Exploring the Digital Thread of Construction Projects

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Abstract –

The construction industry is one of the most information-intensive industries where the success of projects depends on information being accurate, complete, timely, readily available, and understandable by different recipients. As projects become complex and processes become more digitized, the value of capturing, tracking, accessing, and sharing lifecycle-spanning data becomes critical for project stakeholders. One way to capitalize on the value of data is through the concept of Digital Thread. The Digital Thread breaks down the silos of information and makes it accessible to the right stakeholder at the right time, promoting high-fidelity collaboration among stakeholders, enabling richer stakeholder-driven analysis, enhancing decision-making, and increasing transparency and information exchange. With the concept being relatively new in the construction industry, research on Digital Threads remains limited. Thus, this paper addresses the gap by exploring the concept and its pillars. The paper proposes a comprehensive definition of the Digital Thread of the construction project and explores the interconnectivity between people, processes, and data (three pillars) along the construction project Digital Thread. The paper also presents a case study to further investigate the interconnections between the three pillars and proposes a three-Dimensional Digital Thread Infrastructure using the construction phase of the Design Bid Build project in the Middle East. Future work will build on the findings of this paper to create an interface for the Digital Thread schema for the construction project and build a platform to provide all stakeholders with the means to achieve full project lifecycle traceability.

Keywords –

Digital Thread; People; Process; Social Network Analysis; Topology

1 Introduction

Projects in the construction industry require the involvement of a wide range of stakeholders throughout their lifecycle – from conceptual planning to decommissioning [1]. As such, project teams would therefore comprise multiple players employed by various organizations that conduct different businesses [2]. This makes projects both complex and dynamic, as completing project tasks would require information to be accurate, complete, timely, delivered promptly, and readily available in a clear format that can be understandable by different recipients [3,4].

Thus, the success of construction projects relies heavily on the management of the flow of data and information among key players as the project moves from one phase to another [5,6]. However, the multidisciplinary and fragmented nature of the construction industry creates a challenging environment for the seamless flow of data and information, and in return, hinders the successful implementation of the project [7]. This makes lifecycle-spanning data difficult to capture in the construction industry, and the value of such data usually remains unused [8].

1.1 Digital Transformation in Construction

Researchers have noted that the main reason for the inefficient exchange of data between stakeholders among projects is the absence of digitization of construction processes [8]. Advancements in technology driven by the fourth industrial revolution have led to numerous studies that focused on shifting the construction industry into the digital sphere [9,10]. Examples of such studies include investigating cyber-physical systems [11], enabling digital twins [12], exploiting artificial intelligence [13], adopting robotics [14], utilizing wireless and sensing technologies [15], and pushing cognitive and cloud computing across the project lifecycle [16]. Although construction companies are slow to adopt and adapt to digital change, such studies have paved the way for digitization in the construction industry, which in turn enables the digitalization of processes and moves the industry toward the eventual digital transformation and the digital twin of the project [17].

Digital transformation is essentially built on data [18]. While data is the 'engine' of digital transformation, the 'Digital Thread' is the 'amplifier' that capitalizes on the value of data and enables this transformation [19,20]. To develop and achieve the digital twin of the construction project, a digital thread must be established [31]. The concept of Digital Thread has been leveraged in different industrial sectors [21], but the concept remains relatively new to the construction industry [17].

1.2 The Digital Thread

The Digital Thread introduces a unique solution to solve the problems with the information jungle, inconsistency, and disintegration associated with the traditional, fragmented nature of the construction industry. The Digital Thread breaks down the silos of information and makes it accessible to the right stakeholder at the right time, promoting high-fidelity collaboration among stakeholders, enabling richer stakeholder-driven analysis, enhancing decision-making, and increasing transparency and information exchange [17,21,22].

1.3 Research Gap and Objective

Building on the awareness of the construction industry of the Digital Thread potential, this paper aims to enable informed dialog about Digital Thread in the construction industry by achieving two objectives: proposing a comprehensive definition of the Digital Thread of the construction project and exploring the interconnectivity between people, processes, and data along the construction project Digital Thread. The paper is part of an ongoing effort to create an interface for the Digital Thread schema for the construction project and build a platform to provide all stakeholders with the means to achieve full project lifecycle traceability.

2 Research Methodology

To achieve the desired objectives, the authors began by reviewing the existing definitions of Digital Thread and then proposed a comprehensive definition of the Digital Thread for the construction project. Following the definition, the three main pillars of the construction project Digital Thread were discussed: people, processes, and data.

