DOCTORAL THESIS

Digital Twins for Asset Management of Civil Structures: Perceived Potential and Practical Applications

Vanessa Saback

Structural Engineering

LULEÅ
UNIVERSITY
OF TECHNOLOGY

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Luleå 2024

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Preface

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The completion of this thesis is the result of almost four and a half years of research as a PhD Student, this journey has been supported by the gracious help of many. First, I would like to thank my team of supervisors: Prof. Björn Täljsten, Assoc. Prof. Thomas Blanksvärd, and Dr. Cosmin Popescu. Thank you for trusting me when you choose me to be a part of this project and for the invaluable guidance you have provided ever since. I will always be grateful for all the help, and the professional and personal advice you have given me throughout these years.

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Vanessa Saback

Stockholm, August 2024

Summary

The Engineering and Construction (E&C) industry has vast potential to leverage technology for solving current asset management issues, with significant environmental and financial benefits. This study investigates the use of Digital Twins (DTs) for asset management of civil structures, identifying a gap between the perceived potential of DTs and practical applications due to misconceptions, industry fragmentation, and lack of standardizations. To address this, a literature review and experimental programs were conducted, leading to the development and validation of a proof-of-concept DT platform applied to two case studies. The study concludes with a purpose-driven DT roadmap to address the gap between potential and practical applications in the E&C industry.

Background: the integration of Building Information Modeling (BIM) and DTs for asset management in construction offers a promising solution to improve current processes, which are often time-consuming or inefficient. With technology rapidly advancing and the advent of Industry 4.0, there is a growing belief in the transformative potential of DTs to address longstanding challenges within the industry. By leveraging these innovative tools, stakeholders aim to enhance operational efficiency, optimize maintenance practices, and ultimately revolutionize infrastructure asset management.

Aims and objectives: this study aims to investigate the use of DTs to improve asset management processes within the E&C industry. The objectives include a thorough investigation of DTs, establishing their purpose within the industry, proposing a replicable DT methodology, demonstrating the methodology through case studies, and addressing the gap between potential and practical applications to promote DT dissemination.

Methodological approach:

i. Identify problem: thorough literature review and DT investigation (Paper I).
ii. Define solution: understand the purpose of DT applications in E&C (Paper II).
iii. Methodology and Demonstration: propose and demonstrate a replicable DT methodology through experimental work, digital modelling, and case studies (Papers III, IV, and V).
iv. Evaluation: propose a purpose-driven DT roadmap to evaluate the impact of applications, address the gap between potential and applications, and promote widespread DT adoption (Paper VI).

Results: the main results include a deep DT investigation, experimental work with a reinforced concrete beam, snow galleries and a trough bridge, digital models using BIM and finite elements, a scalable DT platform methodology demonstrated in two case studies, and a roadmap from conclusions and lessons learned to promote DT adoption in the industry.

Conclusions: given the particularities of the E&C industry and its assets, DTs can primarily benefit asset management and maintenance processes by enabling real-time monitoring, predictive maintenance, and data integration for improved safety and efficiency. To address the gap between potential and practical applications, two paradigm shifts are proposed: shifting the perception of DTs from a digital model to integrated technology tools, and adopting a generalizable, purpose-focused approach instead of context-specific frameworks.

Keywords: digital twins, BIM, asset management, Engineering & Construction, case studies.

Sammanfattning

Byggindustrin har en enorm potential att effektivisera förvaltning av byggnader och anläggningar, med betydande tekniska, miljömässiga och ekonomiska fördelar. Denna studie undersöker användningen av digitala tvillingar (DTs) ämnade för förvaltning av byggnader och anläggningar där brister identifierats mellan den förväntade potentialen hos digitala tvillingar och praktiska tillämpningar på grund av missuppfattningar, branschfragmentering och brist på standardiseringar. För att belysa detta har en litteraturstudie och praktiska försök genomförts, vilket i sin tur har lett till utveckling och validering av ett konceptbevis (proof-of-concept) av en plattform för digitala tvillingar som har tillämpats på två fallstudier. Studien avslutas med en funktionsanpassad vägkarta (roadmap) för att hantera avståndet mellan potentiella och praktiska tillämpningar för digitala tvillingar inom byggnadsindustrin.

Bakgrund: integrationen av Building Information Modeling (BIM) och digitala tvillingar för förvaltning av byggnader och anläggningar erbjuder en lovande lösning för att förbättra nuvarande förvaltningsprocesser, som ofta är tidskrävande eller ineffektiva. Med snabbt framväxande teknologier och ankomsten av Industri 4.0, finns det en växande förväntningar på digitala tvillingars transformativa potential att hantera långvariga utmaningar inom industrin. Genom att utnyttja dessa innovativa verktyg strävar intressenter efter att förbättra operativ effektivitet, optimera underhållsmetoder och slutligen avsevärt förbättra förvaltningen av infrastrukturens tillgångar.

Syften och mål: denna avhandling syftar till att undersöka användningen av digitala tvillingar för att förbättra förvaltningsprocesser inom byggnadsindustrin. Målen inkluderar en grundlig undersökning av digitala tvillingar, fastställande av deras syfte inom industrin, föreslå en reproducerbar metodologi, demonstrera metodologin genom fallstudier och hantera brister mellan potentiella och praktiska tillämpningar för att främja användningen av digitala tvillingar.

Metodologiskt tillvägagångssätt:

i. Identifiera problem: grundlig litteraturstudie och undersökning av digitala tvillingar (Paper I).

ii. Definiera lösningen: förstå syftet med tillämpningar av digitala tvillingar inom byggnadsindustrin (Paper II).

iii. Metodologi och demonstration: föreslå och demonstrera en reproducerbar metodologi för digitala tvillingar genom experimentellt arbete, digital modellering och fallstudier (Paper III, IV och V).

iv. Utvärdering: föreslå en funktionsanpassad vägkarta (road map) för digitala tvillingar. Här utvärderas påverkan av tillämpningar, hantering av brister mellan potentiella och praktiska tillämpningar samt hur tillämpningar av digitala tvillingar ska främjas. (Paper VI).

Resultat: de viktigaste resultaten inkluderar en omfattande undersökning av digitala tvillingar, experimentellt arbete med en armerad betongbalk, snögallerier för järnväg och en trågbro i armerad betong, digitala modeller med hjälp av BIM och finita elementmetoden, en skalbar plattformmetodologi för digital tvillingar demonstrerad i två fallstudier samt en guide från slutsatser och lärdomar för att främja tillämpandet av digitala tvillingar inom byggnadsindustrin.

Slutsatser: med tanke på branschens och dess tillgångars särskilda egenskaper, är digitala tvillingar främst fördelaktiga för förvaltning och underhåll genom att möjliggöra realtidsövervakning, förutsäga underhåll och dataintegration för förbättrad säkerhet och effektivitet. För att hantera bristen mellan potentiella och praktiska tillämpningar föreslås två paradigmförskjutningar: att ändra uppfattningen av digitala tvillingar från en digital modell till integrerade teknologiverktyg, och att anta en generaliserbar, funktionsanpassad metodik istället för kontextspecifika ramverk.

Nyckelord: digitala tvillingar, BIM, förvaltning, underhåll byggnads- och anläggningsindustri, fallstudier.

Table of Contents

List of Abbreviations

Abbreviation	Description
AI	Artificial Intelligence
AR	Augmented Reality
BI	Business Intelligence
BIM	Building Information Modelling
BMS	Bridge Management System
BOO	Build-Own-Operate
BOOT	Build-Own-Operate-Transfer
BOT	Build-Operate-Transfer
BrIM	Bridge Information Modelling
CDE	Common Data Environment
DBFO	Design-Build-Finance-Operate
DIC	Digital Image Correlation
DSR	Design Science Research
DT	Digital Twin
E&C	Engineering and Construction
FE	Finite Element
FOS	Fiber Optic Sensors
GIS	Geographical Information Systems
GPR	Ground Penetrating Radar
IFC	Industry Foundation Class
IoT	Internet of Things
LCCA	Life Cycle Cost Analysis
LiDAR	Light Detection and Ranging
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NDT	Non-Destructive Testing
RQ	Research Question
SG	Snow Gallery
SHM	Structural Health Monitoring
TRL	Technology Readiness Levels
UAV	Unmanned Aerial Vehicles
VDC	Virtual Design and Construction
VR	Virtual Reality

Chapter 1

Introduction

This chapter presents the background, objectives, and research questions for the thesis, as well as the scientific method deployed to achieve them. The scientific publications appended to the thesis are also introduced and briefly discussed, highlighting their role in the investigation of digital twins (DTs) for the asset management of civil structures.

In this study, a DT is defined as a realistic digital representation of an asset that includes the distinctive feature of a data flow between the physical entity and its digital representation. A DT can have different technological components to improve its representation of the asset's behavior – for instance, a structural health monitoring (SHM) system, automated fault detection, and prediction of future behavior. Asset management of a structure consists of a set of processes to ensure its safe operation and maximize the value of assets over their lifespan, such as condition assessment, risk analysis, prioritization of maintenance and rehabilitation actions. Lastly, civil structures are engineered constructions designed to provide functionality in various civil engineering applications like transportation, water and waste management, and urban facilities, for example.

1.1 Background

Traditionally, the Engineering & Construction (E&C) industry is not recognized for its role at the forefront of technological development. Conversely, the industry is known to have a risk-averse nature and a wariness towards embracing innovative technologies that comes from both the corporate and the client sides. E&C is also a complex and highly fragmented industry, which creates a discouraging scenario for bold technological advancements.

