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From Bricks to Bytes: Navigating Data Management in Construction Technology

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Abstract: With the advent of technological tools, systems, and mechanisms, the operating system in the construction industry has changed enormously. While technological advancements cover a broad area of software and hardware, those involved in data flow have significant roles in data sustainability. The data flow presupposes various requirements, interactions, consequences, and resource utilization and therefore plays a crucial role in construction organizations' success. The importance of the data flow subject and the scarcity of pertinent studies provoked the current research, which aimed at the exploration of the data flow in construction companies and the effects of technological advancements on different stages of this flow. The overarching research question was, "what factors or processes generate data that do not add value to the construction organization." In this context, the added value was considered a tradeoff between all consumed resources, including cost, human resources, hardware and software, and associated challenges on one side and the advantages of data generated on the other side. An extensive literature review was performed to examine the main milestones in the data-generative events in the construction industry, with a special emphasis on recent technological advancements such as BIM, VR, AR, and drones. In addition, a group of construction professionals who were in charge of processes was surveyed to produce empirical data for supplementary analysis. This paper contributes to the body of knowledge by providing a clear analysis of the data flow in construction companies which helps decision-makers to design and implement consistent and coherent data generative systems.
Keywords: Data; Construction companies; BIM; Technological advancements.

1. Introduction

Data management has become a major function of the underlying tier of many industries. It is estimated that the amount of data in the world was 44 zettabytes at the beginning of 2020 [1]. Also, it is estimated that 90% percent of the world's data was created in the last two years, and every two years, the volume of data across the world doubles in size [2]. Most companies are capturing only a fraction of the potential value of data and analytics [3]. Similarly, the construction industry has experienced a data explosion in various sectors. This eruption includes the data that is generated in the design, building, monitoring, and maintenance processes in construction projects. In addition, construction companies use tools and methods to control the quality or enhance efficiency. The enormous amount of data emanates from tools and equipment that require considerable investment. The next area of challenge is the adequacy, responsiveness, and consistency between all hardware and software processing the data. Training is another major challenge that requires time, cost, and coordination. Data storage is another concern that construction managers should solve in a scalable approach. Moreover, the maintenance of the data entails additional resource consumption. These concerns triggered a study focusing on the data flow in construction companies and the advantages and disadvantages of data-generating technologies. A comprehensive literature review was conducted to explore the effects of construction technologies through the lens of data flow. To evaluate the findings, empirical data were also gathered and compared with the published sources. This study contributes to the body of knowledge in construction by highlighting the data flow and its requirements and sequels in construction companies. Since data flow entails a significant amount of required time, energy, and cost, a balanced data management approach helps construction companies efficiently design, implement, and control their data flow, encountering ever-growing technological advancements.

2. Methodology

The main objective of this study was to explore various processes or tools that generate data in construction projects. In the first phase of this research, the review of the literature was limited to the general trend of data flow, traditional software and BIM applications, and emerging technologies in construction. All these areas include tools, methods, or mechanisms that generate data. However, like other industries, the construction industry generates data mostly in an unstructured format, which is very hard or impractical to use. In addition, requirements for generating data, proper methods of data storage, training processes, and retrieving data were the main subjects in this phase. The research questions that were defined for this phase were 1) How has the data generation evolved in the past decades and 2) What are the pros and cons of data flows in construction projects? A qualitative integrative review was used to assess, critique, and synthesize the literature on data flow in construction. The purpose of using the integrative review method was to overview the knowledge base, critically evaluate the trend, and expand on the theoretical foundation of the data generation tools, requirements, and growth as they develop. Four stages of the literature review were defined and executed. These four stages included designing the review, conducting the review, analyzing, and writing the review. In this first phase, a framework for the review was prepared. This framework was developed based on the reach objective and questions. In addition, keywords such as data flow, construction industry, IT, data generation, construction hardware and software, emerging technologies, data integration, data storage, information risks, and their combinations were identified. In the next phase, the review was conducted using search engines such as Science Direct, Scopus, and Google Scholar. After collecting all publications, a collective screening process was performed to identify relevant resources. In the next phase, selected resources were examined and summarized. In the next step, summaries of publications were compared, grouped, and synthesized into different sub-section. And finally, in the last stage, sub-sections prepared before were expanded and described in a logical order. As an additional step, obtaining empirical data and comparing it with the integrative literature review process was deemed appropriate. While the data flow subject provided in the review was broad, a survey was designed to reflect a portion of data flow in construction companies. The survey included three parts: demographic and career information, BIM exploitation, and data governance in construction companies. The survey was developed on the Qualtrics platform, and the link was sent to construction companies in the southeast region through professional organizations such as AGC and ABC. Since the survey was examining the data flow, it was asked the companies to forward the survey link to eligible individuals, including BIM managers, VDC directors, BIM specialists, Software professionals, or similar positions. The data gathering was conducted in spring 2022, followed by a data cleaning step which resulted in 62 subjects. A quantitative approach was used to analyze the data. Also, to examine the internal consistency and reliability of the survey, a Cronbach's alpha measurement was used. A total Cronbach's alpha of .878 was obtained from the overall analysis of the data, which is considered "high" for the internal consistency of the survey [4].