Next, a case study is conducted to further investigate the interconnections between the three pillars of the Digital Thread (data, people, and processes). The case study solely focuses on the digital thread of the construction phase of Design-Bid-Build projects executed in the Middle East. Three interviews were conducted with three subject matter experts with an overage of 12 years in the industry to collect data on 1) the processes that constitute the construction phase, 2) the stakeholders involved in every process, and 3) the sources of data that stakeholders need in each process. The interview data is then organized and translated into a Digital Thread infrastructure and matrix to analyze the connections between the three Digital Thread pillars. A discussion section is then presented.

3 Digital Thread of the Construction Project

The Digital Thread concept emanated from the military aircraft industry as a game-changing opportunity to advance manufacturing and help the U.S. Air Force meet the need for more rapid development and deployment [23]. Digital Thread introduces the concept of digital linkage between materials, design, processing, and manufacturing to provide the agility and tailorability needed to support rapid development and deployment [23]. Following the emergence of Digital Thread in the *2013 Global Horizons: United States Air Force Global Science and Technology Vision report*, [24] referred later to Digital Thread at a National Institute of Standards and Technology (NIST) symposium as a “cross-domain, common digital surrogate of a material system that provides the analytical framework for organizing output from high-fidelity, physic-based model across the entire lifecycle.” A year later and during a National Defense Industrial Association (NDIA) Conference, [25] defined Digital Thread as “an extensible, configurable and Agency enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative data, information, knowledge, and computer software in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system’s life cycle by providing the capability to access, integrate and transform disparate data into actionable information”. [26] later put forth a refined definition stating that digital thread is “an extensible, configurable, and enterprise level framework that seamlessly expedites the controlled interplay of authoritative data, information, and knowledge to inform decisions during a system’s life cycle by providing the capability to access, integrate, and transform disparate data into actionable information”.

[27] then reviewed all existing Digital Thread definitions until the year 2015 and noticed that while the definitions vary, Digital Thread can be environed as the “single authoritative representation of a product”. Digital Thread becomes “the definitive repository of authoritative information containing everything about the system at that instant of time” which means that Digital Thread serves as the primary data and communication platform for an organization’s product at any time during the product lifecycle. [27] also noted that for Digital Thread to be the authoritative source of information, information has to be current and complete. [28] referred to Digital Thread as “the communication framework that

allows a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives [enabling the delivery] of the right information to the right place at the right time."

As interest in Digital Thread continued to grow among practitioners and academics, new definitions emerged. [29] provided a simple definition of the concept as "the flow of information about a product's performance and use from design to production, sale, use and disposal or recycling". [30] stated that Digital Thread is "a data-driven architecture that links together information generated from across the product lifecycle and is envisioned to be the primary or authoritative data and communication platform for a company's products at any instance of time". In a PTC article on *What is Digital Thread,* [31] noted that a Digital Thread creates a closed loop between the digital and physical worlds, documenting how products are engineered, manufactured, and serviced. This link between the phases enables simple, continuous universal access to data. Most recently, Digital Thread is defined by [32] as "a communication network that enables a connected flow of data as well as an integrated view of an asset's data across its lifetime through various isolated functional perspectives, thus promoting the transmission of the correct information, to the correct place, at the correct time."

It can be noted from the synthesis of the existing Digital Thread that manufacturing is often the industry of interest. One of the first applications of Digital Thread in the construction industry is attributed to the United Kingdom's Building Safety Bill requiring a digital "golden thread of information", which is both information about the facility to ensure its safe operation and the information management to ensure that the information is accurate, current, and accessible [33]. Beyond this application, the concept of Digital Thread remains a novice in the construction industry. Thus, there is a need to comprehensively define Digital Thread in the context of construction management.

3.1 Proposed Definition for the Digital Thread of a Construction Project

While the concept of Digital Thread is the same regardless of the industry, to understand how Digital Thread is relevant to an industry, the definition needs to be tailored to the application. Building off the existing definitions, the authors propose the following definition of the Digital Thread of a construction project: The Digital Thread is a data-driven architecture that links traditionally siloed *processes* into a connected flow of *data* that presents 1) a single authoritative source of current and complete data and 2) an integrated view of data gathered, used, and exchanged by the right *stakeholders* across the construction project lifecycle *phases* at the correct time.

