www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

DEVELOPING DIGITAL TWINS FOR BRIDGE INFRASTRUCTURE: ROADMAP AND CHALLENGES FROM A PROOF-OF-CONCEPT R&D STUDY

SUBMITTED: December 2025
PUBLISHED: August 2026
EDITOR: Robert Amor
DOI: 10.36680/j.itcon.2026.039

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SUMMARY: *The exploration of Digital Twins (DT) technology in the Architecture, Engineering, Construction, and Operation (AECO) industry has gained momentum in recent years, with numerous studies proposing frameworks for its development. However, few real-world infrastructure applications have been systematically documented to guide future practitioners and researchers. This study addresses this gap by providing an empirical example of DT design and development through a proof-of-concept research and development (R&D) project. The I-90 Homer M. Hadley Bridge (I-90 Bridge) DT project, led by the University of Washington (UW) DT research team, was selected as a case study to demonstrate the application of DT technology for bridge health monitoring. Using a vignette-style narrative approach, the study integrates data from semi-structured interviews with project team members and project documentation generated during the project to illustrate how the system was conceptualized, developed, and delivered. The findings reveal that interoperability emerged as a consistent theme throughout the project, including technical challenges (legacy systems, proprietary programming, lack of standardization) and organizational challenges (multi-stakeholder engagement, organizational silos). Recognizing these challenges can help practitioners and researchers better identify key problems to address, thereby supporting a successful adoption of DT technologies.*

KEYWORDS: *Digital Twins, Bridge Infrastructure, Organizational Interoperability, Technical Interoperability, Research & Development, Case Study.*

REFERENCE: *Borjigin, O., Sturts Dossick, C., Treece, B., Thonstad, T., Bernard, T., & Motley, M. (2026). Developing digital twins for bridge infrastructure: Roadmap and challenges from a proof-of-concept R&D study. Journal of Information Technology in Construction (ITcon), 31, 917-938. https://doi.org/10.36680/j.itcon.2026.039*

1. INTRODUCTION

Ensuring the safety and performance of bridge infrastructure is a persistent challenge, especially as much of the U.S. inventory nears or exceeds its original design life. In Washington State, for example, the average age of state-owned vehicular bridges is fifty-one (Washington State Department of Transportation, 2024), and the monitoring systems introduced at that time now struggle to keep pace with modern demands (Jeong et al., 2017). Although these legacy systems continue to provide valuable information to infrastructure owners, they often fall short in addressing today's operational requirements (Ogunwole et al., 2023), such as capturing high-frequency data, detecting subtle changes in structural behavior, and integrating with advanced asset management platforms. In this context, the accuracy, frequency, and reliability of monitoring data are no longer mere technical preferences but essential factors that can directly influence operational and maintenance decisions.

Recent advances in enabling technologies, including Internet of Things (IoT) sensors, cloud computing, wireless networking, and real-time analytics, offer opportunities to rethink how bridges are monitored and managed. Together, these technologies provide the foundation for more advanced, integrated, and smart infrastructure management solutions, where interconnected data, automation, and analytics enable more informed decision-making, optimized maintenance, and improved infrastructure performance. Among these, digital twins (DT) have recently gained attention in the architecture, engineering, construction, and operation (AECO) industry. Originally popularized in aerospace and manufacturing, DT is increasingly being explored as a means to transform infrastructure monitoring and decision-making (Agrawal et al., 2022). Costin et al. (2024) argue that by mirroring the success of DT applications in other industries, transportation agencies may be able to achieve smarter, more efficient, and more predictive bridge management systems.

However, the definition of a digital twin remains contested in the AECO industry (Sacks et al., 2020). Whereas aerospace and manufacturing have converged on relatively consistent understandings, the construction sector continues to debate its essential characteristics. Some scholars describe a DT simply as a virtual representation of a physical asset with data communication between them, while others highlight the integration of data, models, and analytics to support lifecycle decision-making. Building on these perspectives, the National Institute of Building Science (NIBS), drawing from the work of Ghorbani & Messner (2024), adopted the following definition as part of its effort toward industry standardization: *"a fit-for-purpose and intelligent virtual representation of [an asset] synchronized at specific frequencies, with an existing or planned connection between the virtual and physical twin that may include analysis and the ability to actuate physical changes from the virtual twin" (p.210).*

Much of the existing research on DT has focused on conceptual frameworks and prototype or pilot-scale implementations, leaving a gap in understanding how these systems are designed and developed under real-world conditions. To address this gap, this paper examines the development of a digital twin system for the I-90 Homer M. Hadley Bridge as a proof-of-concept research and development (R&D) project. Drawing on prior work on interoperability challenges in DT systems (Borjigin et al., 2025), this study analyzes how technical and organizational interoperability challenges emerged throughout the design and development process, and how these challenges shaped development decisions and system configurations. Based on these insights, the paper develops a roadmap to inform the design and implementation of DT systems in complex infrastructure contexts.

The main research questions this paper addresses are: How can DT systems for critical infrastructure be designed and developed within a proof-of-concept R&D project, and what technical and organizational interoperability challenges emerge from the research team's perspective? By addressing these questions, this paper provides empirical insights into how DT systems can be realized in practice, offering valuable lessons for the industry on building and sustaining such systems in complex infrastructure environments. In addition, this project experience offers insights into how large-scale R&D initiatives can be organized and executed, helping future teams navigate similar efforts more effectively.

To investigate this process, we adopted a case study methodology, well-suited to examining complex, real-world phenomena in depth. Data for this study were drawn from project documentation (e.g., proposal documents, meeting minutes), direct involvement in the project, and interviews with research team members, providing a comprehensive account of the project. zs

The remainder of this paper is structured as follows. **Section 2** reviews the literature on interoperability challenges arising from team collaboration and the development and implementation of digital technologies. **Section 3** outlines the methodology adopted in this study, and **Section 4** presents the case study, articulated through a vignette approach. **Section 5** discusses the findings, focusing on interoperability challenges that hinder the deployment of digital twin systems in critical infrastructure. Finally, **Section 6** concludes the paper by outlining the study's limitations and suggesting directions for future research.

2. LITERATURE REVIEW

In this section, we review prior studies on the implementation of digital tools and organizational collaboration to understand the conditions that shape technology development. The review highlights two interrelated themes, organizational interoperability and technical interoperability, that form the analytical foundation of this study. These themes guide the structure of the findings and discussion, illustrating how both organizational coordination and technical integration are essential to realizing a functional DT system.

2.1 Organizational interoperability

With the growing demand for productivity and efficiency, specialization has become a defining feature of modern industries (Taylor, 1911; Turk, 2020). Professionals are trained to excel in specific areas, delegating other responsibilities to those with different expertise. While this specialization has undoubtedly advanced technical proficiency and operational performance, it has also contributed to fragmentation across organizations and disciplines (Fellows & Liu, 2012). This condition is particularly evident in the AECO industry, which has been characterized as a loosely coupled system composed of multiple independent actors with limited integration (Dubois & Gadde, 2002). Within such a structure, different professional groups have developed their own terminologies, work practices, and priorities, often optimizing within their domains rather than pursuing shared project goals (Dossick & Neff, 2010; Hansen, 2014).

In complex projects such as infrastructure management and digital transformation, this fragmented structure has been widely recognized as a barrier to collaboration and coordination (Fellows & Liu, 2012). Prior research on BIM and digital innovation further underscores that effective implementation requires alignment among multiple stakeholders, including owners, operators, designers, contractors, and technology vendors (Succar, 2009). These multi-stakeholder environments introduce challenges in aligning responsibilities, workflows, and expectations, particularly when digital systems demand tighter integration across organizational boundaries (Boje et al., 2020). The concept of organizational interoperability directly addresses this need. According to the European Union's Interoperability Framework (2017, p. 30), organizational interoperability is defined as *"the alignment of business processes, responsibilities, and expectations toward common goals, including the establishment of inter-organizational relationships between service providers and service users."* In this paper, we adopt a narrower interpretation of this concept, focusing on interoperability as it occurs through data governance and goal alignment.