3. Digital technologies in AEC

Within the AEC industry, many see new digitalization trends as opportunities to improve performance and reduce costs [5]. To provide a fundamental perspective on digitalization tools, in this section, the evolution of these tools in the AEC industry is reviewed.

Around a century ago, the volume of data was limited to paper-based technical drawings, letters, and contracts in the AEC, where there was a limited and slow data flow among different stakeholders [6]. In the 1960s, developments in ICTs resulted in the invention of Computer-Aided Design (CAD) tools [7] which created faster and more accurate designing processes and, consequently, a larger amount of data flow between project participants. The next wave of data flow was the evolution of Building Information Modeling (BIM), which expanded the realm of data collaboration to include the entire project lifecycle (see details in section 3). The term "Building Information Model" was first proposed in the early 1990s [8], which has gained widespread acceptance in the past decades [9]. In recent decades, the extensive use of the internet has been considered another wave of data flow in the AEC industry [6]. This wave was intensified by the global emergence of digitalization technologies in recent years, such as Virtual Reality, Augmented Reality, Extended Reality [10], Internet of Things [11], Unmanned Aerial Vehicles [12], 3D Printing [13], etc. Following the literature review of this section, Figure 1 presents a schematic representation of digitalization technology within the AEC industry over time. It should be noted that data volume sizes indicated in Figure 1 are not to scale and are given only as an indication.

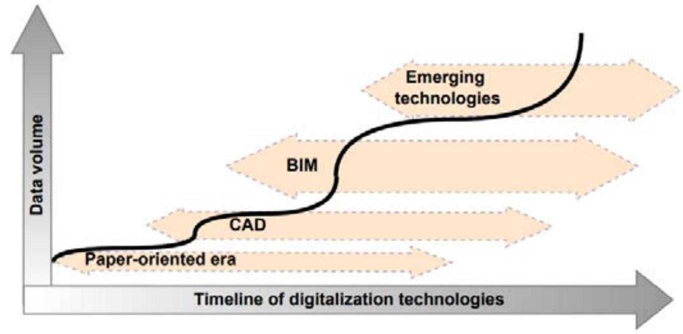

Fig. 1. Schematic AEC digitalization technologies over time.

4. BIM

According to Eastman et al. [14], BIM can be defined as "a modeling technology and associated set of processes to produce, communicate, and analyze building models". Designed as a three-dimensional digital representation of buildings, BIM models consider building elements as an object with a broad array of information, including both geometric and semantic information [14]. This capability of BIM allows real-time collaboration between different project participants as it provides a centralized and consistent database of information for all parties in a project [15].

Despite mentioned advantages of the adoption of BIM, there are barriers hindering the implementation of BIM in the AEC projects. In outlining the factors limiting the application of BIM, Sun et al. [16] divided them into five categories: technology, cost, management, and personnel issues, as well as legal barriers. One of the most important barriers in the technology category is related to interoperability issues associated with BIM tools [17]. Another significant barrier is related to the direct and indirect costs of BIM implementation. In Hardin and McCool's [18] estimation, the direct and indirect cost of using BIM is around $112 thousand.