However, the fourth industrial revolution, also known as Industry 4.0, has been driving digital transformation across every sector of the economy, including E&C. With technology rapidly advancing, there is increasing interest and pressure within the industry to adopt more modern and efficient methods. Despite its economical relevance, E&C ranks among the least digitized sectors (McKinsey Global Institute, 2015), so there is a growing belief in the transformative potential of digitalization tools to address longstanding internal challenges.

The E&C industry is a major producer of waste, which leads to higher carbon emissions and environmental pollution, and a major consumer of natural resources, with most resource consumption being linear (Stipanovic, et al., 2023). From bridges to buildings and infrastructure, assets within the E&C industry have long life spans. Ensuring the safe operation of these assets throughout their life cycle reduces their climate impact and requires regular inspections to determine maintenance needs. Current processes adopted by the industry, however, can be time-consuming and even inefficient, so they have become a target for improvement through emerging technologies. Digital twins are one of these technologies that has gain significant notoriety in the past decade.

A digital twin offers a platform that can integrate current condition data from sensors and visualize the results in a 3D model, perform simulations, and conduct fault detection and diagnostics in a common data environment (CDE) accessed by multiple stakeholders. Therefore, DTs are perceived as enablers of predictive maintenance for structural assets within the framework of Industry 4.0, along with Building Information Modelling (BIM) to provide informed 3D models for both new and existing structures.

The technologies that compose a DTs are already available in various forms; non-destructive testing (NDT), live SHM through various sensors, and BIM models, for example. NDT can assist in creating a more accurate representation of an asset by detecting hidden defects, determining as-is material properties, and ensuring construction quality compared to as-designed data. Using remote and contactless technology, such as advanced optical methods combined with UAV, can yield better results than traditional methods by improving inspection accuracy and efficiency, eliminating human error, and providing opportunities to create historical records of deterioration progress (Popescu, et al., 2019). However, these technologies often operate in isolation, lacking integration into a unified platform accessible to stakeholders and capable of capturing comprehensive life cycle information. The appeal of a DT lies in its potential to integrate and connect that information throughout the life cycle of a structure to facilitate interpretation and decision making and promote circular economy.

Despite the existence of such technologies, their post-construction utilization remains limited, particularly in E&C where linear thinking still prevails over circular economy principles. In turn, considering the prolonged life spans of assets and associated operation and maintenance costs amplifies the importance of life cycle analysis in E&C. The fragmented nature of the industry further complicates matters, blurring lines of responsibility between construction and ownership and creating ambiguity regarding who should bear the costs associated with implementing a DT. Consequently, while there is widespread recognition of the potential benefits of digital twins in E&C, the maturity level of practical applications has not increased proportionally.

Therefore, there is a significant gap between perceived potential and level of development of practical DT applications in E&C. Misconceptions concerning basic DT definitions and requirements persist in the literature; this gap is seldom addressed but there is rather a proliferation of scattered and context-specific DT frameworks. Addressing this gap and establishing industry standards are necessary to unlock the full potential of DTs and promote its widespread adoption.

This has prompted a thorough investigation of DT technology in this thesis, to understand its origins, capabilities, practical applications, objectives, and the factors hindering its further advancement.

1.2 Hypothesis, Aim, and Objectives

Hypothesis

The hypothesis states that despite the trending status of digital twins as a subject, there is still a significant gap between perceived potential and practical applications.

Aim and objectives

Standardization, maturity level classifications, clear business models, and strategic analysis are essential for the successful adoption and practical implementation of digital twins in the Engineering & Construction industry.

The aim is to investigate the use of digital twin technology to improve current asset management processes within the engineering and construction industry.

The objectives of the thesis are:

i. Perform a thorough investigation of digital twins in the literature, including the construction industry as well as others, to identify its origins, definitions, and applications.
ii. Determine the purpose of digital twins within the engineering and construction industry.
iii. Propose a scalable and replicable methodology for a digital twin platform for asset management of civil structures.
iv. Demonstrate the proposed methodology through a proof-of-concept case study.
v. Address the gap between perceived potential and practical digital twin applications in E&C to promote further dissemination.

1.3 Research Questions

The following research questions are proposed to comply with the aim of this research project:

I. What is the status of digital twins, in terms of both perceived potential and maturity level of practical applications, in Engineering & Construction compared to other industries?

II. What is the purpose of Digital Twin applications in the Engineering & Construction industry?

III. How can a digital twin improve asset management and maintenance in Engineering & Construction?

IV. How can the Engineering & Construction industry bridge the gap between perceived potential and practical applications and effectively implement digital twins to leverage the benefits of this technology?

1.4 Scientific Approach

A structured scientific approach was deployed to fulfill the research objectives of this thesis. First, a systematic literature review was conducted on DTs, the status of this field of research, and existing gaps. The objective of the review was to ensure a comprehensive understanding of the background and current state of DTs. The review was divided into three main steps: (i) defining the search strings, (ii) performing searches in Scopus, the selected database, and (iii) assessing the retrieved articles. The strings were defined based on keywords identified in primary references retrieved during a preliminary exploratory review. The selected keywords were divided into subject groups: BIM, bridges, DTs, management, inspection, monitoring, and maintenance. The search results were limited within an acceptable range from 2010 to 2020, in Paper I, and continuously until 2024 to ensure the latest results. The detailed methodology for the review as well as its results and conclusions are presented in Paper I.

The initial review on DTs revealed that, even though there was plenty of literature due to its trending status as a research topic, there remained a lack of clarity concerning definition, purpose, and status of practical applications. Therefore, a focused investigation of practical DT applications in prominent industries was conducted to clarify the specific purpose and maturity levels. The results from this investigation are presented in Paper II.

Informed by theoretical investigations, a practical and scalable methodology for implementing DTs in asset management was proposed. It is important to state that this is not a linear process, and there is not a single DT solution. Therefore, different approaches were tested, and iterations of the methodology were proposed before a DT platform was applied to the case studies in this research. The first case study, named Snow Galleries, is introduced in Paper III, the DT methodology and its application for the Snow Galleries is presented in Paper IV, and its application in the second case study, named Trough Bridge, is in Paper V. Other iterations of the DT methodology and proposed frameworks can be found in additional publications (Saback de Freitas Bello, et al., 2022; Saback de Freitas Bello, et al., 2021).

After the proposed methodology was validated and tested in a real-world context, the research focus was turned to evaluating the impact of such efforts, understanding what is hindering a more widespread adoption of DTs across the industry, and how to bridge the gap between the perceived potential and practical applications. This discussion is presented in Paper VI.

An illustration of the scientific approach, based on a design science research (DSR) approach (Peffers, et al., 2014), is presented in Figure 1.

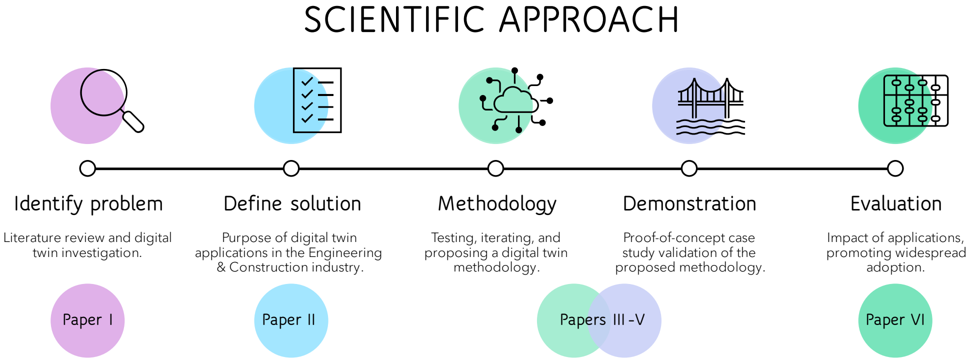


Figure 1. Scientific approach.

1.5 Limitations

The limitations of this study can be outlined as follows:

- Scope of practical application: the thesis primarily focuses on proposing a methodology and demonstrating proof-of-concept applications rather than implementing full-scale, real-world solutions.
- Resource constraints: limitations in resources, particularly in terms of external collaboration and funding, restricted the ability to further develop and operationalize the proposed DT platform.

- Technology challenges: additional software development expertise was required to address the technical challenges associated with DT development, so a collaboration with an external developer was conducted.
- Real-world validation: the potential of the proposed DT platform was demonstrated through case studies, but industry collaboration still is required to further validate the results.
- Evolving technological landscape: the rapid evolution of Artificial Intelligence (AI) and other emerging technologies presents uncertainties regarding their impact on DT development and implementation, highlighting the need for ongoing research and adaptation.

1.6 Outline of the Thesis

This is a compilation thesis, composed of an extended summary followed by appended research papers. This summary consists of seven chapters, briefly described as follows:

Chapter 1 – Introduction presents the background, objectives, and research questions for the thesis, describes the scientific approach to achieve them and introduces the appended papers.

Chapter 2 – Digital Twins Investigation presents the state-of-the-art for topics essential to the construction of this thesis, such as the origins of the DT, issues with current asset management processes for civil structures, and the transformational potential of Industry 4.0.

Chapter 3 – Experimental Work and Digital Modelling presents the laboratory work conducted for the research and the corresponding digital models.

Chapter 4 – Digital Twin Platform presents the methodology, requirements, and collaboration process to develop the proposed DT platform.

Chapter 5 – Case studies introduces the case studies for implementation of the DT platform and their importance in the overall context of this research.

Chapter 6 – Conclusions presents the concluding remarks for this research, including the answers to the research questions and hypothesis.

Chapter 7 – Future research proposes how this research can be continued based on its conclusions and limitations.