One manifestation of these coordination challenges is the persistence of organizational silos, particularly between Operational Technology (OT) and Information Technology (IT) teams. This divide has been increasingly discussed in digital infrastructure and construction contexts, where the integration of physical systems with data-driven platforms depends on organizational alignment across technical domains with differing roles, expertise, and priorities. Traditionally, OT and IT groups have operated separately, with OT focusing on maintaining and optimizing physical infrastructure such as sensors and control systems, and IT prioritizing data management, cybersecurity, and information systems. Despite their complementary functions, their differing priorities—operational reliability versus data security—often lead to misalignment during digital system development. Studies (Dossick et al., 2023; Osburn et al., 2023) show that IT departments are frequently brought into projects only after major decisions have been made by OT teams, resulting in delayed coordination, unresolved cybersecurity concerns, and fragmented governance structures. This pattern reflects broader knowledge and boundary challenges identified in organizational theory, where differences in expertise and interpretive frameworks hinder effective collaboration across groups. The IT and OT divide thus exemplifies how organizational silos persist even within a single institution, underscoring the need for early, cross-functional collaboration and shared governance in digital transformation efforts.

Interoperability challenges also extend beyond intra-organizational boundaries to collaboration across organizations. In the transportation sector, collaboration is a common challenge as identified by Meyer et al. (2005). Agencies such as state Departments of Transportation (DOTs) and local transit authorities often have distinct priorities, project delivery processes, and information systems shaped by their regulatory environments or funding structures. Although collaboration between these agencies is essential—particularly for projects that span state highways or shared assets—their differences create barriers, and additional coordination efforts are often required. As a result, even routine tasks such as planning maintenance activities become complicated and time-consuming. These misalignments make it difficult to build a reliable, long-lasting collaboration mechanism among agencies.

2.2 Technical interoperability

Unlike other digital tools commonly used in construction, such as BIM, DT systems are integrations of multiple technologies rather than standalone applications. This is where the concept of technical interoperability becomes increasingly important. It can be defined as *"the ability of two systems to understand each other and use the functionality of the other, which represents the capacity to exchange data and share information and knowledge"* (Duarte-Vidal et al., 2021, p. 2).

Tuhaise et al. (2023) provided a holistic review outlining the key technological layers necessary for achieving interoperability in DT systems, including data acquisition, data transmission, digital modeling, data and model integration, data processing and analysis, and the service layer. Each layer contains multiple technologies and standards, which, while offering flexibility, also introduce complexity in integration. For example, the IoT serves as a core enabling technology within the data acquisition layer. However, as Sinche et al. (2020) identified, at least seven IoT management protocols and four IoT management frameworks currently exist, each with distinct structures, requirements, and compatibilities.

In addition to technological diversity, variations in programming languages across systems introduce another layer of complexity in achieving interoperability. Research shows that programming languages evolve rapidly, with some becoming outdated yet still embedded in existing systems (Orlowska et al., 2021; Yaofei Chen et al., 2005). This diversity is further amplified by the fact that different vendors often develop their products using distinct programming environments and proprietary languages, which limits cross-platform compatibility. Unless devices are plug-and-play, with vendors' predefined functions requiring only high-level configuration, developers must navigate multiple coding environments.

As articulated by several researchers (Ghorbani & Messner, 2024; Singh et al., 2021), DT functions as a System of Systems (SoS)—a collection of interdependent subsystems, each capable of operating independently yet contributing to a larger integrated framework. In the I-90 Bridge DT project (Borjigin et al., 2025), multiple standalone systems were implemented, including the GPS module, weather station, and strain gauge network. Each subsystem captured a specific aspect of the bridge's performance, and when combined, they produced a more comprehensive understanding of the bridge's condition. Through this integration, the individual systems collectively formed a higher-level SoS that enabled holistic monitoring and analysis of the bridge.

However, not all systems were newly developed. In many infrastructure projects, legacy systems continue to provide essential operational value. Integrating these existing systems into newer digital frameworks presents a persistent challenge (Irani et al., 2023). Their limited flexibility and reliance on outdated architectures often require extensive customization, interface development, and data translation to ensure compatibility. These adaptations require substantial technical effort and can inadvertently introduce cybersecurity vulnerabilities (Osburn et al., 2023), as each additional connection point increases the system's exposure to risk.

2.3 Research gap

Although organizational and technical interoperability have been widely examined in applied settings, few studies have explored these issues within the context of DT implementation. In particular, limited attention has been given to how interoperability challenges emerge, evolve, and are managed in real-world DT projects. These challenges are especially important in critical infrastructure projects, where multiple organizations, legacy systems, and evolving technologies must operate together. This study addresses this gap by providing an empirical example drawn from a real-world R&D project, offering insights into how interoperability is negotiated across organizational and technical boundaries.

3. RESEARCH DESIGN AND METHODOLOGY

This section outlines the research methodology adopted to develop and present the roadmap. It begins by examining the suitability of the case study approach for investigating complex, real-world phenomena. This is followed by a detailed description of the data collection and analysis procedures, including the specific techniques and tools employed throughout the study. Figure 1 provides an overview of the research design used in this study.

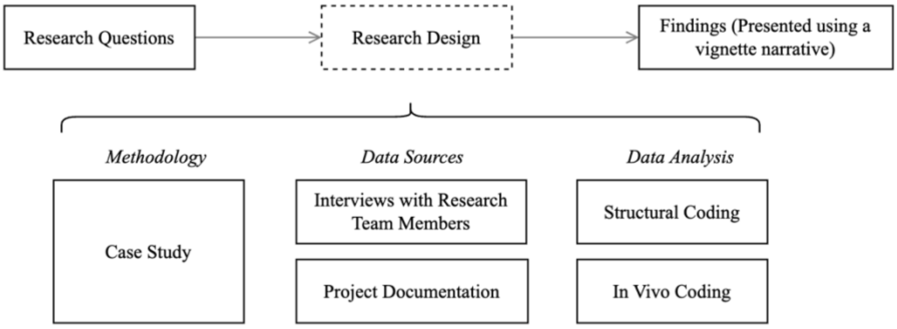

Figure 1: Research design.

3.1 Case study methodology

The selection of a research methodology is largely determined by the nature of the research questions being addressed. In this study, our objective was to understand *what happened during the development of a DT system* and *how the research team approached each step*. These "what" and "how" questions call for a methodology that captures the details of events, processes, and interactions, while allowing the researcher to move beyond surface-level description to uncover deeper contextual meanings. For this reason, a qualitative methodology was considered most appropriate, with case study research offering the strongest alignment with the study's aims.

A case study can be broadly defined as an empirical inquiry that investigates a contemporary phenomenon within its real-world context, particularly when the boundaries between the phenomenon and the context are not clearly evident (Yin, 2018). Case study research acknowledges that social and technological processes are complex, context-dependent, and often intertwined with organizational, cultural, and environmental factors. By embedding the phenomenon under investigation within its real setting, case study research enables what Geertz (1973) refers to as "thick description," a rich and nuanced account of the case that captures both its uniqueness and its broader significance.

This makes the case study approach especially suitable for exploring new technology development in real-world infrastructure settings. Unlike quantitative approaches such as experiments or surveys, which typically aim to control variables or eliminate external influences, case studies preserve the complexity of the environment in which the phenomenon occurs. In doing so, they allow researchers to analyze the interplay between technical, organizational, and contextual factors that shape the development and implementation of innovations.

3.2 Data collection

To capture the process in as much detail as possible, data were collected using multiple methods, including interviews with research team members and records of project meetings. The following section describes the procedures used for each method and explains how these data sources were integrated to provide a comprehensive account of the case.