3.2 Pillars of Construction Project Digital Thread

The proposed definition highlights three main pillars for the Digital Thread of the construction project: people, processes, and data. *People* represent the internal and external stakeholders involved in the realization of the construction project from conception to decommissioning. *Processes* are the various steps or functionalities that constitute the various phases of the construction project lifecycle.

These three main pillars can be represented by the fundamental *who*, *when*, and *how* questions asked at each project phase:

- *Who* is involved? (people)
- *When* is the party involved? (process)
- *How* does the data flow between the people and across the processes? (data)

Quality data is what prevents a broken Digital Thread, and thus, the third question on *how* is a complex, multi-dimensional question that embodies the management of the data lifecycle. Proper data management depends on the understanding of how data is produced, obtained, and used, and transparency regarding data sources and uses is critical [34].

4 Case Study

Creating the schema for the construction project Digital Thread depends on understanding and mapping out the relationships between the three main pillars: people, processes, and data. To further investigate the dynamics between the three pillars, a case study is conducted for the construction phase of Design-Bid-Build (DBB) projects in the Middle East.

Three subject matter experts (SMEs) in Middle East construction projects with a total of 45 years of experience working for contractors and performing project management consulting services were asked to perform three tasks: (1) identify the main processes in the construction phase of a DBB project, (2) identify the stakeholders who are involved in each of those processes, and (3) identify the sources of data that the stakeholders need to successfully complete each process. The case study was limited to collecting data sources and did not get into the detail of the different data formats used by stakeholders. Moreover, the use of data was limited to simply stating the sources of data for a particular process and indicating all involved stakeholders. Future work will detail the relationships between the data sources, data format, and data users.

Once the data was gathered, a three-dimensional Digital Thread Infrastructure was developed to map the three pillars of the Digital Thread: processes, stakeholders, and data source. The infrastructure and the interview data were then translated into a matrix which was later used to visualize a network topology of three pillars and perform social network analysis.

4.1 Three-Dimensional Digital Thread Infrastructure

The three pillars of the construction project Digital Thread were mapped in the three-dimensional Digital Thread Infrastructure which outlines the fundamental elements of the Digital Thread, as shown in Figure 1. The SMEs identified 21 processes in the pre and post-award phases of the construction phase; 39 stakeholders between contractors, engineers, subcontractors, employer(s), and other parties; and 37 sources of data.