1.7 Appended Papers

The core of this thesis consists of five journal papers and one conference paper. Three of the journal papers have been published and two are under review, the conference paper has been accepted for presentation, which will be held in September 2024. The appended papers are briefly presented in this session, including the author's contribution to each of them.

PAPER I

Saback, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2022). Asset Management of Existing Concrete Bridges Using Digital Twins and BIM: a State-of-the-Art Literature Review. *Nordic Concrete Research*, 66(1), pp.91-111. https://doi.org/10.2478/ncr-2021-0020

The first paper is a review of the literature, in which a systematic methodology was adopted to conduct a thorough review of topics related to the core research problem. The initial focus was on DTs for asset management of bridges, so the review also covered bridge inspection, Bridge Information Modelling (BrIM), and bridge management systems. This review was essential to comprehend the field of DTs' research and its shortcomings, as well as current issues with asset management of bridges.

My contribution was defining the methodology, performing the review, and writing the manuscript.

PAPER II

Saback, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2024). Analysis of Digital Twins in the Construction Industry: Practical Applications, Purpose, and Parallel with other Industries. *Buildings*, 14(5), 1361. https://doi.org/10.3390/buildings14051361

Even though DTs have become a widely discussed topic, there is still significant misconception concerning their definition and purpose within the E&C industry. This paper was aimed at performing a deep investigation into practical DT applications in E&C and other prominent industries to assess the optimal purpose of this technology for assets in the construction industry. A combination of literature review, multi-case study analysis, and comparative analysis was deployed to conduct this investigation. This paper also served as a platform for presenting conclusions regarding the status of DT applications and elucidating the contrast between perceived potential and how far practical applications have come.

My contribution was conducting the review, identifying the case studies in the literature, conducting the comparative analysis, and writing the manuscript.

PAPER III

Saback, V., Gonzalez-Libreros, J., Daescu, C., Popescu, C., Garmabaki, A.H.S., & Sas, G. (2024). Adapting to climate change: snow load assessment of snow galleries on the Iron Ore Line in Northern Sweden. *Front. Built Environ.* 9:1308401. https://doi.org/10.3389/fbuil.2023.1308401

The Snow Galleries on the Iron Ore Line were selected as a case study to apply the DT methodology defined from the previous theoretical investigation. The galleries had been damaged due to excessive snow loads, so a monitoring system was instrumented to track current snow loads in selected frames. This paper introduces the Snow Galleries case study, presenting findings from previous SHM system results, site visits, and finite element (FE) models. Detailed information about the case study is provided in this paper to establish a foundation and set thresholds for the following paper presenting the DT of the snow galleries.

My contribution was gathering and analyzing all previous data and results, conducting further snow load calculations, formulating the discussion and conclusions, and writing the manuscript.

PAPER IV

Saback, V., Eliasson, J., Daescu, C., Gonzalez-Libreros, J., Popescu, C., Blanksvärd, T., Täljsten, B., & Sas, G. (2024). Digital Twins for asset management: case study of Snow Galleries in northern Sweden. Submitted for publication in *Structure and Infrastructure Engineering* on April 17th, 2024, and currently under review.

Paper IV presents the DT of the snow galleries case study. In this paper, the SHM data from the instrumented frame in Snow Gallery 13A was connected to its 3D model in a common data environment. The temperature in the gallery and live snow loads are visualized in the 3D environment to assist decision making and facilitate predictive maintenance. The proof-of-concept DT presented in this paper represents a practical effort towards applying the purpose of DTs for asset management of civil structures. This case study particularly benefits from real-time data and the potential of predictive maintenance to reduce the need for routine inspections under extreme weather conditions.

My contribution was conducting the literature review, defining the DT methodology, collaborating for the development of the digital interface, creating the 3D model, formulating the discussion and conclusions, and writing the manuscript.

PAPER V

Saback, V., Eliasson, J., Gonzalez-Libreros, J., Popescu, C., Blanksvärd, T., Täljsten, B., & Sas, G. (2024). Digital Twins for asset management: platform for predictive maintenance and Trough Bridge case study. IABSE Congress San Jose, Costa Rica, September 25th to 27th 2024. Accepted for presentation.

The DT platform developed in Paper IV was applied to a perform a live demonstration of a pre-test for the Trough Bridge case study. The bridge was instrumented with fiber optic sensors before casting, and during the demonstration the sensor data was displayed in real time together with the 3D model of the bridge on the DT platform. The objective of this paper was to show scalability and replicability of the proposed DT by creating a common data environment for another structure and with a different set of sensors.

My contribution to this paper was collaborating on the development of the DT platform, creating the BIM model for the trough bridge, participating in casting, and instrumenting the bridge, and writing the manuscript.

PAPER VI

Saback, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2024). Purpose-driven roadmap for widespread adoption of Digital Twins in the Engineering & Construction industry: RC Chimney case study. Submitted for publication in *Construction Innovation: Information, Process, Management* on August 9th.

Paper VI addresses the gap between DT’s perceived potential and practical applications through a purpose-driven roadmap. The study highlights how context-specific DT frameworks have hindered widespread adoption and proposes viewing DTs as a tailored pack of existing technologies chosen based on the digitalization initiative's purpose. The methodology includes a literature review, DT investigation, and a case study analysis of a RC chimney. The proposed roadmap comprises assessment, purpose definition, technology selection, implementation, and optimization stages.

My contribution was conducting the review and DT investigation, developing the roadmap, analyzing the case study data, and writing the manuscript.

1.8 Additional Publications

Apart from the research papers appended to this thesis, a Licentiate thesis and conference papers have been published by the author as well. These publications are listed in this section, but not appended to this thesis.

Licentiate Thesis

Saback, V. (2022). Digital Twins for Asset Management of Structures (Licentiate dissertation). Luleå University of Technology. Retrieved from https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-93161

Conference Papers

Saback, V., Gonzalez-Libreros, J., Daescu, C., Hojsten, T., & Sas, G. (2023). Evaluation of the snow loads on the snow galleries on the Iron Ore Line in Northern Sweden. ce/papers, 6, 221-228. https://doi.org/10.1002/cepa.2744

Saback, V., Popescu, C., Täljsten, B., & Blanksvärd, T. (2023). Analysis of Digital Twins in the Construction Industry: Current Trends and Applications. In A. Ilki, D. Çavunt, & Y. S. Çavunt (Eds.), Building for the Future: Durable, Sustainable, Resilient. fib Symposium 2023 (Vol. 350, pp. 110). Lecture Notes in Civil Engineering. Springer. https://doi.org/10.1007/978-3-031-32511-3_110

Saback, V., Mirzazade, A., Gonzalez-Libreros, J., Blanksvärd, T., Popescu, C., Täljsten, B., Daescu, C., & Petersson, M. (2022). Crack monitoring by fibre optics and image correlation: a pilot study. In Challenges for Existing and Oncoming Structures - Report. IABSE Symposium Prague 2022 (pp. 437-444). https://doi.org/10.2749/prague.2022.0437

Saback de Freitas Bello, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2022). Framework for Bridge Management Systems (BMS) Using Digital Twins. In Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021) (Vol. 200, pp. 78). Lecture Notes in Civil Engineering. Springer. https://doi.org/10.1007/978-3-030-91877-4_78

Saback de Freitas Bello, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2021). Bridge management systems: overview and framework for smart management. In IABSE Congress: Structural Engineering for Future Societal Needs, Ghent, Belgium, 22-24 September 2021, published in IABSE Congress Ghent 2021 (pp. 1014-1022). https://doi.org/10.2749/ghent.2021.1014

Saback de Freitas Bello, V., Popescu, C., Blanksvärd, T., & Täljsten, B. (2021). Framework for facility management of bridge structures using DTs. In IABSE Congress: Structural Engineering for Future Societal Needs, Ghent, Belgium, 22-24 September 2021, published in IABSE Congress Ghent 2021 (pp. 629-637). https://doi.org/10.2749/ghent.2021.0629

Chapter 2

Digital Twin Investigation: State-of-the-Art

2.1 Definitions and Origins

The origins of the concept now known as the DT can be traced back to a presentation about product life-cycle management given by Michael Grieves in 2002. The presentation outlined a system including a physical component, a corresponding virtual component containing all available information on the physical counterpart, and a mechanism for mirroring (or twinning) changes between the real and virtual spaces (Grieves & Vickers, 2017). It also suggested that the virtual and physical components should remain linked throughout the entire life cycle of the physical component, from its inception and manufacturing to its operational phase and eventual disposal.

Years later, in 2010, DTs were first used by the aerospace industry when NASA brought the concept to replicate the life of air vehicles in its Technology Roadmaps (Shafto, et al., 2010). Since then, other industries have gradually ventured into exploring DT applications for their assets as well, eventually reaching the peak in interest seen today.

From its initial concept, illustrated in Figure 2, the definition a digital representation of an asset which includes a data flow between the asset and its digital representation, i.e., a DT, has been clear in its requirements. However, with the surge in popularity, some aspects of this DT definition have become hazy. The crucial link component is often overlooked, and many have started labeling any digital model as a DT to join the trend.

Obtaining a CDE that enables the required double-sided data flow of a DT is one of the hardest challenges in its conception. For some assets, the characterization of this data flow can be very straightforward. For instance, considering how common smart thermostats have become, it is easy to see how modifying a variable on the DT of a building, like the temperature in a room, would impact the physical entity directly (digital to physical data flow). Nonetheless, this double-sided data flow is not as simple in other assets within E&C.