BIM introduced a new real-time collaboration between project parties, which in turn needs a change in all traditional workflow, including existing file management methods, client billing practices, and deliverables [16]. This means that organizations need time and cost to accept all these changes. The fragmentation nature of construction projects is pointed out as a factor resulting in participants' hesitation to use BIM as they see each project as a unique and not reproducible product [16]. Furthermore, the lack of adequate expertise among the majority of project personnel is pointed out as another prominent limiting factor on the way of BIM implementation [19].

5. Emerging technologies

5.1 VR, AR, MR, XR

Before going into details on these technologies—which can often seem confusing when viewed together—it's important to clarify the differences and overlaps between these terms [20]. Figure 2 represents the overlap and differences between AR, VR, MR, and XR terms.

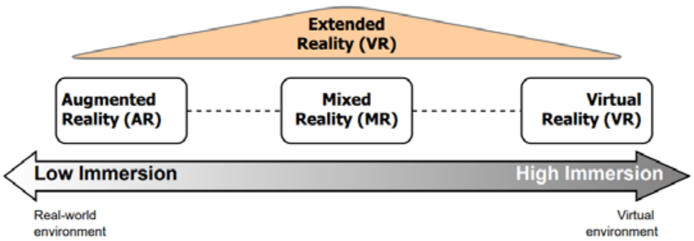

Fig. 2. Representation of differences between AR, MR, VR, and XR based on their immersion level [adopted from [21]]

In comparison to other industries, such as manufacturing, and medical operations, the applications of AR/MR/VR in the AEC are in their infancy [22]. The incorporation of VR and BIM is often studied to improve design, decision-making [10], and education [23,24]. According to Rankohi and Waugh's [25] study, non-immersive forms of AR are preferred by project managers and field workers to keep track of project progress and defects. AR is applied to visualize underground utilities to enhance utility maintenance [26]. Excavation safety is another area that attracted attention when it comes to the application of AR in the AEC [27]. In terms of MR application, Alizadehsalehi and et al. [28] looked into how the integration of BIM and MR from the perspective of lean construction can enhance construction performance.

5.2 Internet of things

Internet of Things (IoTs) is defined as a network of objects connecting through the internet, capable of collecting and transmitting data using sensors [29]. Many studies incorporated the real-time data obtained from IoTs with BIM. This can also be combined with other technologies to leverage BIM capabilities. For example, BIM, IoTs, and VR are used to provide real-time site visualization [30]. IoT real-time data are also combined with BIM to enhance equipment operation in construction sites [31]. Resource monitoring [32], communication improvements [33], and progress monitoring [34] are some of the IoT applications in the AEC industry. Despite these applications, there are some issues hindering IoT applications in the AEC. Interoperability problems are mentioned as a major roadblock on the way of IoT development in the AEC [35]. The massive amount of data that is generated from IoT and BIM will cause problems in cloud-based data storage [11], resulting in other data-related issues like security [33].

5.3 Unmanned aerial vehicles in the construction sector

The commercial use of small Unmanned Aerial Vehicles (UAVs) or Drones is predicted to transform many industries, including AEC [36]. UAVs can be applied to monitor construction progress through a comparison between real-time videos and architectural plans [37]. Some studies also deployed UAVs and some flight patterns as a time- and cost-effective way to generate 3D models from built assets [38]. Aerial assessment of pavement surface [39], safety inspection on construction sites [40], and construction education [41] are among many applications related to the adoption of UAVs in the AEC industry.

Despite UAV applications, there are some challenges with UAV adoption in construction projects. For example, UAVs have serious limitations in harsh climates [41]. It should also be noted that most investigated UAV applications in the AEC are efforts to provide a cost- and time-effective source of real-time data collection for the fragmented and dynamic nature of construction projects. As a result, they also contribute to issues related to a massive volume of data in construction, such as data storage.