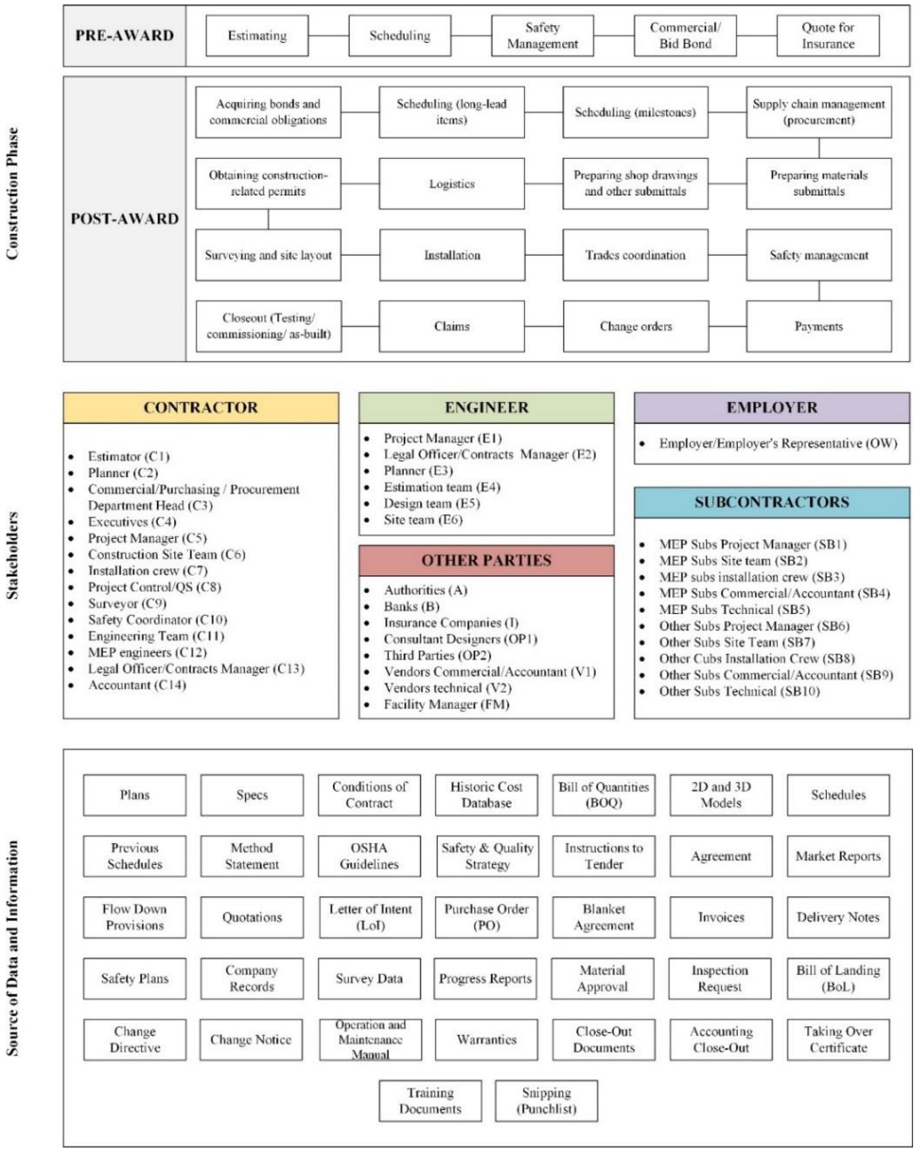

Figure 1. Case study fundamental elements of the digital thread.

4.2 Analysis Matrix

For every construction phase process, the SMEs were asked to select the stakeholders who are involved as well as the sources of data that the process requires. The selections were then transformed into a binary analysis matrix where the rows represented the processes and the columns represented the stakeholders and the sources of data. A value of "1" was given to selected stakeholders and sources of data, and a value of "0" was given to the stakeholders and sources of data that were not selected.

For example, for the "estimating" process, the SMEs selected eight sources of data and seven involved stakeholders. Thus, the columns representing the seven sources (plans; specs; conditions of the contract; historic cost database; BOQ; schedules; 2D and 3D models) and the 14 stakeholders (OW; E1; E4; E5; C1; C4; SB1; SB4; SB5; SB6; SB9; SB10; V1; V2) received a value of "1" while all remaining columns received a value of "0". The rest of the processes followed the same procedure.

4.3 Results and Analysis

4.3.1 Network Topology

The analysis of the three pillars begins by first exploring the relationships between stakeholders at a high level (i.e., main entities), construction processes (pre- and post-award), and data sources (i.e., what information stakeholders need to perform their tasks). A network topology (Figure 2) was constructed from the matrix to build connections between the high-level stakeholders, processes, and data sources. Results from the network topology show that:

- The engineer, contractor, and subcontractor are the high-level stakeholders that were most involved in the construction phase.
- The processes that require a high concentration of stakeholders' involvement include acquiring bonds and commercial obligations, payments, claims, and close-out.
- The processes that involve various data sources include scheduling milestones, supply chain management (procurement), installation, payments, change orders, claims, and closeout.
- The most utilized data sources are plans, specs, conditions of contract, and bill of quantities (BOQ). These data sources flow across various processes and are needed by the majority of the stakeholders.

4.3.2 Social Network Analysis

Additional analysis was performed to understand the relationships and dynamics of stakeholders at a detailed level. Based on the preliminary matrix, **E1** (E-Project Manager), **C5** (C-Project Manager), **SB6** (Other Subs Project Manager), **SB1** (MEP Subs Project Manager), and **V1** (Vendors Commercial/Accountant) had the highest number of functions that they were involved in. To further understand the information sharing among stakeholders and collaboration, social network analysis (SNA) was performed on the matrix. The SNA networks consist of two elements: nodes represented by circles and edges represented by straight lines. Nodes can vary in size depending on the SNA