It is hard to develop a business case that justifies the investment and the complexity of implementing a DT (ARUP, 2019). In E&C, this cost is more easily absorbed by civil structures and infrastructure, due to their long lifespans and high maintenance costs. However, particularly for these assets the digital to physical data flow is trickier to obtain. The perspective of a command performed on a digital model directly modifying a bridge or a railway, for example, is not as likely to occur. Therefore, rather than direct modifications, the digital to physical data flow in these scenarios presumably needs to go through a person that, informed by system intelligence, triggers actions in benefit of the structure. That clarification is important to approach the development of DT applications incrementally, while maintaining the correct conceptual framework. Rather than rapidly pursuing overly complex DT applications, the focus should be on gradual growth and refinement, based on a clear purpose, and ensuring that each step aligns with the core principles of DTs.

Besides the systematic review presented in Paper I, other literature reviews on DTs can be found in, for example: Jiménez Rios et al. (2023), Rogage, et al. (2022), Thelen et al. (2022), De-Graft, et al. (2021), Sepasgozar (2021), Lu et al. (2020), Cimino et al. (2019), Lu & Brilakis (2019), Khajavi et al. (2019), and Kritzinger et al. (2018), and Negri, et al. (2017).

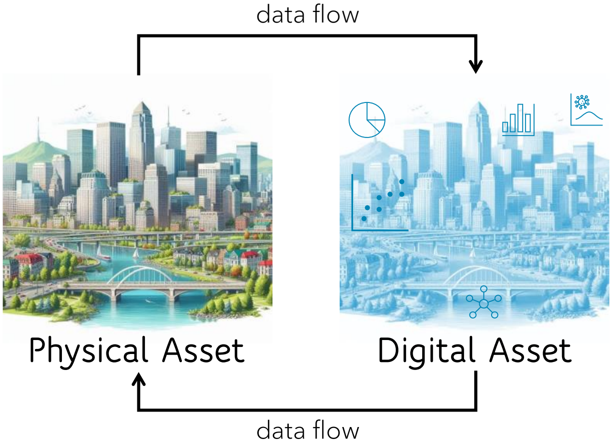


Figure 2. Illustration of the concept of digital twins.

2.2 Asset Management of Civil Structures

Assets in the construction industry, such as buildings and civil structures, have long lifespans. Consequently, many structures and infrastructures worldwide are nearing the end of their operational lifespans. Most bridges on the national road networks in the European Union were built in the last 50 years, although some are much older (Woodward, et al., 2001). As infrastructure ages, the need for maintenance increases, as well as effective monitoring systems to identify structural problems at an early stage and guarantee public safety (Casas & Cruz, 2003). Rehabilitation of infrastructure identified as unsafe causes significant financial and environmental costs, making regular maintenance essential.

Regular assessments of structural health and maintenance interventions are essential to guarantee the safe operation of structures within their intended design life and beyond (Morgenthal, et al., 2019). Providing timely maintenance as an alternative to demolition and reconstruction of structures that have been deemed unsafe is much more sustainable and cost-effective. The importance of adopting more sustainable strategies is particularly heightened in the current context of environmental concerns. Therefore, proper asset management that ensures timely maintenance of existing structures has less environmental and financial impact, offering a better overall approach for the life cycle of civil structures.

Considering the three-pillar definition of sustainability—economic, social, and environmental aspects—life-cycle cost analysis (LCCA) is an optimal tool to promote sustainability by extending the life of existing assets (Casas, 2024). Optimizing interventions minimizes costs associated with demolition, reconstruction, and maintenance; socially, it extends the life of heritage assets, guaranteeing safety, functionality, and availability to users; and environmentally, it reduces the use of natural resources and energy, as well as gas emissions (Casas, 2024). Property developers have recognized the importance of sustainable practices, but they still face challenges on adopting sustainable criteria in the projects' procurement (Desivyana, et al., 2023). This includes selecting suppliers, products, and practices that are environmentally friendly, socially responsible, and economically viable throughout the lifecycle of a project.

Mirzaei, et al. (2014) conducted a survey covering twenty-five infrastructure management systems, used to manage approximately 1.000.000 objects, from eighteen countries. Figure 3 presents the surveyed systems, their respective countries, and the number of managed objects (bridges, culverts, tunnels, retaining structures and other objects). Each country handles infrastructure management independently, however, adopting a degree of standardization in infrastructure management could facilitate sharing knowledge and experience between managing agents, thereby improving the management systems (Mirzaei, et al., 2014). Some improvements to current management systems identified in Paper I include incorporating BIM of inventory, life cycle analysis and simulation of future degradation for predictive maintenance.

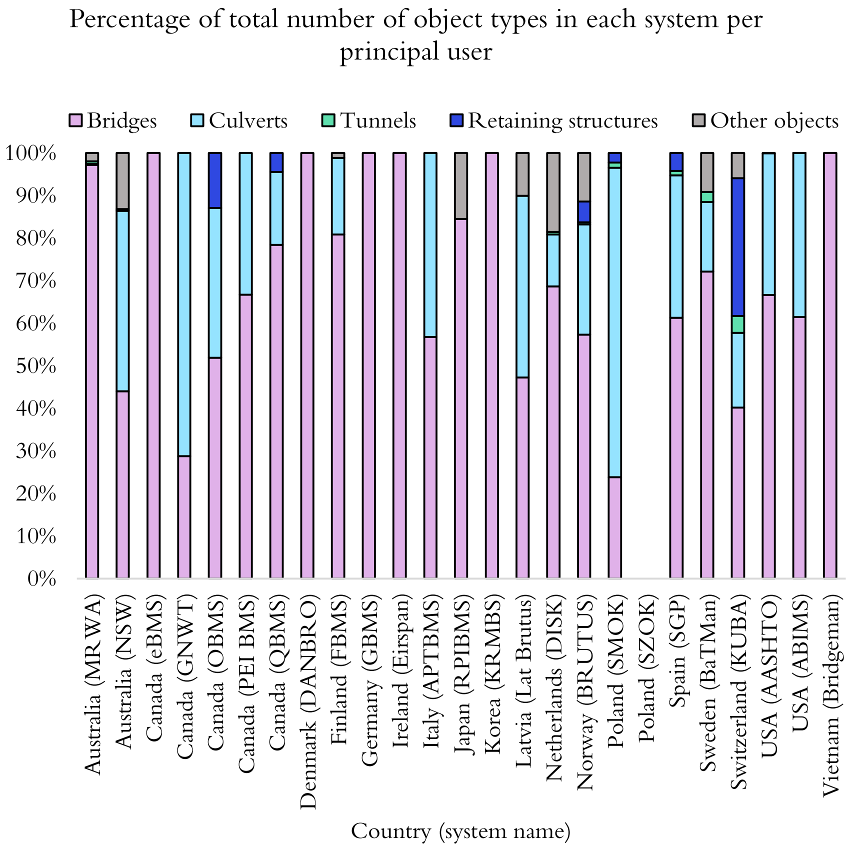


Figure 3. Percentage of object types in each surveyed system. Adapted from Mirzaei, et al. (2014).

An inspection is the first step in the management process, wherein inspectors evaluate the physical and functional state of individual structural elements and the overall bridge (Safi, et al., 2013). Routine inspections are scheduled quality assessment procedures conducted periodically to assess a structure's health during its service life (Isailovic, et al., 2020). Current bridge inspection procedures, for example, primarily rely on visual assessments and manual field measurements conducted by bridge inspectors, who examine each component to identify visible signs of damage. Non-destructive testing may be conducted to complement the visual inspection as well. The findings and observations are then recorded through field inspection notes, hand-drawn sketches, and photographs (Popescu, et al., 2019). Lastly, rating criteria are applied to ascertain the bridge's condition, followed by the implementation of rehabilitation procedures (Khan, 2015).

These current inspection procedures, however, present significant challenges. The E&C industry predominantly relies on traditional building maintenance systems that use paper reports and Excel spreadsheets for data transfer, potentially leading to service delays and inefficient maintenance practices (Sapp, 2017; Hosamo, et al., 2022). As concluded in

Paper I, most of the issues with current practices relate to time consumption, limited accuracy and impracticality of manual sketches, knowledge transfer between inspection periods, and limited access to certain bridge sites. Furthermore, most systems do not allow remote access and do not include BIM of inventory. Therefore, it is easy to see how the increasing proliferation of innovative technologies holds immense appeal and potential for improving current processes.

As deterioration of crucial infrastructure is a growing concern, technological advancements for detecting and monitoring damage have been progressing rapidly to enhance the evaluation of these structures. The increase in physical infrastructure and advancements in technology have led authorities to explore methods for enhancing the efficiency of maintenance activities (Powers, et al., 2018). To handle the volume of data necessary for optimal infrastructure management, managing agents are required to employ increasingly advanced computerized management systems to enhance their decision-making process (Mirzaei, et al., 2014). Therefore, intensive research is underway to explore approaches that replace human visual inspections with automated and systematic assessments (Isailovic, et al., 2020).