5.4 3D printing in construction

To make the leap from traditional construction methods to an approach in which automation plays a central role, various researchers have explored how additive manufacturing (AM), commonly known as 3D printing (3DP) could be applied. 3DP technologies started to become commercially viable in the mid-1990s and have since grown into mainstream manufacturing methods [42]. However, it is still in an early stage, and steps remain to take for the full adoption of this technology in the AEC industry [43].

One of the benefits is that 3DP enables the construction of more complex shapes in a more cost-effective manner [44]. Furthermore, it can be applied as an executive arm of BIM technology, allowing an autonomous construction process [45]. As a practical example, Zhang et al. [46] designed and constructed a bus station in less than 12 hours without relying on formwork.

6. Data management

6.1 Data management practices

With the AEC industry evolving and becoming more digital at an unprecedented rate (see section 2-2), data management practices have become essential. The main objective of data management is to facilitate the interoperability of data so that entities in a project can share data smoothly with each other [47].

As the term “AEC” suggests, the industry is frequently mentioned as a highly fragmented industry [47]. Moreover, different phases of a project, like tender, design, construction, and operation and maintenance, often employ heterogeneous information systems, which are produced by competitor vendors with evolving releases [48].

In addition to these issues, construction project data is often treated as assets that are owned by construction companies, clients, regulatory agencies, and consultants. In this situation, construction companies don’t have full control over their data, leading to negatively affecting data potential [49]. In response to all these problems, a fully interoperable and integrated data network is an indispensable need of the AEC industry in the current state and future.

6.2 Data integration

A considerable amount of attention has been drawn in the AEC literature to reach an interoperable and integrated network among different parties. International Alliance for Interoperability (IAI) or recently known as buildingSMART, which aims to improve the exchange of information in the AEC industry, developed "Industry Foundation Classes" or IFC as a standardized, digital description of the built environment and an open international standard-ISO 16739-1:2018 [50]- for exchanging information [51]. The most recent release (IFC 4.3) includes data definitions for infrastructure assets over their lifecycle, which is essential for developing integrated models. However, the full IFC schema is too exhaustive to be used for data exchange, and in this situation, Model View Definitions (MVDs) have been created to standardize data exchange for a particular use case [52]. This brings a considerable number of MVDs (about 20) applied by different software tools, causing a chaotic environment between MVDs and exchange information requirements and, eventually, confusion for end-users [52].

6.3 Bad data

An assessment of 3900 professionals across the construction industry found that "bad data"-defined as inaccurate, incomplete, inaccessible, inconsistent, or untimely and unable to be used to make actionable decisions-may have cost the global construction industry $1.85 trillion. However, companies with the appropriate strategy for behaving with the evolving amount of data in the AEC industry can benefit from improved performance. Furthermore, it is reported that more than half of data during the project lifecycle is "bad data", accounting for $88 million cost in reworks [53].

6.4 Data security

Privacy and data security have become prominent topics in today's digital world, and the AEC industry isn't an exception [54]. In addition to this, the decentralized nature of construction requires companies to exchange a great deal of data, such as supplier details and bid details, among themselves, which increases data security risks [55]. When these risks are put along with the current growth rate of data in the AEC industry, the significance of cybersecurity can be understood. However, the AEC industry lacks an industry-wide cybersecurity framework, like what is applied in the healthcare industry [56]. A UK government report indicates that 15% of construction firms have experienced cyber-attacks, which include 77,000 cases in the form of hacks and viruses [57]. For example, cyber-attacks targeted a construction company called "Turner" in 2015 and exposed all employee details, including name, address, social security number, and tax data [58].

6.5 Big data

The growing amount of data flow through the widespread use of emerging technologies resulted in an increasing interest in applications of big data in the AEC industry [18]. Leveraging enormous amounts of data in projects can enable the AEC industry to more effective resource management and better risk mitigation, which turn into better revenue [59]. However, Boyd and Crawford [60] stated some general concerns about applying big data. First, the outcomes of big data are highly dependent on the data quality. Second, small companies have limited access to large data, causing large companies to dominate the industry market. Third, there is a significant concern about ethical issues in data use. In addition to these, there are many technical issues that can impact big data advantages, including data redundancies, lack of expert staff, and investment and maintenance costs [61].