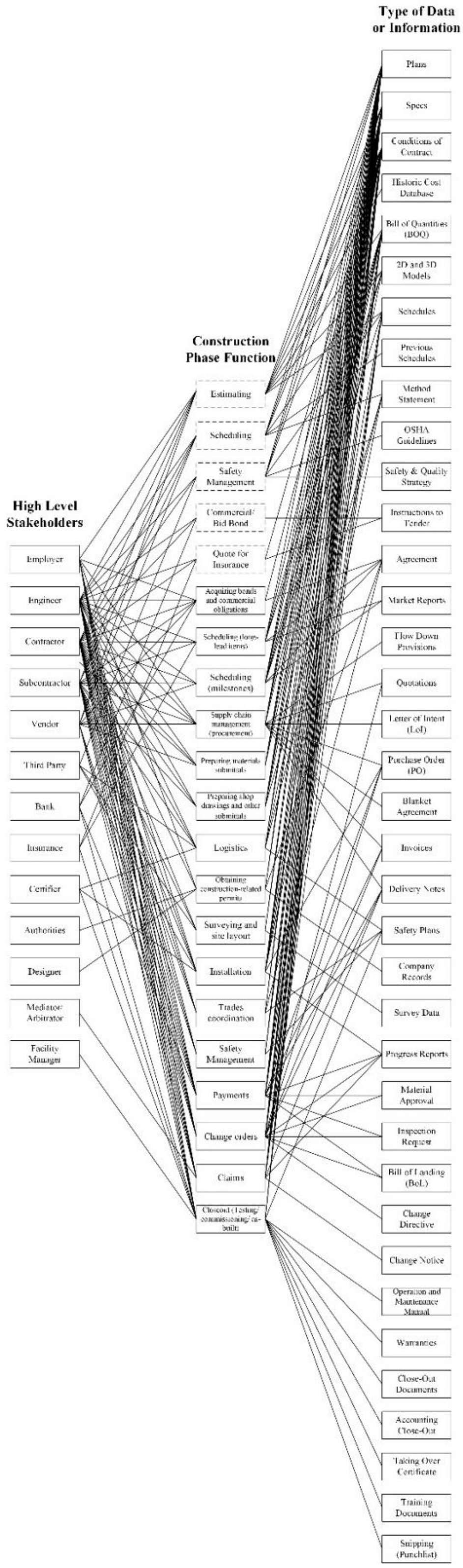

Figure 2. Network topology for the case study.

metrics used, while edges can vary in thickness based on the weight of the connection between two nodes. In this paper, two SNA metrics were used: 1) Degree Centrality (DC) – a normalized metric that represents the number of edges that one node possesses and the extent to which the node dominates the network [35], and 2) Closeness Centrality (CC) – a normalized metric that represents the extent to which a node is close to other nodes and the extent to which the close nodes are studied together [36].

In this research, the nodes represent the stakeholders who are involved in the construction phase, while the edges represent the construction phase processes. The size of the node varies by degree centrality – i.e., the bigger the node, the more processes the stakeholder has collaborated on with other stakeholders. The thickness of the edges represents the number of processes that the two nodes that the edge connects have collaborated on – i.e., the thicker the edge, the more collaboration and data exchange is needed between the two stakeholders.

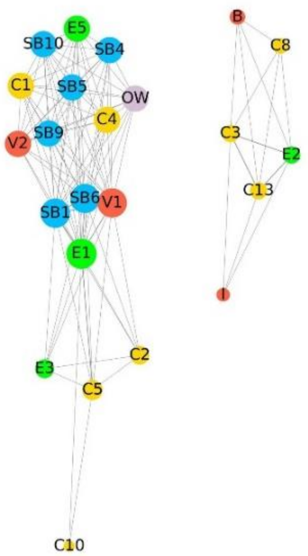

Figure 3. Pre-award network.

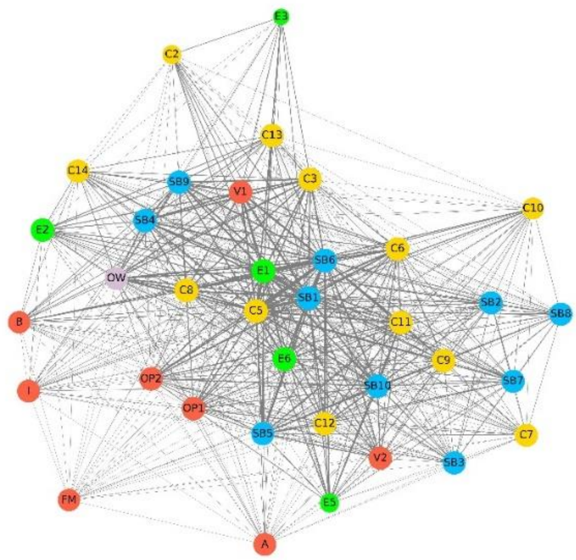

Figure 4. Post-award network.