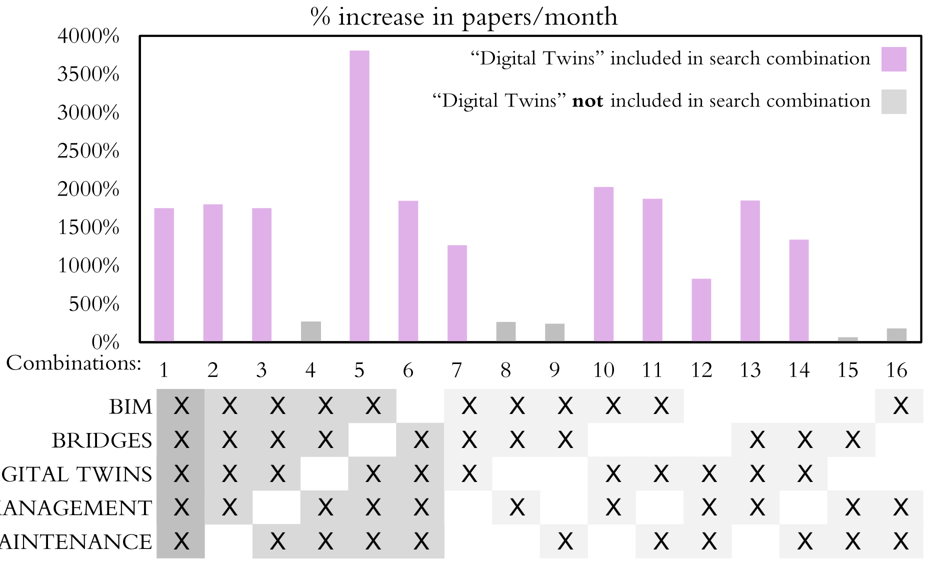
Digital inspection reporting is one strategy that offers significant benefits, such as time savings, enhanced use of 3D models, and easier remark location (Cusumano, et al., 2024). However, its organizational use is still minimal and, to fully realize its potential, companies must standardize data collection and improve data quality, ensuring it meets both contractors' and inspectors' documentation needs (Cusumano, et al., 2024). Monitoring technologies deployed to improve the efficiency of structural health assessment of civil structures include, for example, fiber optic sensors (FOS), unmanned aerial vehicles (UAV), laser scanning, light detection and ranging (LiDAR), photogrammetry, ultrasonography, and ground penetrating radar (GPR). Different studies that have deployed these techniques can be seen in Paper I.

The scope of asset management systems for bridges and civil structures is based primarily on inspection, structural health monitoring, and rehabilitation (Khan, 2015). Management tasks are commonly divided into modules such as inventory management, inspection, condition analysis, and maintenance planning. For optimized system operation, these modules should be integrated to minimize redundancy and user input (Powers, et al., 2018). Understanding the concept of a DT illuminates its appeal for asset management of civil structures. A DT provides a platform to integrate different technologies with an informed 3D model that replicates an asset’s behavior through a dual-sided data flow. It can include informed BIM models, real-time inspection data updates, condition monitoring from sensors, maintenance planning through fault detection and predictive modeling, risk assessment, and cost analysis, all within a CDE accessible to all stakeholders. Furthermore, implementing an effective predictive maintenance program requires big data from sensors, an automatic fault detection and diagnostics platform, and BIM for streamlined data transfer and visualization, which DTs can integrate throughout a structure's lifecycle (Hosamo, et al., 2022).

2.3 Current Status: Trends and Gaps

The development of DTs aligns with the growing intelligence of products and systems in Industry 4.0 (Singh, et al., 2022), which aims for higher operational efficiency, productivity, and automation (Thames & Schaefer, 2016; Lu, 2017). DTs are enabling technologies of Industry 4.0 as they contribute to the convergence of the physical and digital worlds, creating intelligent environments where machines and sensors are interconnected (Folgado, et al., 2024). Thus, they address key challenges faced by the E&C industry, such as poor productivity, timing and budget issues, skilled labor shortages, and sustainability concerns (TWIN VIEW, 2023). Reflecting this elevated level of confidence is DT's global market valuation, predicted to reach $184.5 billion by 2030 from its 2020 valuation of $3.21 billion (Daugherty, et al., 2022). In this context of elevated trust in the potential of DTs associated with huge monetary prospects to the industry, DT research has skyrocketed.

To illustrate the increase in research interest, the searches held during the systematic literature review for Paper I were repeated in Saback, et al. (2023). For Paper I, in 2020, the five groups of keywords (BIM, bridges, DT, management, and maintenance) were searched in sixteen different combinations: one with the five groups, five with four groups, and ten with three groups, with results limited from 2010 to 2020. When this process was repeated, the sixteen searches were given a new time constraint from 2021-2023. Then, the average number of papers published per month in each search combination was calculated and the results from 2010-2020 and 2021-2023 were compared. The results are presented in Figure 4. The main difference was between groups that contained and did not contain the keywords for "digital twins." The highest increase for a combination including the keywords for "digital twins" was almost 4000%, while the increase in combinations without "digital twins" did not reach 500%. This analysis quantitatively shows how DTs have significantly grown as a subject of interest in academia, due to the appeal and demand from the industry.



Combinations:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BIM	X	X	X	X	X		X	X	X	X	X					X
BRIDGES	X	X	X	X		X	X	X	X				X	X	X	
DIGITAL TWINS	X	X	X		X	X	X			X	X	X	X	X		
MANAGEMENT	X	X		X	X	X		X		X		X	X		X	X
MAINTENANCE	X		X	X	X	X			X		X	X		X	X	X

Figure 4. Percentual increase in papers published per month from 2010-2020 to 2021-2023, in sixteen different keyword combinations.

To overview what this surge in research represents, Paper I reviews relevant DT frameworks, while Paper II investigates practical DT applications in operation across various industries. Later studies include, for example, Pregnolato, et al. (2023), Turk, et al. (2022), Kosse, et al. (2022), Boje, et al. (2023), Wang, et al. (2022), and Hosamo, et al. (2023), whose framework integrates DTs with BIM, Internet of Things (IoT), and machine learning (ML) for enhanced fault detection and diagnostics in building systems, using real-time sensor data and predictive maintenance algorithms to aid facility managers in decision-making. Consilvio, et al. (2023) present an architecture that integrates DTs and decision support functionalities to improve road asset management by combining legacy data with new inspection technologies, leading to better maintenance planning, reduced costs, and increased road network availability. Furthermore, Rafsanjani & Nabizadeh (2023) outline the key technologies driving the transformation of the E&C industry, including BIM, IoT, Virtual Design and Construction (VDC), Digital Twin, AI, and Augmented Reality (AR)/Virtual Reality (VR), highlighting their roles in enhancing efficiency, productivity, and decision-making throughout the project lifecycle. The authors also discuss challenges in implementing real-time connectivity for these technologies, i.e., compatibility issues, data sensing and analysis, security concerns, data management, and interdisciplinary collaboration. Lastly, Honghong, et al. (2023) classified DT-related papers into three directions of implementation of DTs for bridges: data-driven model updating (Lin, et al., 2021; Kang, et al., 2021; Girardet & Boton, 2021; Hyoung, 2019; Jiang, et al., 2021; Ritto & Rochinha, 2021; Ho, et al., 2018; el Jazzar, et al., 2020), 3D scan-based surface model reconstruction (Lu & Brilakis, 2019;

Mohammadi, et al., 2021; Shao, et al., 2020), and BIM platform-based data integration (Kaewunruen, et al., 2021).

Despite this surge in research, the number of proposed DT frameworks, the elevated confidence in DT potential, and monetary perspectives, tangible examples of operational DTs are still the minority. Most publications merely address what a DT "can do" to improve current processes, but still lack practical examples. There is still misconception surrounding the DT concept, and completed DTs in practice currently have low maturity levels (ARUP, 2019; MEED, 2021; Lazoglu, et al., 2023).

The challenges hindering the development of DTs are discussed in Paper I, Paper II, and in all appended papers. Here, a concise overview is presented, spanning across the key issues. These include a lack of clarity regarding the purpose of DT applications, which often results in overly ambitious frameworks attempting to comprise all DT benefits simultaneously. Transitioning such frameworks into practical applications proves challenging compared to beginning with small-scale implementations, which enable visualization of issues that only emerge once a framework is put into practice. Moreover, DT applications are often achieved by companies and are consequently protected by intellectual property, thus hindering knowledge sharing in academia. Additionally, the highly fragmented nature of the E&C industry results in scattered frameworks tailored for different assets with distinct needs. The distinction between the responsible for investment in the DT and who will benefit from its operation during the asset's lifecycle further complicates matters. Furthermore, a rush to engage in the DT conversation due to its trending status leads to misconceptions, intensifying the difficulty in building upon existing knowledge. Many "digital twins" in literature are more accurately described as "digital models" or "digital shadows" (Kritzinger, et al., 2018), lacking full DT capabilities. Then, the field might appear more advanced than it is, and it complicates advancing knowledge over wrongful classifications. While the benefits of DTs have been recognized, translating them into practical applications faces numerous challenges. Mainly, automating the two-way data flow, addressing other data-related issues, and the need for advanced programming expertise. Furthermore, the absence of industry-specific standards and a clear digital transformation strategy hinder progress.

Implementing digitalization in asset management requires addressing both technical and human factors. While the necessary technical tools and methods exist, though they require significant financial investment, the greater challenge lies in training personnel to handle digital aspects, which requires adaptation and strong leadership (Casas, 2024). Effective training and workforce management for skilled workforce, along with securing sufficient funding, are essential for successful DT implementation (Casas, 2024).

2.4 Purpose and Applications for E&C

Despite the unbalance between theoretical potential and operational DT applications, along with various remaining challenges, the advancement of everyday technology makes it undeniable that digital transformation and technologies like DTs will be a reality even for E&C. Therefore, efforts should be directed towards developing industry-relevant solutions, investing in adaptable technologies tailored to specific asset needs, and generating tangible results that extend beyond theoretical applications.

While DTs offer significant benefits, not every object requires the intense and regular flow of sensor data they demand, nor is the investment always financially justified (IBM, 2023). More case studies are still needed to demonstrate the viability of DTs within E&C (Pregnolato, et al., 2023). Developing a functional digital replica of an asset and continuously updating it in real-time is both expensive and challenging. Therefore, when considering the advantages of investing in a DT, it is crucial to have a clear focus on purpose. Existing frameworks might not be directly replicated because they are tailored to specific assets and their needs. Therefore, understanding the purpose and objectives of the investment is essential when developing a DT.