3.2.1 Research team interviews

Interviews, as widely recognized in qualitative research, are a common and effective data collection method. They are particularly well-suited for intensive case studies that focus on a small number of individuals. Interviews allow researchers to access aspects of experience that cannot be directly observed, such as feelings, perceptions, and thought processes. In this sense, an interview can be understood as a purposeful conversation designed to elicit specific information essential to addressing research questions (Merriam & Tisdell, 2016).

In this study, interviews were conducted with members of the research team who were directly involved in the design, development, and coordination of the DT project. This selection aligns with the study's research question, which examines how DT systems are developed under real-world conditions within an academic R&D context.

The research team plays a central role in this process, engaging with multiple institutions and agencies throughout the project's lifecycle. Their perspectives provided valuable insights into how decisions were made, challenges were addressed, and solutions were adapted in practice, offering a unique understanding of the interoperability issues encountered during implementation.

When designing interview questions, several considerations need to be taken into account. One important dimension is the structure. Interviews can be conducted in a structured, semi-structured, or unstructured format, each suitable for different research purposes. A structured interview is essentially an oral version of a written survey, often used to collect demographic or factual information. An unstructured interview, by contrast, has no predetermined questions and is most appropriate when researchers have little prior knowledge of the topic under investigation. A semi-structured interview combines the advantages of both formats: it follows a guiding framework while allowing the flexibility to probe, identify emerging themes, and ask follow-up questions. However, this approach requires strong research skills in recognizing and pursuing phenomena as they arise. For this study, the semi-structured format was chosen.

The questions were organized into four parts, each focusing on a different dimension of the participants' perspectives. The first part gathered background information and self-introductions, allowing interviewees to situate their roles within the project context. The second part focused on project storytelling, inviting participants to narrate their experiences and describe their specific contributions. The third part encouraged reflection and evaluation, prompting interviewees to discuss the challenges they encountered as well as the critical factors that contributed to the project's success. Finally, the fourth part served as a wrap-up, offering interviewees the opportunity to raise questions, share additional insights, or address aspects not covered by the interviewer, thereby ensuring a more complete account of the project. The full list of interview questions is provided in Appendix A.

In conducting the interviews, we also made use of digital tools such as Zoom, iPad, Apple Pencil, and Freeform application. Although all interviews were conducted in person, Zoom was used to record the sessions and capture the process of interviewees' note-taking. The iPad and Freeform application were used to facilitate brainstorming, as several questions required participants to visualize or sketch their responses. This approach not only helped interviewees organize their thoughts more systematically but also enabled them to articulate their answers more clearly. In total, four semi-structured interviews were conducted by R4 (reference Table 2) with the rest of the research team (R1, R2, R3, and R5), each lasting approximately one hour.

A pilot interview was conducted to validate the interview questions and the use of digital tools, and no major issues were identified.

3.2.2 Project documents

One of the strengths of adopting a case study approach is its flexibility in incorporating multiple data collection methods (Yin, 2018). In addition to interviews with each research team member, we also compiled project documents, including two proposal documents and twenty-four meeting minutes, to construct a more complete view of the project. Document analysis provided another lens through which to understand the project's development. However, because these documents were originally created for purposes other than research (Merriam & Tisdell, 2016), we treated them cautiously. They may reflect the perspectives or biases of the individuals who produced them. In this study, we used project documents primarily to supplement the narratives articulated through interviews and to triangulate the overall account of the project. When ambiguities arose regarding specific events in the project's development, we cross-referenced them from the corresponding time period to validate and clarify the sequence of events. In cases where interviews did not capture events, these documents served as supplementary sources to fill those gaps.

Additionally, as a member of the research team and the interview facilitator, R4 wrote a self-reflection of the project prior to the pilot interview. This interview followed the same structure as the interview questions, allowing them to articulate initial perspectives while minimizing the influence of participants' responses on how those perspectives were framed.

This reflexive account allowed R4 to incorporate their own perspectives and experiences into the dataset while also acknowledging the researcher's positionality. The reflection was subsequently included in the final analysis to enrich interpretation and provide transparency regarding the researcher's role in the study.

3.3 Triangulation and validity

Given the inherent characteristics of qualitative methodology and the data collection methods adopted in this study, minimizing bias while preserving a comprehensive account of the phenomenon was an important consideration. To address this, we employed methodological triangulation by drawing on multiple data sources, including interview data and project documents. The flexibility of the semi-structured interview format also allowed us to ask participants to reflect on perspectives raised by others, thereby cross-validating key themes. For example, when one interviewee highlighted cybersecurity as a main consideration in the project, this point was later corroborated in other conversations.

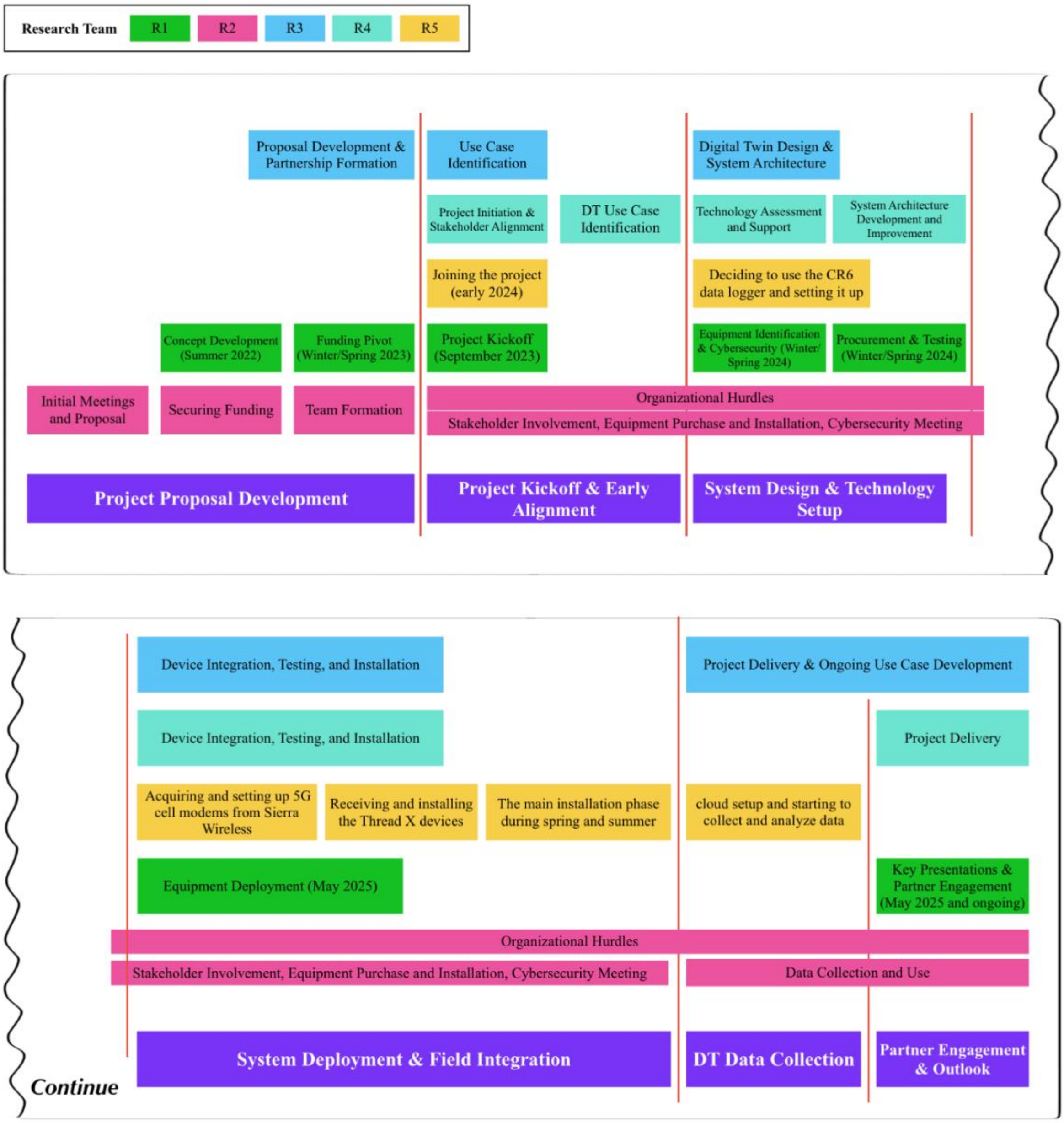

Figure 2: Individual project milestones and the consolidated timeline.