7. Empirical data

The first section of the survey included questions about the demographic and career information of participants. While the majority of participants were male (76%), the percentage of female participants (24%) was higher than the general percentage of female professionals in the construction industry (9%). Except for the age range of "under 26", the distribution of other age ranges (26-35, 36-45, 46-55, and 56+) was similar. In addition, the majority of participants (77%) reported "Construction" as their background, while the remainder included "Architecture," "Engineering," "Business," and "Others." Moreover, the highest percentage in the work experience was for the "25+ years" group, following the "5-15 years" one. Also, half of the participants reported Field/Tech Engineer as their titles. The percentages of each group are shown in Table1.

In the next section, the purview of participants' work was explored, as they were asked to specify the size of their companies (number of employees) as well as the number of projects they were working on at the same time. As shown in Figure 3, the highest percentage was for the "11-50 employees" group, followed by "51-200 employees" and "500+ employees" groups. In addition, the two highest groups for the number of projects were "6-10" and "2-50" projects, with 45% and 40%, shown in Figure 4.

The next section of the survey covered topics related to BIM and other technologies that companies might use. A BIM or VDC office that oversees and manages the digital workflow is one factor that impacts data flow in companies. The existence of a BIM/VDC/Emerging technologies was the subject of the first question in this section, for which 68% of participants reported that they did not have a separate office for managing their models and data flow. Participants were asked to specify who typically generated their BIM models in the next question. The possible groups included “BIM/VDC office,” “Pre-Con Group,” “Designer/Architect,” “Subcontractor,” and “It varies by case,” and the percentages reported were 16%, 8%, 26%, 18%, and 32%, respectively. In addition, the extent of use of BIM and emerging technologies such as VR and AR was the subject of the next questions. In both areas, the majority of responses indicated a very low level of use in companies, as shown in Figure 5.

Table 1. Demographic Information

Gender (%)	Female			Male	
	24			76	
Age – Years (%)	Under 26	26-35	36-45	46-55	56+
	5	23	23	25	24
Background (%)	Construction	Architecture	Business	Engineering	Other
	77	6	5	10	2
Experience - Years (%)	1-3	4-7	5-15	16-25	+25
	6	6	29	23	36
Position (%)	VDC Manager	VDC Specialist	Project Manager	Field Eng.	Business/IT
	10	5	27	50	8