DTs can be employed in all steps of an asset's life cycle: project design and development, monitoring construction progress, predictive maintenance, and simulation of scenarios. At the project and design stages, DTs provide realistic visualization and allow for the simulation of design scenarios and feasibility assessments, enhancing collaboration and clarity while reducing rework, resulting in improved efficiency and cost savings. During construction, real-time monitoring with a DT enables project managers to track progress, identify bottlenecks, and ensure adherence to schedules and budgets by detecting deviations early. Additionally, DT simulations of performance against disasters such as fire, floods, or earthquakes help engineers identify vulnerabilities, enhance safety measures, and ensure compliance with safety standards, ultimately improving disaster preparedness and response.

In the literature, De-Graft et al. (2021) proposed applications of DTs in construction, structural system integrity, facilities management, monitoring, logistics processes, and energy simulation. Honghong et al. (2023) conducted a thorough review of DTs and proposed a framework for DT-enhanced BIM to shape the full life cycle of bridge engineering. Rogage et al. (2022) focused on monitoring earthwork operations during the construction phase of large infrastructure projects through their proposed DT application. The data collected from the monitoring system proposed by Leander et al. (2023), including accelerometers and strain gauges, provided detailed information on a damage event, showing the system's utility in identifying structural damage and facilitating timely inspections to ensure bridge safety and integrity. Hagen et al. (2022)

showed the importance of online monitoring and DTs for risk and condition-based maintenance through the case study of a Norwegian bridge. In modular construction, digitalization plays a crucial role in advancing automation, as production processes remain largely manual (Kosse, et al., 2022). Research efforts to integrate DTs into prefabricated concrete element production are still in the initial stages, mostly comprising conceptual frameworks that address accuracy in design and fabrication, as seen in the works of Kosse et al. (2022), Lee and Lee (2021), Tran et al. (2021), and Rausch et al. (2021).

Digitalization presents several opportunities to benefit asset management: it improves available methods and tools with new data gathering techniques, image processing, remote sensing, digitalized visual inspection, and automation (Casas, 2024). However, asset owners have identified that the challenge with inspection, NDT, and SHM lies in translating extensive data into meaningful information to optimize decision-making, so Casas (2024) proposes the definition Key Performance Indicators (KPIs) so that, guided by engineering expertise, digitalization can effectively transform data into actionable insights.

Further examples of DT's purpose and applications are discussed in Paper II, which concludes that predictive maintenance might be the most important contribution of DTs within E&C due to the particularities of its assets. An E&C asset's lifespan largely surpasses its development phase; therefore, the maintenance and operation stages are where DTs can yield the greatest value. Even though the costs associated with fabricating E&C assets are high, the maintenance costs over the asset's lifespan are even higher.

SHM systems can trigger structural condition checkups and help in avoiding adverse situations like prolonged downtime, unnecessary inspections, and structural failure, thus accumulating valuable information for maintenance decisions (Neves, et al., 2019). For emergency planning and management, SHM can provide real-time data on the condition of structures, aiding in decision-making pre- and post-seismic events (Giordano & Limongelli, 2020). The premise behind predictive maintenance is that regular monitoring of an asset's condition will ensure the maximum interval between repairs and reduce the number and cost of unscheduled disruptions due to failures, thus reducing the overall cost of maintenance (Mobley, 2002). Increased equipment life, higher efficiency, and cheaper labor costs are all possible benefits of a predictive approach to maintenance (Hosamo, et al., 2022). Furthermore, ensuring proper functionality of a structure or infrastructure often impacts directly on the safety of its users, consequently, in the case of E&C assets, society in general. It does not replace traditional maintenance management methods, but it is a valuable addition to a comprehensive maintenance program (Mobley, 2002).

Predictive maintenance is a key enabling step of Industry 4.0, mostly discussed in the manufacturing domain (Thelen, et al., 2022). Hosamo et al. (2022) identified three elements needed to implement a practical predictive maintenance program: (i) big data collection from sensors; (ii) a platform that can implement automatic fault detection and diagnostics to improve the maintenance system and predict the faults; (iii) BIM to serve as an information source and repository, to avoid traditional methods in data transfer and visualize the results in a 3D model. Therefore, by providing a platform that can integrate these three elements, a DT can be an enabler of predictive maintenance (Thelen et al., 2022).

2.5 Maturity Level Classification and Standardization

Due to their complexity, DTs are often categorized into different maturity levels. Although most maturity level classifications present similarities, a universally recognized standard has yet to be established. The surge in popularity of the term "digital twin" has made it challenging to discern at first glance the cases that properly follow the concept and to evaluate their level of development. A standard classification for DT level of development would mitigate this issue, facilitate progress and knowledge sharing, and provide some much-needed clarity to this field of study. Then, instead of different "digital twin" allegations, there could be, for example, a "digital twin – level 1", accompanied by a clear set of criteria to advance to level 2.

Digital twin maturity level classifications have been proposed by, for example, Honghong et al. (2023), Lazoglu et al. (2023), MEED (2021), Evans et al. (2020), ARUP (2019), and a compilation of classifications proposed by companies B&N, AFRY, IBM and Autodesk are presented in Saback et al. (2023). There have also been focused E&C efforts, such as the Federal Highway Research Institute in Germany, which began a concept study for the unification of DT bridge components (Zinke, et al., 2023). In SHM efforts, Limongelli et al. (2024) proposed guidelines to support the design and implementation of monitoring systems for bridges. In general, the proposed DT maturity levels vary from basic virtual representation to autonomous decision-making DT capabilities.

This study adopts the classification proposed by ARUP (2019), also applied in Lazoglu et al. (2023), based on the concepts of fidelity, learning, intelligence, and autonomy. Autonomy refers to the system's ability to operate independently without human intervention. Intelligence involves the DT's capacity to simulate human cognitive functions and perform tasks on its own. Learning represents the twin's capability to independently acquire knowledge from data, thereby improving its performance without explicit programming. Finally, Fidelity relates to the system's accuracy, indicating how closely measurements, calculations, or specifications match the real-world system. The five maturity levels are presented in Table 1.

Table 1. Detailing the 5 DT maturity levels in terms of autonomy, intelligence, learning and fidelity. Adapted from ARUP (2019).

	Autonomy	**Intelligence**	**Learning**	**Fidelity**
Level 1	No autonomy (user-controlled)	No intelligence	No learning component	Low accuracy (conceptual model)
Level 2	User-assisted: prompts and notifications of system activity	Reactive: DT responds to stimuli	Responsive: DT programmed using an extensive list of commands	Low to medium accuracy: DT can be used to extract measurements
Level 3	Partial autonomy: DT can alert and partially control the system	Learning intelligence: DT can learn from historical data to make decisions	Supervised training: DT trained using supervised learning	Medium accuracy: DT is a reliable representation of the physical world
Level 4	High autonomy: DT can perform critical tasks with little to no human intervention	Collaborative intelligence: DT can understand the needs of other intelligent systems	Unsupervised training: DT trained using unsupervised learning	Medium to high accuracy: DT can provide precise measurements
Level 5	Full autonomy: DT can operate safely with no human intervention	Awareness intelligence: DT is self-aware with human-like intelligence and self-awareness	Full learning: DT uses reinforcement learning and interacts with environment	High accuracy: DT can be used in life safety and critical operational decisions

Besides a universally recognized maturity level classification, standardization in general has been acknowledged as prerequisite to drive progress of DTs in the industry. A major issue that the construction industry is facing regarding its productivity is the lack of standardization and mass manufacturing, with a large portion of the work consisting of unique items that must be made at the area where the products must be used (Stipanovic, et al., 2023). The first step to practically establish DTs in E&C is to develop common standards and processes tailored to the industry's practices and assets (Pregnolato et al., 2022). Furthermore, generally accepted and standardized regulations are required to develop DT applications that cover a wider range of infrastructures (Zinke, et al., 2023).

Standardization for DTs in E&C can cover several areas to help proper dissemination across the industry. For example, data standards would ensure consistency in data formats, enabling seamless integration and interoperability between different systems and platforms, while also including security measures to protect sensitive data and safeguard against unauthorized access and cyber threats. This would allow DT systems to interact seamlessly with other digital technologies, such as BIM, IoT devices, and AI platforms. Communication standards are needed for data exchange between the physical and digital components of the DT, as well as between various stakeholders involved in the lifecycle of the structure. Regulatory compliance standards within the DT could ensure obedience to industry-specific requirements, such as building codes, safety regulations, and environmental guidelines.

When developing standards for DTs in E&C, it is important to consider their alignment with Sustainable Development Goals (SDGs) (United Nations, 2015). DTs support several SDGs by optimizing processes and promoting sustainability across various sectors. According to Sepasgozar (2021), by enhancing resource and energy management, efficiency, and planning, DTs associate with SDGs 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land).

In addition to standardization, continuous research and investments in technological advancements are needed to address existing challenges in DT development and implementation. To expand DT applications, interdisciplinary collaboration between experts from various fields, such as engineering and computer science, is required, as well as educating and training professionals to work on those applications. Lastly, encouraging industry adoption and implementation by ensuring that the purpose of the DT is fulfilled is essential to facilitate the widespread adoption of DTs in E&C.