3.4 Data analysis

A distinctive feature of qualitative research, compared to quantitative approaches, is the timing of data analysis. Rather than postponing analysis until all data have been collected, it is often recommended that researchers begin the analytic process as soon as the first data set is available. This early engagement allows for iterative refinement, such as identifying emerging themes and incorporating these insights into subsequent interviews (Merriam & Tisdell, 2016).

The analysis we present in this paper began immediately after the first pilot interview. The interview was transcribed, and responses were coded using a structural coding approach. This method is well-suited for organizing data from multiple participants and semi-structured data collection protocols, as it enables the categorization of the data to examine commonalities, differences, and relationships across comparable segments (Saldaña, 2025, p. 146). For instance, we compiled the answers to the question *"If you were to tell the story of this project, what major milestones or turning points would you highlight?"* into a table, with each participant's name used as a column heading. This approach facilitated comparison across participants and supported the creation of a holistic set of milestones by referencing multiple perspectives. Figure 2 is a visualization of the project milestones by integrating inputs from each team member. The same method was applied to other questions.

The analysis of project documents began after all interviews had been completed, specifically following the analysis of the milestone question described above. This process allowed us to organize the documents chronologically, which, in turn, helped us identify causal relationships and outcomes more clearly.

Once the data were structured, in vivo coding was applied to responses associated with interview question 6, which focused on challenges experienced during the project development process. In vivo coding uses participants' own words or short phrases directly drawn from the qualitative data, preserving the language and meanings they express (Saldaña, 2025, p. 154). This approach keeps the analysis grounded in participants' lived experiences. For example, one interviewee described the difficulty of integrating the data logger system with cloud services, noting that "*it was not designed to do so*," and that it "*took several weeks to figure out how to actually get it to work successfully*." Phrases such as "not designed to do so" were coded directly to represent challenges related to system incompatibility and interoperability limitations. The codes were then analyzed and grouped into broader code categories and code themes, as shown in Figure 3. For example, the code "not designed to do so" described above was grouped into the code category "system and service integration," which was subsequently classified under the broader code theme of technical interoperability challenges. A corresponding code theme, organizational interoperability challenges, was also identified through the coding process. Table 1 **Error! Reference source not found.**summarizes the analytical structure developed through the coding process, presenting the relationships between the identified code categories and overarching code themes. Because in vivo coding generated a large number of first-cycle codes, only the higher-order code categories and code themes are presented here for clarity.

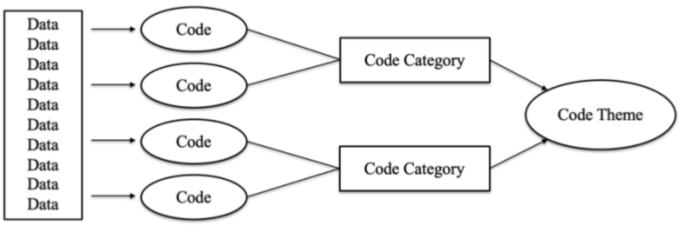

Figure 3: Coding Process (adapted from Saldaña, 2025).

Table 1: Code Themes and Code Categories.

Code Theme	Code Category
Organizational Interoperability	Multi-stakeholder Engagement
	Organizational Silos
Technical Interoperability	System and Service Integration
	Lack of Standardization
	Legacy Equipment

3.5 Presentation of findings

To present the findings of this case study, we adopted a vignette-style narrative approach. Instead of organizing the findings as isolated themes, we describe the implementation process chronologically around major project milestones. This allows readers to understand how the identified challenges emerge throughout the project. The narrative is guided by the themes identified through the coding process, while the code categories are used to organize the discussion section.

A vignette-style narrative is a well-established approach in qualitative research for representing contextually grounded accounts of social processes (Agostini et al., 2024). It provides detailed, temporally structured portrayals of events, allowing readers to follow the unfolding of actions and interactions in their natural context (Erickson, 1985). Beyond this descriptive representation, this approach is distinguished by its ability to convey interpretive dimensions of the phenomenon. Its validity is grounded not only in accuracy but also in its capacity to evoke a response in the reader and prompt reflection on practice (Geelan, 2006). In other words, the vignette-style narrative allows readers to engage with and make sense of the phenomenon more intuitively.

Table 2: Research team introduction.

Pseudonym	Role	Background	Expertise
R1	Primary Investigator (PI)	Background in journalism and public sector communications; former Washington State Department of Transportation (WSDOT) communications manager with experience in stakeholder engagement and emergency response. Currently Director of the Mobility Innovation Center at the UW, leading applied research projects on technology and innovation in transportation.	Emerging technologies in transportation, project management, communication
R2	PI	PhD in Civil Engineering from UW with experience in large-scale experimental testing of bridges and infrastructure systems. Former researcher at NIST focused on metrology and aging infrastructure. Work includes instrumentation, distributed sensing, and applying digital twin technologies with IoT and 5G.	Bridge structural health analysis, experimental testing, instrumentation and sensing, aging infrastructure
R3	Co-PI; Senior Faculty	Degree in Civil Engineering and PhD focused on 3D models and digital databases in the process and power sector. Research expertise includes BIM, implementation of emerging technologies in the building sector, and more recently, cybersecurity in the built environment, IoT, and digital twins.	BIM, cybersecurity, DT
R4	Student Researcher	PhD candidate in Building and Construction Science, with a focus on organizational change management in the construction and cybersecurity culture research.	Construction organizational change management, cybersecurity culture, DT
R5	Student Researcher	Background in civil engineering with a specialization in structural engineering; holds both bachelor's and master's degrees in civil engineering; experienced primarily in building projects, with bridges as a more recent area of focus.	Structural health analysis

Furthermore, adopting this approach positions the study between conventional and more experimental forms of qualitative writing. While conventional approaches often emphasize standardized and distanced reporting, and highly experimental writing may become overly subjective, the vignette provides a balanced approach that integrates both structure and reflexivity (Langer, 2016). In this study, writing is not treated as a final step to summarize findings, but as part of the interpretive process through which meaning is constructed. This allows the researcher to incorporate their involvement and perspective in a transparent and controlled manner. As a result, the vignette-style narrative helps make it visible how interpretations develop through storytelling while maintaining a clear focus on the research object.

In this style of writing, capturing the setting by asking questions such as who is present, where and when the event takes place, what is happening, and how it unfolds is important (Agostini et al., 2024). These guiding questions help situate the reader in the context, enabling them to understand the scene as experienced by the researcher. In presenting the vignettes, the analytical focus can be positioned either at the beginning or the end of each episode, depending on how the narrative is structured. In this study, the focus is introduced at the beginning. These focuses serve as a storyline that connects the events across episodes while maintaining a clear analytical direction for the reader.

4. I-90 HOMER M. HADLEY BRIDGE DIGITAL TWIN PROJECT

In this section, the case study is presented by first introducing the project team and the stakeholders involved. The narrative is then developed using a storytelling approach to trace the project's evolution from its inception to the present.