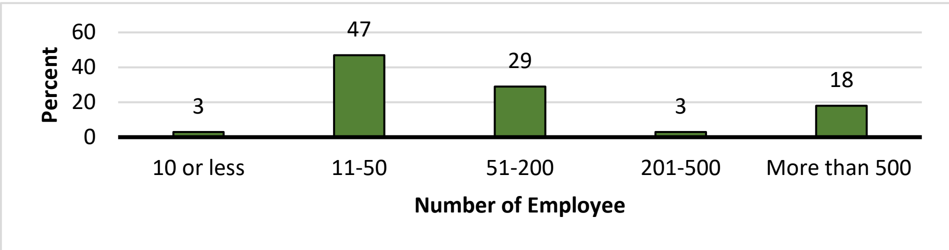

Fig. 3. Percentage of number of employees

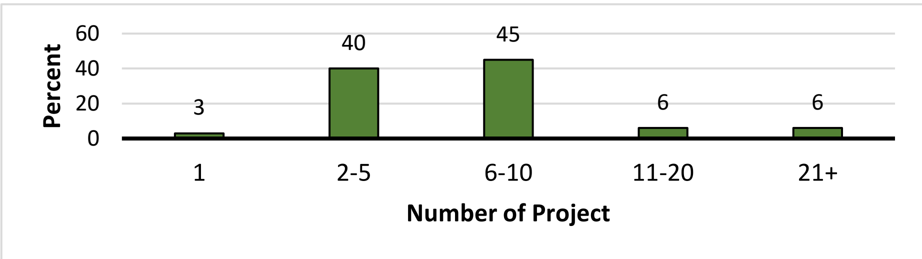

Fig. 4. Percentage of number of projects

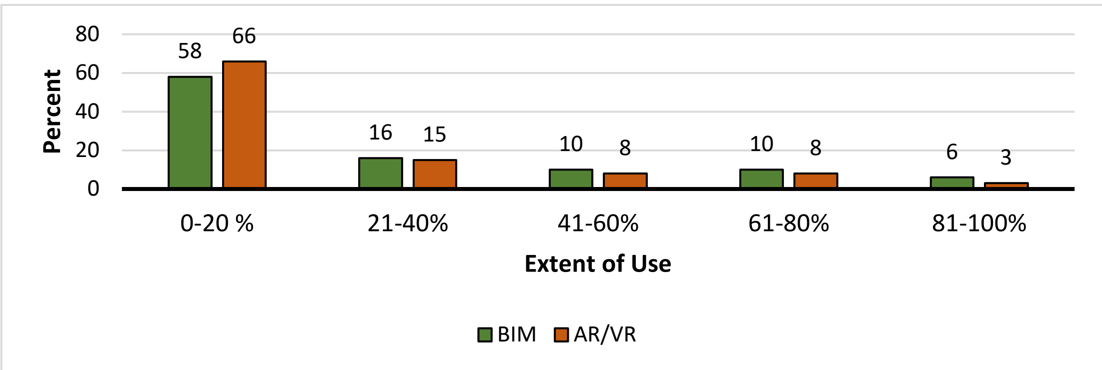

Fig. 5. Percentage of the extent of use of BIM and VR/AR

In addition, various applications of BIM were specified and provided in a matrix to be rated using a five-level Likert scale. Among the items, “Coordination between different trades” and “Clash detection” had the highest scores (2.68 and 2.48, respectively), and “Energy analysis” and “Integration with project cost) gained the lowest scores (1.48 and 1.56, respectively). However, there was no average score at or above the mid-point (3 out of %), as shown in Figure 6.

Also, the main driver of any investment in BIM or new technologies such as VR/AR or drones was provided in a list containing “Market analysis,” “Client need/request,” “Being a pioneer,” “Technology capability,” and “Higher efficiency.” Participants were asked to select one for their companies. The percentages of items were 0, 45, 6, 18, and 31, respectively, as shown in Figure 7. These numbers indicated the approach of companies in response to short-term impacts.