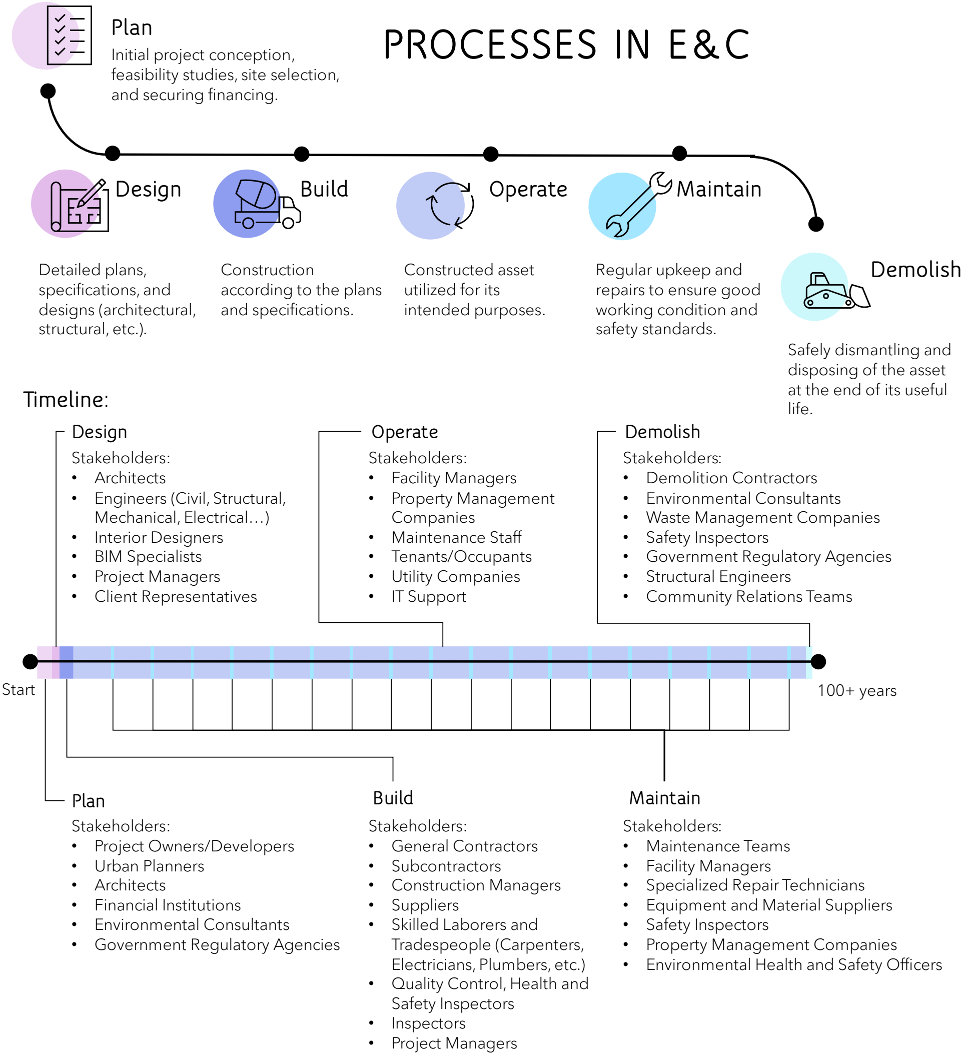
2.6 Industry Fragmentation

E&C is a highly fragmented industry comprising various segments, each with unique assets, production chains, and needs. These segments include, for example, building, infrastructure, and industrial construction, specialty trades (e.g., plumbing, electrical work), renovation and remodeling, real estate development, and demolition. This fragmented nature complicates ownership of E&C assets throughout their production chain, which, in turn, creates an uncertainty about who should invest in and benefit from the profits of creating and maintaining a DT.

In different industry segments, the financial responsibilities and benefits of a DT can be distributed among stakeholders at various stages of a project's lifecycle, making it challenging to establish a unified approach towards DT investment and utilization. That hinders the development of clear business models for DTs and, consequently, their propagation across the E&C industry.

E&C cannot simply replicate existing models from other industries due to the specificities of its assets and the fragmentation within the industry itself. Each segment caters to specific assets, stakeholders, and production chains, each with its own purposes and priorities. This fragmentation leads to the development of context-specific frameworks that are often not transferable or scalable across different projects or segments within E&C.

The E&C industry is currently linear, not circular, and DTs have the potential to assist in making it circular, which offers numerous benefits associated with the circular economy. A typical production chain for an asset within E&C is composed by various stages following a linear approach, illustrated in Figure 5. Although this is not the focus of this study, understanding these processes, different contract types and their influence on DTs is important for addressing the broader adoption of DTs.



Plan
Initial project conception, feasibility studies, site selection, and securing financing.

Design
Detailed plans, specifications, and designs (architectural, structural, etc.).

Build
Construction according to the plans and specifications.

Operate
Constructed asset utilized for its intended purposes.

Maintain
Regular upkeep and repairs to ensure good working condition and safety standards.

Demolish
Safely dismantling and disposing of the asset at the end of its useful life.

Design
Stakeholders:
- Architects
- Engineers (Civil, Structural, Mechanical, Electrical…)
- Interior Designers
- BIM Specialists
- Project Managers
- Client Representatives

Operate
Stakeholders:
- Facility Managers
- Property Management Companies
- Maintenance Staff
- Tenants/Occupants
- Utility Companies
- IT Support

Demolish
Stakeholders:
- Demolition Contractors
- Environmental Consultants
- Waste Management Companies
- Safety Inspectors
- Government Regulatory Agencies
- Structural Engineers
- Community Relations Teams

Plan
Stakeholders:
- Project Owners/Developers
- Urban Planners
- Architects
- Financial Institutions
- Environmental Consultants
- Government Regulatory Agencies

Build
Stakeholders:
- General Contractors
- Subcontractors
- Construction Managers
- Suppliers
- Skilled Laborers and Tradespeople (Carpenters, Electricians, Plumbers, etc.)
- Quality Control, Health and Safety Inspectors
- Inspectors
- Project Managers

Maintain
Stakeholders:
- Maintenance Teams
- Facility Managers
- Specialized Repair Technicians
- Equipment and Material Suppliers
- Safety Inspectors
- Property Management Companies
- Environmental Health and Safety Officers

Figure 5. Linear processes in E&C chain of production.

As seen in Figure 5, the stages in the production chain of a civil structure involve different stakeholders and vary in duration. During the Planning stage, stakeholders include project owners, architects, and financial institutions. The Designing stage requires engineers, while Building needs general contractors and construction managers, among others (refer to Figure 5 for a detailed list). Even though the initial stages are relatively short compared to the lifespan of 50 to 100 years for some civil structures, they comprise many steps and different stakeholders.

Developing a DT for lifecycle management of such structures requires well-defined transition plans to ensure the continuity of the DT's benefits throughout the process chain. One approach to achieve this is by specifying these details in a contract. The E&C industry employs different contract models to manage its complex projects and allocate risks and responsibilities appropriately, such as Build-Operate-Transfer (BOT), Build-Own-Operate-Transfer (BOOT), Design-Build-Finance-Operate (DBFO) and Build-Own-Operate (BOO) (Akbiyikli & Eaton, 2005). Figure 6 illustrates these contract types.

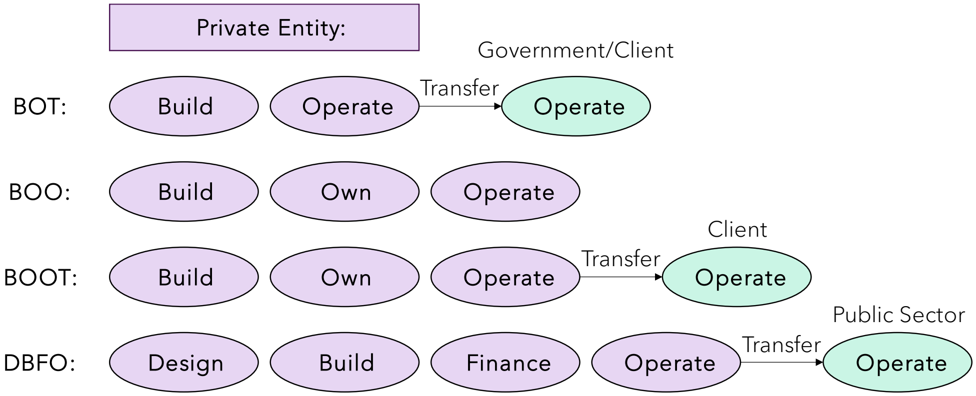


Figure 6. Examples of contract types within E&C.

BOT is a project financing model in which a private entity designs, builds, and operates a facility for a specified period before transferring ownership to the government or client. This model is often used for infrastructure projects such as toll roads and bridges, allowing the private sector to recoup its investment through operation revenues. The BOOT model includes an extended operation period before the transfer, providing the private entity with a longer timeframe to manage and profit from the facility. In the DBFO model, the private sector designs, builds, finances, and operates the project for a set period, after which the ownership is transferred back to the public sector. This model is frequently used for large-scale public infrastructure projects, facilitating private investment while ensuring public ownership in the long term. Finally, the BOO model entails a private entity building, owning, and operating a facility indefinitely, often applied to projects where long-term private sector control and investment are beneficial, such as in certain utilities and commercial developments. These models provide flexibility in financing and managing large infrastructure projects, balancing public and private sector interests.

Regardless of the contract type, the successful implementation of DTs requires well-defined transition plans, clear agreements on data ownership, maintenance responsibilities, and long-term management to ensure the benefits are fully realized throughout the asset's lifecycle as the project goes through different stakeholders. One potential solution could be the inclusion of a stakeholder, such as a Digital Twin Transition Manager, who is present throughout the contract to oversee and manage these aspects.