4.1 Research team

Currently, the project focuses primarily on the development of DT systems. Accordingly, only the core team members directly involved in this phase are introduced here. The team consists of five individuals with diverse backgrounds and interests, representing different entities within the university. Table 2 summarizes the above information.

Each team member played a distinct role and contributed their expertise to the study. The absence of any one of them would have made the successful completion of this project difficult. R1's extensive experience in communication was vital for maintaining relationships with numerous stakeholders from diverse organizations, each with its own unique expectations. R2's expertise in structural engineering enabled them to translate user needs and expectations into engineering problems that could be systematically addressed. R3's expertise in cybersecurity and digital twin systems helped the team develop a stronger understanding of DT concepts and address cybersecurity issues during the early phase of the project. Finally, R4 and R5, as student researchers, were responsible for implementing project goals and addressing emerging technical challenges.

Table 3: Stakeholders and partnerships.

Stakeholder	Bridge Role or Contribution (*)
WSDOT	The owner of the bridge
Sound Transit	Own the light rail on the bridge
Microsoft	Azure IoT*
Bentley Systems	iTwin Platform*
WSP USA	Bridge Modeling Support*
T Mobile	5G Network*
SEMTECH	Router*
COMPASS IoT	Traffic Data Support*

4.2 Stakeholders and partnerships

A distinctive feature of this project lies in its complexity, both in terms of the number of stakeholders involved and the nature of their relationships. To achieve the "thick description" discussed earlier, it is important to identify who the stakeholders are, what roles they play, and how their relationships shape the project. For the purposes of this study, the stakeholders can be categorized into two broad groups: those with a direct interest in the bridge and those with an interest in in integrating their products into the DT system. The first group includes organizations with direct responsibility for, or use of, the bridge, such as WSDOT and Sound Transit. The second group consists primarily of industry partners who contributed in-kind support to the project, providing products or technologies for validation within the university research context and in support of the bridge's infrastructure. Table 3 provides a brief overview of the stakeholders involved in the study.

WSDOT, as a government agency, encompasses many divisions and departments. In this study, two groups within WSDOT were especially important: the research office and the bridge office. The research office provided essential information and resources to advance the project, while the bridge office contributed technical knowledge about the bridge's condition and parameters.

In the first phase of the study, WSDOT was the primary public agency involved, supporting both technical and organizational aspects of the project. Sound Transit, while not directly engaged during this early stage, has more recently expressed interest in the study. As the operator of the light rail system that runs across the bridge, Sound Transit remains an important stakeholder, particularly for future phases of the project.

4.3 Project development

This section adopts a vignette-style approach, organizing project events around key milestones and timelines identified by participants. Their responses were compiled and arranged chronologically to illustrate the project's evolution over time, with the key themes summarized in Table 4.

The case examines how the UW team and our partners developed and implemented the I-90 Bridge DT system under real-world conditions, where challenges of technical interoperability and organizational interoperability were closely intertwined. Each phase demonstrates how different forms of alignment, across systems, institutions, and professional domains, were continuously negotiated to make the DT system operational. The following subsections present these phases and the key decisions that shaped the project's development.

Table 4: Project milestones and key themes.

Milestones	Focus of the Phase	Key Topics	Challenges	Types of Interoperability
Project Proposal Development	Initiating collaboration and defining purpose	Early project idea development; industry/agency collaboration; funding application	Securing funding and establishing cross-agency partnerships	Organizational
Project Kickoff & Early Alignment	Establishing structure and defining shared value	Team recruitment; early use case exploration	Bridging organizational silos between IT and OT teams; addressing emerging cybersecurity concerns	Organizational
System Design & Technology Setup	Designing the technical architecture and integration plan	System design and configuration	Integrating legacy systems and managing complexity from proprietary data standards	Technical
System Deployment & Field Integration	Moving from design to operational testing	Layout planning; installation; ST involvement	Late involvement of ST revealed communication gaps and organizational silos	Organizational
DT Data Collection	Managing real-time data flow and system performance	Data collection; cybersecurity concerns	Emerging cybersecurity concerns (data security level)	Technical
Partner Engagement & Outlook	Reflecting on lessons and sustaining collaboration	Sound Transit commitments; next phase	Sustaining partner commitment	Organizational

4.3.1 Project proposal development

The project began in the summer of 2022 with an initial idea of applying DT technology to transportation infrastructure, specifically bridges. At this early stage, the concept remained exploratory, and the team focused on identifying possibilities and building a shared vision. As R1 noted, "someplace starts the idea," emphasizing that the project was still taking shape.

During this period, R1 played a central role in advancing the idea. Drawing on their background, they began cultivating relationships with both academic and industry partners. They engaged colleagues, including R2, and reached out to organizations such as Microsoft, Bentley Systems, and T-Mobile to explore potential collaborations. At the same time, they initiated conversations with WSDOT and Sound Transit, recognizing that agency involvement would be essential for ensuring the project's real-world applicability and long-term impact. These early interactions required aligning different organizational priorities and expectations, highlighting the complexity of cross-agency collaboration from the beginning.

As these relationships developed, attention turned to securing resources. R1 and R2 worked closely to navigate the funding landscape, preparing and submitting proposals to programs such as the State Transportation Innovation Council (STIC) and the Innovative Bridge Technologies/Accelerated Bridge Construction-University Transportation Center (IBT/ABC-UTC). Securing funding proved to be a major challenge, as it required not only technical justification but also coordination across multiple stakeholders. While not all applications were successful, these efforts helped establish the project's foundation and clarified its direction.

Through these early activities, the project gradually moved from an abstract idea toward a more structured initiative. The combination of stakeholder engagement and funding efforts shaped the trajectory of the project, while also revealing the level of coordination required to move forward. R1's leadership, particularly their ability to connect partners and sustain momentum through funding uncertainties, played an important role in transforming the initial concept into a viable research effort.

4.3.2 Project kickoff & early alignment

After securing letters of support from industry partners and forming the core research team, which included R1, R2, and R3, the project held its first kickoff meeting in September 2023. Conducted virtually on Microsoft Teams, the meeting brought together representatives from all partnering organizations to confirm their commitments and contributions in terms of devices, software, and services. The discussion marked a shift from developing the concept to coordinating the work, as participants began to define roles, responsibilities, and expectations. In doing so, the meeting established an initial structure for collaboration and aligned diverse organizations around a shared project purpose.

Prior to the kickoff, R1 invited R3 to join the team, leveraging their expertise in BIM and cybersecurity within the built environment. Their Ph.D. student, R4, also became involved, aligning the project with ongoing doctoral research. As R1 recalled, "bringing R3 on board was definitely the right move," while also acknowledging the challenge of integrating new partners with different priorities and workloads. The expansion of the team reflected a deliberate effort to build both technical and organizational capacity, but it also required additional coordination given differences in roles and availability among team members.

Following the kickoff, the team established a rhythm of monthly stakeholder meetings and weekly internal meetings to track progress and define next steps. Early discussions focused on identifying DT use cases. At this stage, however, these use cases were largely conceptualized within the research team, without direct stakeholder input. As a result, the team lacked a clear understanding of how end users would apply or benefit from the system. R2 recalled that the initial use case was "very abstract and narrow," primarily focused on monitoring anchor cables of the floating bridge. R1 connected this to a broader objective, noting, "We do this to help the state transportation agency better manage bridge infrastructure in a smarter way." These exchanges highlighted the limitation of defining use cases solely within the research team, without direct input from end users. Without grounding in operational needs, early use case identification remained abstract and risked misalignment with how the system would be applied in practice.

To address this gap, the team interviewed bridge stakeholders to better understand operational contexts and user needs. R3 proposed the approach, and Their team led the effort, while R1 leveraged their connections to coordinate access. Participants included the Traffic Management Center (TMC), the Bridge Structures/Geotechnical Team, and the Maintenance Team, each contributing a distinct perspective on bridge operations. Through these interviews, the team was able to refine and contextualize use cases, grounding them in actual workflows and decision-making needs.