Two social networks were created: one for the pre-award (Figure 3) and one for the post-award (Figure 4). It can be observed in Figure 3 that the pre-award network is *disconnected* because the nodes are portioned into two subsets: one subset includes parties that engage in administrative processes at the organizational/ institutional level (i.e., bank, insurance, legal office, etc.) and the second subset includes parties that get involved in the day-to-day processes at the project-level. A *disconnected* network indicates that there are two communication channels between some stakeholders. On the other hand, the post-award network is *connected* because there is a path between every pair of nodes in the graphs indicating that all involved stakeholders are connected and data flow from any stakeholder to any and/or every other stakeholder through the pairwise communication channels.

Based on the calculated centralities (both degree as well as closeness), the analysis of the pre-award shows that **E1** (E-Project Manager) is the most dominant stakeholder indicating that the Project Manager of the Engineering firm is a key player in the three project-level processes during pre-award. **E1** was followed by **SB1** (MEP Subs Project Manager), **SB6** (Other Subs Project Manager), and **V1** (Vendors Commercial/Accountant). It could be surprising that none of the contractor's internal stakeholders were highlighted in the centrality analysis, and this is justifiable because, at this phase of the project, the contractor has not selected their project manager.

The analysis of the post-award network shows that **E1** (E-Project Manager), **C5** (C-Project Manager), **C8** (C-Project Control/QS), **SB1** (MEP Subs Project Manager), and **SB6** (Other Subs Project Manager) are the most dominant stakeholders. Compared to pre-award, the contractor becomes a major player post-award and is represented by the Project Manager and Project Control/Quantity surveyor (QS).

4.4 Discussion

The results of the analysis of the pre and post-award highlight that there are key players that flow from one phase to another (such as E1, SB1, and SB6), there are major players that join the project at a later stage (such as C5 and C8), and there are supporting stakeholders whose role, although not dominant, is vital for supporting the various processes. Understanding who is involved, when they are involved, and what sources of data they need is fundamental for advancing the application of Digital Thread in the industry.

As presented in the proposed definition, Digital Thread enabled the right person to access the right data, at the right time. The Digital Thread is thus a data problem and understanding how data flows between stakeholders and across processes throughout the construction project lifecycle is key to achieving Digital Thread-enabled decisions on the project.

The connections between these three pillars are often taken for granted in the construction industry. However, developing an efficient architecture for the Digital Thread of the construction project depends on a thorough analysis of the dynamics between people, processes, and data. Understanding what data is exchanged, between who, and when is essential for organizations to build the Digital Twin of the project using correct and accurate data. Having a well-established Digital Thread that holistically considers the entire construction project lifecycle and ecosystem is fundamental for the digital transformation of the industry. The data encompassed in the Digital Thread is important for all stakeholders and supports short- and long-term decisions and could lead to better project predictability and performance, greater collaboration and transparency between stakeholders, and more standardization of the industry.

The explicit discussion of the relationships between the stakeholders is also valuable to technology providers and provides them with the necessary information to develop integrative solutions that are congruent with the Digital Thread. Additionally, delineating the answers to each of the above-mentioned questions (who, when, and how) build the infrastructure needed to support AI-driven solutions. Moreover, the results could be used as an educational tool to train less experienced stakeholders about their role in the project, the stakeholders that they will engage with, and the sources of data that they will need.

The approach presented in this paper lays the foundation for this premise and for developing a Digital Thread schema for the construction project. By providing a generic model of who can be involved in the project, what processes they will engage in, and what sources of data they will need, supply chain traceability becomes a reality.

5 Conclusions

This paper provides the construction industry with a comprehensive definition of the Digital Thread of the construction project and explores the interconnectivity between people, processes, and data – the three pillars of the Digital Thread. A case study is performed to investigate the connections between the three pillars during the construction phase of the DBB project in the Middle East. Network topology and SNA were employed to explore interconnections between people, processes, and data by presenting and analyzing a three-Dimensional Digital Thread Infrastructure.

This study does come with limitations. The interviews did not delve into the data formats used by stakeholders for the different data sources, the relationships highlighted in the networks are unidirectional, and the analysis was limited to the construction phase of a DBB project. Further studies will tackle the limitations by accounting for the flow of data to indicate the sender and recipient, analyzing the remaining phases of the project, and comparing networks across different project delivery systems. Future work will also leverage the findings of this paper to create an interface for the Digital Thread schema for the construction project and build a platform to provide all stakeholders with the means to achieve full project lifecycle traceability.

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