from the contractor's point of view. This research can promote the use of CDEs in the construction projects to increase efficiency and productivity in the industry. Hence, this study contributes to the AEC literature and industry by presenting an overview about the CDE functions that are utilized in the construction phase of BIM-based construction projects. The functions and processes may vary by companies. Therefore, the results could be extended by adding different domains in the future studies.

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