At the same time, the interviews revealed deeper organizational challenges. Differences between IT-oriented approaches, such as IoT-based data integration, and existing operational practices rooted in OT systems became increasingly visible. While some stakeholders expressed interest in the digital twin concept, others highlighted constraints tied to current systems. As one participant noted, “We do not use Internet of Things; we only use Supervisory Control and Data Acquisition (SCADA) systems, which operate through an internal network.” This distinction pointed not only to differences in technical infrastructure but also to concerns related to data security and system control. These emerging cybersecurity considerations, along with the need to bridge IT and OT perspectives, became central challenges shaping the project’s early alignment phase.

4.3.3 System design & technology setup

In early 2024, the project entered the system design phase, where previously identified use cases needed to be translated into a feasible technical architecture. The team identified several potential applications, including bridge alignment and anchor cable monitoring. At this stage, R2 focused on determining the sensors and equipment required to support these use cases. Given the nature of the monitoring tasks, the system was structured into two components: one for event-triggered monitoring, which required high-frequency data capture to detect rapid changes, and another for long-term monitoring, which operated at predefined intervals and was less sensitive to short-term fluctuations.

As the design progressed, resource constraints began to shape technical decisions. After reviewing supplier quotes against the available budget, the team realized that not all required equipment could be procured. To address this limitation, R2 adapted sensors previously developed in their lab, including an older dynamic vibrating wire analyzer. While not originally intended for this application, it provided a practical workaround. As R2 explained, “new systems are expensive, and the upfront costs are significant, so having legacy equipment from the lab that we could use for the study definitely saved money; it was really serendipity for us.” These decisions reflected the need to balance ideal system design with available resources.

At the same time, attention turned to integrating components from different sources into a unified system. R5 was recruited to assist with understanding the technologies provided by project partners, while R4 also contributed to this phase. But much of the implementation work was carried out by R2 and R5. A key task was integrating legacy systems with a modern IoT hub, which quickly revealed technical interoperability challenges. The legacy system relied on a proprietary programming language with limited documentation, making it difficult to extract and utilize the necessary data. In addition, differences in communication protocols prevented direct integration with the IoT infrastructure. To address these issues, R5 developed workarounds and custom solutions to bridge the gap between systems. These efforts highlighted not only the complexity of integrating old and new technologies but also the broader lack of standardization in the IoT ecosystem.

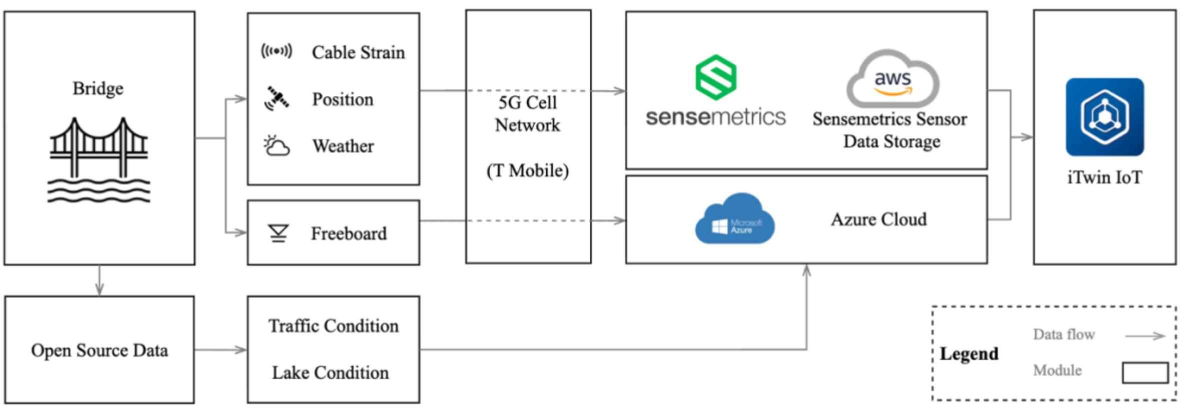

Figure 4: I-90 DT project system architecture.

With continued effort from the team and support from the eScience Institute at the UW, the system architecture was gradually developed and implemented (Figure 4). The resulting design illustrates how products and services from multiple technology providers were integrated to support the project's goals. While functional, the architecture was not optimal. It reflected the reality of working with heterogeneous systems, including reliance on bundled services and the absence of standardized data communication protocols. As a result, multiple cloud storage solutions were required to support different functions, such as data transfer and storage.

These design choices also introduced new considerations. Each additional interface between systems increased the complexity of the architecture and raised cybersecurity concerns, as more connection points created greater exposure to potential vulnerabilities. Thus, technical design decisions were closely tied to emerging security considerations, further shaping the system development process.

Additionally, the extended project timeline and reliance on multiple external partners introduced further coordination challenges. Communication with company representatives was often inconsistent, as points of contact changed more frequently than expected. In some cases, representatives transitioned to new roles or responsibilities, limiting their availability to support the project. When replacements were assigned, additional time was required to onboard them and re-establish shared understanding. In other situations, positions remained unfilled, delaying progress. In one case, a partner organization was unable to provide the support it had initially committed to, requiring the team to identify alternative solutions and resulting in several months of delay. These coordination issues further complicated the integration process and underscored the interdependence between technical development and organizational support.

4.3.4 System deployment & field integration

After multiple rounds of lab testing and troubleshooting, the team reached a point where the system was ready for field deployment. However, several questions remained unresolved, particularly regarding the placement of sensors and the routing of cables on the bridge. Given the scale and complexity of the I-90 bridge, with its numerous pontoons and anchor cables, full coverage was not feasible. As a result, the team needed to prioritize locations that would provide the greatest value for both monitoring and research purposes. To inform these decisions, the team worked closely with bridge engineers, holding a series of discussions to evaluate feasible installation points. Through this process, two locations were selected: the midpoint pontoon and the first pontoon on the east side. The midpoint pontoon was chosen because it experiences the most lateral movement, which could influence bridge operations, while the east-side pontoon represents the first point of contact with the light rail system, offering an opportunity to observe interactions between the pontoon and rail operations.

In late May 2025, R2 and R5, assisted by a bridge engineer, transported the equipment and cables onto the bridge and began installation. The work initially proceeded as planned until WSDOT's liaison to Sound Transit became aware of the activity and raised concerns about potential risks to the rail system. This prompted a request for further clarification and broader coordination. In response, the project team organized a briefing with Sound Transit's East Link team to explain the technical scope, installation plan, and expected system behavior. During these discussions, it became clear that Sound Transit's concerns were closely tied to their cathodic protection system, which is designed to prevent electrical current from accelerating corrosion in anchor cables. The introduction of new instrumentation raised questions about potential interference. To address this, R1 provided a detailed explanation of the system and clarified that the sensors and equipment would not disrupt existing operations.

This interaction revealed a coordination gap between the organizations. Although the team had previously engaged with Sound Transit, more than a year had passed, and the personnel involved had changed. As a result, prior alignment did not fully carry over, and the team needed to re-establish shared understanding. At the same time, Sound Transit expressed renewed interest in the project and a willingness to become more actively involved. While the additional coordination did not delay installation, it introduced new uncertainties that required the team to adapt their approach. This included clarifying the purpose of the instrumentation, evaluating potential impacts on existing systems, and adjusting communication to address stakeholder concerns. Through this process, the team strengthened collaboration and improved mutual understanding across organizations. The installation was ultimately completed in early August, marking the transition from system setup to operational testing.

4.3.5 DT data collection

Following installation, the system began to generate its first real-time data streams from the bridge. This marked a critical milestone that the team had been anticipating for over a year. The arrival of live data shifted the project from system setup to operational use, allowing both researchers and stakeholders to observe how the system performed under actual bridge conditions. The bridge engineers, in particular, responded with strong interest, as even data from two pontoons demonstrated immediate practical value.