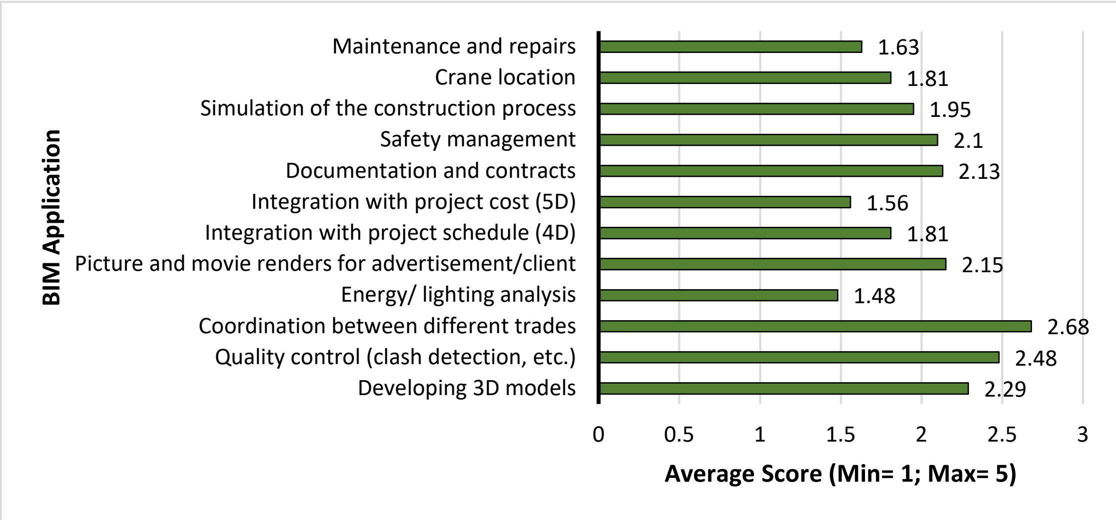

Fig. 6. Average score of BIM application

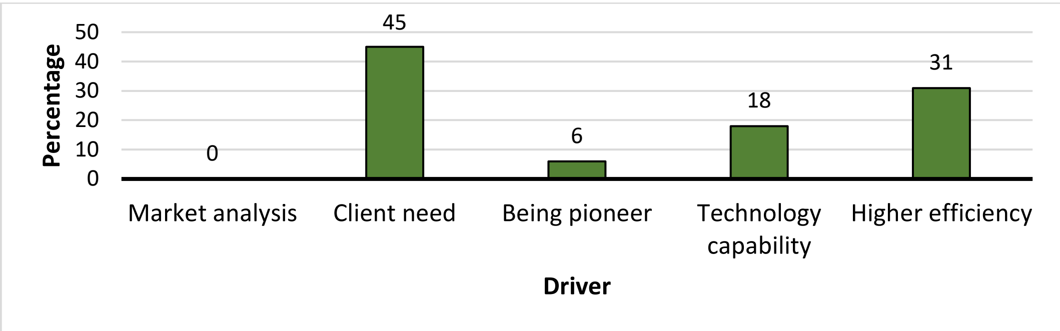

Fig. 7. Percentage of investment driver

Also, participants rated the extent to which they referred to archived information for a project when it was delivered. The percentage of each frequency item is shown in Figure 8.

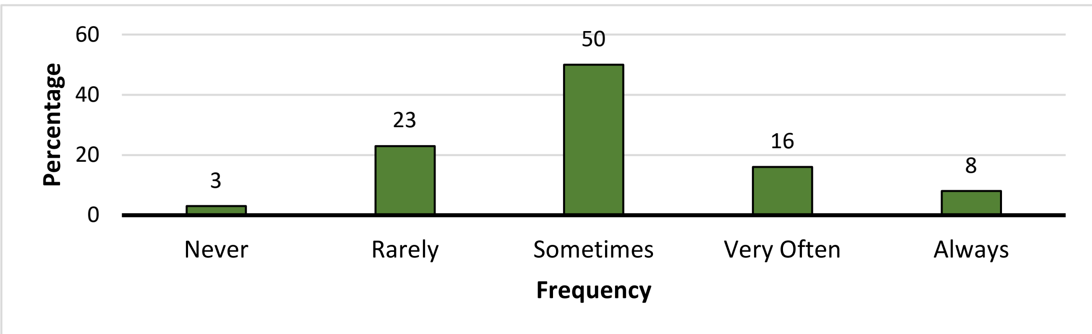

Fig. 8. Percentage of referral to archive information

8. Discussion

The data flow in construction entails a multitude of aspects that impact the outputs. While these aspects mainly emerge at the organizational tier, they are emanated from project activities. The necessities of construction execution, improvement in construction material and methods, and increasing advancements in applicable technologies generate more data in various stages of construction projects. The unprecedented data quantity, quality, type, and size growth has placed construction organizations' leaders and directors in a unique yet unsystematic position. Project managers and directors should plan the data generation, execute the data transmission, store it in standard formats, and retrieve it as necessary. As shown in the Literature Review and Empirical Analysis sections, the review of this process from the beginning to the end reveals various important strands, as discussed below:

Use of BIM/VDC: The prevalent use of rich 3D models, and especially BIM models, has assisted construction entities, including designers, engineers, sponsors, constructors, and vendors, in improving their work processes. These improvements comprise enriched models and plans, effective communication, organized construction, visualized building methods, and efficient management. However, not all construction companies use these features. Moreover, BIM/VDC potentials are not adequately exploited in construction companies. Aligned with sources used in the Literature Review section and as depicted in Figures 4 and 5, various applications of BIM/VDC are generally underutilized. An example of such underutilization is using a fully-loaded BIM model for 3D visualization. Changing design and construction models from 2D to 3D and then to nD BIM models exponentially increases the data generated. Throughout this data generation, training, integration, software and hardware, and storage impose new challenges and issues for construction companies.