The availability of real data also changed how stakeholders engaged with the project. During discussions, Sound Transit began to explore how such data could be integrated into its daily bridge monitoring practices. As R3 noted, "people don't usually see the value of a technology until they see the results it produces." This proved true in this case. While the project had faced funding and timeline constraints, the ability to capture data during light rail operations created new opportunities for engagement. As R1 emphasized, this phase helped re-engage Sound Transit more directly and positioned them as an active participant in the next stage of development.

With tangible system outputs now available, the team revisited use case exploration. Presenting stakeholders with actual bridge data enabled more concrete and informed discussions about potential applications. Rather than relying on abstract scenarios, stakeholders could now relate system capabilities to their existing workflows, strengthening alignment around how the digital twin could support both WSDOT and Sound Transit.

At the same time, the transition to real-time data introduced new technical challenges, particularly related to cybersecurity. A central question emerged: what data, if any, should be classified as confidential under Protected Critical Infrastructure Information (PCII) under the regulations? To address this, WSDOT's bridge engineering team convened an in-person meeting at the bridge maintenance office, bringing together the UW research group, WSDOT IT personnel, and representatives from the Department of Homeland Security (DHS).

The discussion was intensive, lasting more than two hours, and reflected differing perspectives on data security and risk. While the group ultimately agreed that the bridge data itself did not qualify as PCII, WSDOT decided to reference PCII guidelines as a precaution. Concerns raised by DHS focused on the potential for data manipulation, where altered values could lead engineers to make incorrect decisions. These discussions highlighted that, beyond system functionality, ensuring data integrity and security became a central consideration in managing real-time data flows.

4.3.6 Partner engagement & outlook

The project concluded with a complete DT system and several use cases identified for end users. Partner companies were satisfied to see their products and services integrated into the infrastructure system in support of academic research. The research team was encouraged by Sound Transit's renewed involvement, recognizing that their continued contributions will be critical to the project's expansion and pursuit of new goals.

5. DISCUSSIONS

This discussion is organized by the code themes and categories, as presented in **Error! Reference source not found.Error! Reference source not found.**: organizational interoperability and technical interoperability. These themes represent the core areas where the project team encountered real-world barriers and learned practical lessons during system development and deployment.

5.1 Organizational interoperability

Implementing a DT system in a real-world infrastructure context requires engaging diverse stakeholders operating across organizational boundaries. This section focuses on the human and organizational dimensions of the project, examining how people, institutional structures, and coordination processes collectively influenced the development and deployment of the system.

5.1.1 Multi-stakeholder engagement

The case study illustrates the complexity of coordinating a large network of stakeholders across academia, government, and industry in DT development. The project involved collaboration among WSDOT, the bridge owner, Sound Transit, the light rail operator, and several industry partners, each with distinct priorities and operational constraints. While this diversity was essential for project development, it also introduced persistent coordination challenges that required ongoing negotiation and communication.

Early engagement, led by R1, played a critical role in aligning stakeholders around a shared vision. Drawing on their background in public-sector communication and transportation innovation, they facilitated connections between research objectives and agency priorities, helping secure letters of support and initial resources during the project's formative stage. However, evidence from interviews and project interactions suggests that sustaining this alignment became increasingly difficult over time. Differences in institutional priorities, combined with frequent changes in organizational points of contact, led to recurring misalignment and uncertainty. For instance, when one industry partner revisited its earlier commitment to provide sensors, the research team was required to renegotiate expectations and adjust its implementation plan. Similarly, during system installation, Sound Transit's bridge team requested additional clarification to ensure compatibility with existing infrastructure and safety protocols. Although this did not delay installation, it introduced new coordination demands and required the team to remain flexible and responsive.

This observation reinforces prior research on the challenges of coordinating multiple stakeholders in construction and infrastructure projects, where fragmentation, disciplinary boundaries, and loosely coupled organizational structures complicate collaboration and alignment among actors (Boje et al., 2020; Dossick & Neff, 2010; Fellows & Liu, 2012; Succar, 2009). However, this study extends the existing literature by showing that stakeholder engagement is not only about achieving initial alignment but also about maintaining continuity in participation over time. In this case, shifts in personnel, evolving institutional priorities, and changing commitments disrupted alignment and required repeated renegotiation, suggesting that instability in stakeholder involvement is an important but underexplored dimension of coordination.

This further indicates that sustaining stakeholder engagement in infrastructure DT projects is not a one-time alignment effort but an ongoing process of managing evolving expectations and organizational dynamics. Continuous communication, iterative alignment, and sensitivity to changing contexts emerged as critical factors. In this case, proactive strategies, including early involvement of key personnel and regular stakeholder meetings, helped maintain progress despite uncertainties.

Overall, the case indicates that successful multi-stakeholder engagement depends not only on the presence of multiple actors but also on the quality and continuity of relational management among them. Leadership focused on communication, the establishment of shared goals, and the ability to adapt to shifting institutional conditions appears to be a key enabler for advancing DT initiatives in complex, real-world settings.

5.1.2 Organizational silos

Organizational silos emerged as a key barrier to coordination both within individual institutions and across organizational boundaries.

Within WSDOT, siloed communication between departments, particularly between IT and OT, shaped how digital technology adoption was perceived and implemented. Early project activities were primarily conducted with the bridge office, without direct involvement from the IT office. As reflected in interviews and project interactions, this limited early consultation later led to concerns related to system integration and cybersecurity. Some engineers expressed hesitation toward adopting internet-based data transmission, viewing it as misaligned with established operational practices. From their perspective, internal intranet systems were considered more secure, while internet connectivity introduced additional risks and uncertainties. These observations point to a broader organizational pattern in which digital initiatives are often led by OT teams, with IT engagement occurring only in later stages. This pattern is consistent with prior research highlighting the separation between IT and operational domains and the challenges this creates for integrating digital technologies in infrastructure systems (Dossick et al., 2023; Osburn et al., 2023). The findings further suggest that earlier involvement of IT stakeholders can help proactively address compatibility and security concerns, while also building organizational confidence in adopting new technologies.

Across organizations, siloed structures also influenced collaboration between WSDOT and Sound Transit, the two primary public stakeholders. Although they share ownership and operational responsibilities, their awareness of and engagement with the project evolved differently. During early system design and site visits, the research team observed that both agencies maintained separate systems for monitoring and managing the bridge, with limited integration or information exchange. This separation reflects institutional boundaries that shape how information is managed and shared, consistent with prior studies that describe the construction industry as a loosely coupled system with limited integration across actors (Fellows & Liu, 2012). Sound Transit was not actively involved during the initial Digital Twin design phase and became directly engaged only during field deployment, when its engineering team raised concerns about potential interference between newly installed sensors and their existing systems. While this did not delay installation, it revealed how limited early communication had allowed misunderstandings to accumulate over time.

These findings suggest that organizational silos, both inter- and intra-institutional, are not merely structural conditions but actively shape how technologies are interpreted, adopted, and integrated. In this case, silos contributed to delayed alignment, increased uncertainty, and additional coordination efforts. More importantly, this study extends existing literature by showing that the effects of silos are not limited to communication barriers but also influence the timing and sequencing of stakeholder involvement, which in turn shapes interoperability outcomes. Late engagement of key actors, particularly IT stakeholders and external agencies, introduced additional integration challenges and required reactive coordination. Overcoming these barriers requires deliberate strategies, including early cross-functional engagement between IT and OT, integrated communication channels across organizations, and sustained collaboration throughout the project lifecycle.

5.2 Technical interoperability

Technology integration presented another major challenge in developing a functional DT system capable of serving end-users. This section examines the key technical issues encountered during the project, focusing on three interrelated dimensions: system integration, protocol standardization, and adaptation of legacy equipment.

5.2.1 System and service integration

In the current market, a wide range of DT enabling technologies is available, offering users the flexibility to design systems tailored to their specific needs. This diversity is beneficial in principle, as it supports customization across different contexts. However, the project revealed that the practical use of these technologies is often constrained by their proprietary nature. Many commercial products must be bundled with their own associated services or cloud platforms, such as Sensemetrics, which manages sensor data through Amazon Web Services (AWS). While these integrated ecosystems offer streamlined functionality within their own environments, they limit interoperability and reduce opportunities for seamless integration with other systems.

This observation supports existing research on technical interoperability, which highlights the complexity of integrating heterogeneous systems composed of multiple technologies, platforms, and standards (Duarte-Vidal et al., 2021; Tuhaise et al., 2023). This study further extends the existing literature by showing that, beyond technical diversity, vendor-specific ecosystems introduce an additional layer of constraints that shape integration decisions in practice. In this case, interoperability challenges were not only the result of differing protocols or programming environments, but also of dependencies embedded in proprietary platforms that limited system design flexibility.

Even when technical solutions exist to overcome these restrictions, they often come at the expense of system performance or security. In our design, for example, two separate cloud storage platforms were required to accommodate different vendor specifications. From a cybersecurity standpoint, this configuration increased the system's exposure to potential vulnerabilities. These constraints not only increased system complexity but also reinforced reliance on vendor-specific ecosystems, requiring significant effort from the research team to bridge and synchronize data across multiple platforms.

5.2.2 Lack of standardization

The interoperability challenge was further exacerbated by the lack of standardization within the IoT domain. Existing IoT devices and platforms operate using a variety of programming languages and connection protocols. In this project, the team encountered this fragmentation directly. Integrating sensors, gateways, and cloud services from multiple vendors required extensive experimentation and the development of custom interfaces.

These findings align with prior research that highlights the diversity of IoT protocols and frameworks as a key challenge for achieving interoperability (Tuhaise et al., 2023). However, this study extends the existing literature by showing that the absence of standardization shifts the integration burden to project teams, increasing reliance on external expertise and iterative problem-solving. In this case, the team frequently depended on vendor support and specialists to configure and troubleshoot system connections.

This suggests that interoperability challenges are not only technical but also knowledge-dependent. As a result, system integration becomes a process of trial and error rather than straightforward configuration, increasing implementation time and uncertainty in real-world DT projects.

5.2.3 Legacy equipment

Interoperability challenges were also evident in the integration of legacy equipment into the DT system. In this project, older sensing and data acquisition devices were intentionally reused to reduce costs and leverage existing resources. However, integrating these systems into the new DT environment proved difficult due to differences in architecture, programming environments, and communication protocols.

These findings align with prior research that highlights the challenges of integrating legacy systems into modern digital infrastructures (Irani et al., 2023), where outdated architectures often require extensive customization and interface development. However, this study extends the existing literature by showing that legacy systems are not merely technical constraints but also active components that shape system design decisions. In this case, the use of legacy equipment required the team to adapt to the system architecture and develop workarounds, thereby influencing the DT system's complexity and configuration.

This suggests that interoperability in infrastructure contexts must be understood across both technological and temporal dimensions, where older and newer systems coexist. Rather than replacing legacy systems entirely, DT implementation often involves integrating and extending their functionality within new digital environments. As a result, achieving interoperability requires balancing innovation with continuity, ensuring that existing systems remain functional while enabling new capabilities.

6. CONCLUSION

This paper presents a case study examining how DT systems are designed, developed, and implemented under real-world R&D conditions within a bridge infrastructure context through collaboration among multiple stakeholders. The findings demonstrate that successful DT implementation depends not only on technological integration but also on aligning organizational priorities and practices. Interoperability challenges emerged at multiple levels, highlighting the complex interplay between technical systems and institutional boundaries.

At the organizational level, the study revealed that differences in work practices and communication patterns across institutions created barriers to coordination. Organizational silos, for example, IT and OT, led to misaligned priorities. However, early involvement, continuous dialogue, and adaptive coordination helped bridge these divides, allowing shared understanding to evolve over time. At the technical level, the integration of multiple platforms and service ecosystems exposed difficulties associated with legacy systems, proprietary standards, and data exchange protocols. These challenges required ongoing negotiation and customization to achieve interoperability across systems.

By examining an academic–industry collaboration initiative, this study contributes to the existing body of knowledge on interoperability by revealing how organizational and technical dimensions are interdependent and must be managed in parallel throughout system development. It provides empirical evidence that DT implementation is a complex process that requires significant effort and patience.

This study was based on a single DT project within a university R&D context, which may limit the generalizability of its findings. Future research could explore the implementation of DT across different infrastructure types or compare strategies between public- and private-sector projects to validate and expand these insights. Additionally, cybersecurity emerged as an important concern in this study. Future work could examine how data protection and system resilience are integrated into DT development.

Ultimately, understanding interoperability as a dynamic process of alignment between people, organizations, and technologies provides a foundation for advancing the digitalization of infrastructure systems and ensuring that future DT implementation plans are well considered.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support and in-kind contributions of the organizations that participated in this pilot study: Bentley Systems, Challenge Seattle, Compass IoT, eScience Institute, Federal Highway Administration (FHWA), Innovative Bridge Technologies/Accelerated Bridge Construction-University Transportation Center (IBT/ABC-UTC), Microsoft, Semtech, the State Transportation Innovation Council (STIC), T-Mobile, UW Information Technology (UW-IT), the Washington State Department of Transportation (WSDOT), and WSP USA. Organizations are listed alphabetically, and their order does not reflect the nature or extent of their contributions.

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APPENDIX A: INTERVIEW QUESTIONS AND PROTOCOLS

Interviewer Instruction

Tools: Laptop, iPad & Pencil

Considering the interactive nature of the interview questions, an iPad and Apple Pencil will be used for sketching and brainstorming. The interviewer should first set up the Zoom meeting and log in from both the laptop and the iPad. The session will be recorded on the laptop, while the iPad will be used to share the screen and capture the brainstorming process.

Request consent before recording the interview.

Warm up

What is this project about?
This is an applied research project in which academic researchers are collaborating with a government agency to develop a digital twin system for infrastructure monitoring using off-the-shelf products. The outcomes of this project are expected to provide empirical insights into the factors practitioners should consider when developing Digital Twin systems for real-world infrastructure contexts.

Goal of the interview
Each member of the research team has played a distinct role in the development of the digital twin. Interviewing them will help capture the project's story from multiple perspectives and document the system's development progress comprehensively.

Part 1: Interviewee & Project Background

1. Please tell me about your professional background and area of expertise as it relates to the I-90 digital twin project.
2. How did you become involved in the I-90 Digital Twin research project?
3. What is your role and your responsibilities on the project? Please share with me an example of your work on the project.

Part 2: Project Experience

4. If you were to tell the story of this project, what major milestones or turning points would you highlight?
5. For each milestone you mentioned, can you walk me through what happened?
   - Who was involved?
   - What was discovered?
   - What was discussed or decided?
6. During each of those milestones:
   - How did you feel?
   - What challenges or conflicts did you encounter?
   - How were they addressed or resolved?

Part 3: Lessons & Insights

7. Looking back, what stands out to you as the most important factors for moving the project forward?
8. Were there any tensions between different roles, disciplines, or organizational priorities during the project? Can you give examples?
9. One theme of this paper is interoperability. What does that mean to you? How has interoperability been a challenge on this project? We define both organizational and technical interoperability.

10. What lessons from your experience here might help others implement similar digital twin projects?

Wrap up

11. Is there anything else that comes to mind that we have not yet had a chance to discuss?
12. Is there someone else you think I should interview?
13. Do you have any questions for me?