Emerging technologies: Augmented reality, virtual reality, construction wearables, robots, drones, artificial intelligence and machine learning, modular construction, 3d printing, and blockchain are among the technologies appearing in construction companies and projects. These technologies are massively dependent on a high volume of data. The data generated throughout the application of each technology is partially used as inputs for the same system. However, the consistency of data structures and their secondary uses are of concern in construction data management. The avalanche of data generated in these systems demands ever-increasing quantity and quality of supporting devices and protocols to design, apply, simulate, monitor, store, and retrieve data. Therefore, finding a balance point to leverage the costs and gains is essential to effectively manage the data flow in construction companies.

Data integration: As discussed in the section 6, the integration of data created at different stages with various methods and tools is vital. Many applications and tools are currently devised to import data from the previous process stage of the precedent component, and thus when the output and input data are not consistent, the data integration becomes arduous or expensive. As a result, the data flow stops at the end process of the antecedents. This discontinuity leaves a high volume of data suspended after their initial use. These data blocks with different types, structures, and volumes are stockpiled with storage and maintenance expenses. This fact, on a broader scale, is displayed in Figure 7, where only 24% of participants in the survey reported a frequent referral to past information.

CapEx and OpEx: Information technology's capital and operating expenses remarkably depend on the data flow in construction projects. To generate data, construction systems, tools, methods, and protocols, including design-related systems, pre-construction systems, execution tools and methods, monitoring equipment, reporting methods, and maintenance systems, require a relatively large amount of investment in hardware and software. In addition, training costs, development teams, updating personnel and systems, and archival procedures accrue additional costs. When planning and developing a data system for a construction company, all these costs should be taken into account. With the consideration of all these cost areas, the cost benefit break-even point may require a more robust data management plan.

Unstructured Data: It is estimated that up to 90% of data is unstructured [62] and it is growing at 55-65 percent each year [63]. Unstructured data include text files, photos, video files, audio files, social media sites, presentations, and so forth. Construction companies have to gather, process, mine, integrate, store, track, index, and report professional insights from unstructured data. Without analysis tools, it would be impossible for the construction industry to manage the unstructured data that it generates efficiently. However, the common trend in construction companies does not indicate this approach. While generating unstructured data and its growth are inevitable, construction companies need to consider sustainable and balanced data generation and use.

Data size and abundance: Construction companies have experienced revolutionary changes in the past decades. From the time that a construction project plan could be sufficiently stored on a floppy disc until now that giant files are saved on clouds, companies have renovated or expanded their software and hardware systems. The exponential growth of technology has steered construction companies to acquire the latest version of each IT-related system. This temptation has resulted in considerable expenditures as recurring costs. The output of such pioneer systems, however, has been consistent with the company's legacy systems. In other words, data in larger size and quantity have been produced and used by some island sectors in companies, but other sectors or areas did not need or could not input the data. Another issue about large or abundant data is the lack of integrity or continuity between projects, as shown in Figure 7. The inconsistency between data types, software, and hardware has prevented all IT-related systems from operating at an optimum pace.

9. Conclusion

This paper reviewed the construction industry's data flow and its generation, application, storage, and maintenance process. The study's main goal was to explore different aspects of the data flow in construction companies. The study strived to shed light on various overlooked issues or pitfalls of data flow in the construction industry. Considering this research's scope and objectives, a review of data and software and hardware systems in construction was deemed required. A comprehensive literature review was performed to collect, analyze, evaluate, and summarize data and IT-related resources in the construction industry. As a revolutionary technology, BIM was explicitly examined, and its relevant issues and consequences were discussed. In addition, a survey collected empirical data from 62 eligible experts (e.g., VDC/BIM professionals and project managers) to compare the findings with professional insights. As a result, the data analysis showed the alignment between the discussions derived from the literature and expert judgment. The findings of this research emphasize a diligent design and implementation of data flow in construction companies. However, generalization of the results is not warranted. More subsection-focused literature reviews will assist in scrutinizing the data flow in more detail. Another limitation in this study was inconsistency in the data governance and data policy among construction companies which made finding data management best practices impossible. In addition, the categorization of the study based on construction sectors will reveal similarities and differences between various construction sectors. Further studies will include independent reviews of merging technology and their interactions with the data flow in construction.

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