These particularities of processes, stakeholders, and contracts are key reasons why DTs are not more advanced in the E&C industry, aside from the technological challenge of creating an operational DT. Unlike other industries that have clear products and clients, the E&C industry often has ambiguous client definitions. For example, in the case of a bridge, society at large can be perceived as a client since the public uses the asset. Furthermore, even within the same type of asset, such as a bridge, there are variations; a steel bridge and a concrete bridge present different challenges in monitoring and modeling uncertainty, with steel being generally less complex. This adds another layer of complexity to the development and implementation of DTs in E&C.

To better illustrate these concepts, consider two examples: a commercial building and a highway bridge. In the building project, multiple entities are involved at various stages. A construction company is typically responsible for building the structure. They might invest in a DT for the construction process, including design, planning, monitoring progress and ensuring quality. After construction, the developer sells units to private individuals or companies. At this stage, the developer aims to recover their investment and make a profit from the sales – the early conception or long-term benefits of the DT are not directly relevant to the developer once the units are sold. Once the building is occupied, a property management company or a homeowners' association takes over the maintenance, and monthly fees from tenants or residents cover maintenance costs. They might invest in a DT for ongoing benefits like predictive maintenance, energy efficiency, and safety monitoring.

For infrastructure projects like highway bridges, the situation is slightly different but similarly complex. A construction company builds the bridge based on contracts funded by the government. The government is usually responsible for financing the entire construction process, potentially including the initial deployment of DT technology to ensure quality control and compliance with design specifications. After the bridge is built, a government or municipality agency takes over its operation and maintenance. This agency is responsible for the bridge's upkeep, safety inspections, and repairs. The benefits of using a DT include enhanced monitoring of the bridge's structural health, predictive maintenance to prevent failures, and optimized lifecycle management. However, the initial investment for these benefits is separate from the construction budget, and ongoing funding needs to be justified within public sector constraints.

The main challenge in both examples is the separation of ownership, investment, and benefits among different stakeholders. The initial investment is typically made by the developer or construction company, with a focus on short-term gains (selling units or completing the project on time). The long-term benefits are realized by the entities responsible for operation and maintenance (property management companies, homeowners, or government agencies), who focus on extending the life of the structure with safety, comfort and reducing maintenance costs.

While academia and tech-consultants frequently discuss DTs, it is crucial to consider these practical terms of the industry and the challenges associated with adopting this technology on the frontline. Casas (2024) identified one of the issues limiting the practical implementation of DTs within E&C as the different points of view and objectives between researchers and practitioners. Solving the technological challenges is imperative to have an operational DT, and this is where most DT frameworks currently focus. However, the practical implications of DT adoption, such as ownership, business models, and integration into existing processes, need to be addressed as well.

Chapter 3

Experimental Work and Digital Modelling

The main purpose of the experimental work held in this study was to provide data for a DT application, channeling lessons learned from the theoretical investigation. Given the complexity of developing a DT and the importance of remaining faithful to the DT concept, the proposed application was designed to start small and provide practical utility within the context of asset management of structures. By starting small, the plan aimed to identify and address issues faced during development and operation.

The approach involved creating a CDE to integrate current condition information from SHM and a BIM model in a DT to assist in decision-making, as illustrated in Figure 7. In the literature, various types of instrumentation and sensors were identified, including NDT, photogrammetry, laser scanning, ground penetrating radar, infrared scanning, fiber optic sensors (FOS), unmanned aerial vehicles (UAV), light detection and ranging (LiDAR), and total stations, as documented in Paper I. Each of these options offers satisfactory results for different purposes; however, the final selection of instrumentation for the experimental programs was based on availability, functionality, cost-benefit ratio, and resources.

This section presents the experimental programs and their respective digital models developed during the study, covering three case studies here named FOS beam, Trough Bridge, and Snow Galleries (Figure 8). The digital models were created using BIM in Revit (Autodesk, 2024) and FE analysis in Atena (Cervenka Consulting, 2024). The sensors used included strain gauges, FOS, and Digital Image Correlation (DIC). Since all experiments have been described in detail in appended or additional publications, this section focuses on their contributions to the aims of this thesis.

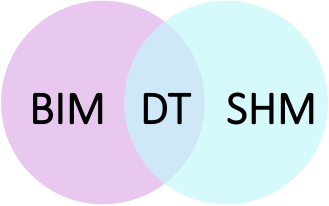


Figure 7. Schematic illustration of integrating BIM and SHM in a DT.

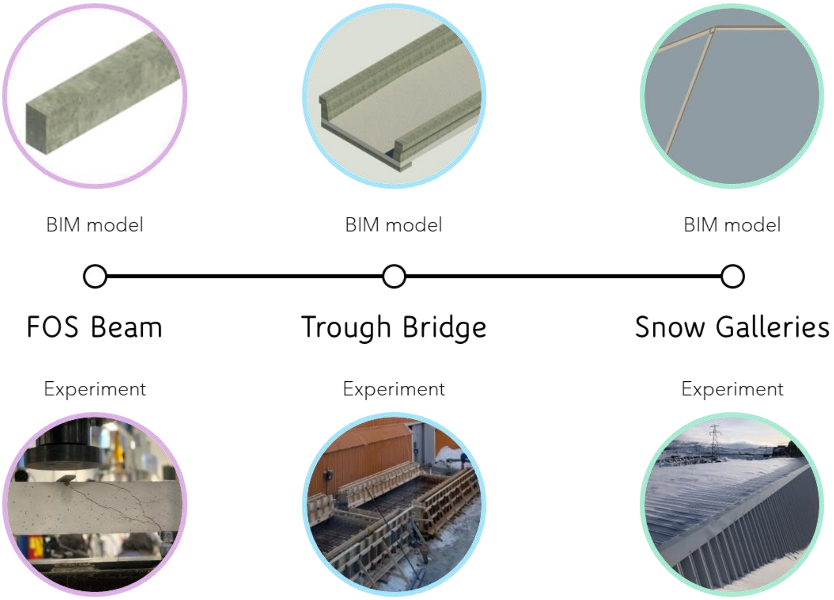


Figure 8. Experimental work and digital modelling illustration.

3.1 FOS Beam

The first experimental program, named FOS Beam, consisted of a small reinforced concrete beam specimen instrumented with FOS. This program was designed to be a pilot study for working with FOS, DIC, BIM and FE modelling. The FOS Beam was part of an experimental program and digital modelling but was not included in the proposed DT platform, which was applied directly to the other case studies, i.e., Snow Galleries and Trough Bridge.

Figure **9** illustrates a timeline for the project and its tasks; for the FOS Beam experiment, I was involved in all stages.

The beam was subjected to a three-point bending test until failure. Two different positions were tested for the FOS: bonded with epoxy glue into a groove carved in the rebars and bonded with adhesive tape outside the rebars. The strains measured by the sensors in both cases were compared, and the fibers inside the groove presented better results. The most successful outcome was then replicated in the following case study, named Trough Bridge. The cracks detected from strains measured by FOS in the rebar were compared with the surface measurements from the DIC system. To prepare the front surface of the beams for DIC, any holes were filled with wall putty, the surface was completely painted with white contrast spray paint, and a black speckle pattern was applied using a proper roller. The fiber optic system used in the FOS Beam experimental

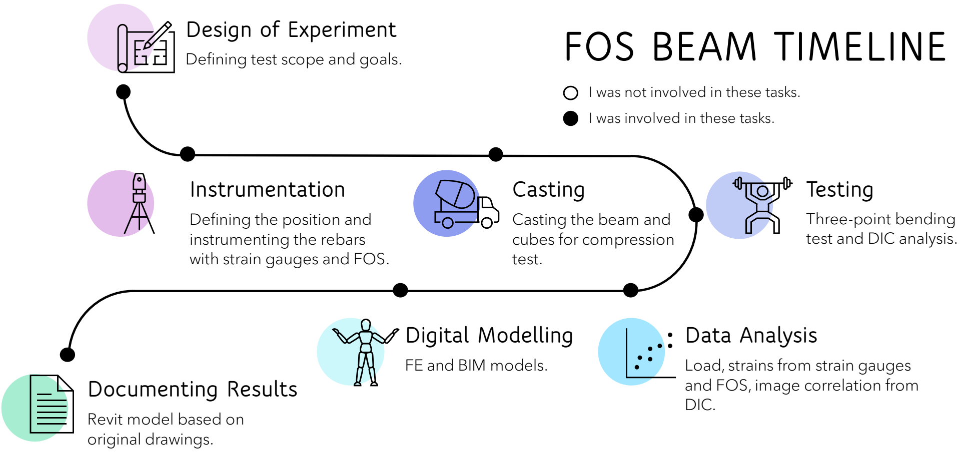


Figure 9. Timeline of the FOS Beam project.

program was ODiSI 6, from Luna Innovations (Luna Innovations Incorporated, 2020), and the DIC system was ARAMIS 5M. A BIM model of the beam was created in Revit (Autodesk, 2024) and a FE model was created in Atena (Cervenka Consulting, 2024).

DIC offers several benefits for assessing concrete structures. It is a non-contact, optical measurement method that captures surface displacement and deformation efficiently, making it a valuable alternative to traditional sensors (Hoult, et al., 2016). DIC's quick implementation and convenience facilitate the rapid and accurate evaluation of concrete cracking, a critical indicator of structural degradation, thus reducing the time and subjectivity associated with visual inspections (Mohan & Poobal, 2017). The existing condition of many important concrete structures can be assessed through the detection and monitoring of cracking; for example, in concrete bridge decks, crack openings beyond 0.15 to 0.2 mm will allow excessive penetration of water and chloride ions, leading to the corrosion of steel reinforcements (Casas & Cruz, 2003).

Besides monitoring concrete cracks, analyzing reinforcement strain, particularly tensile strain, is important for assessing the safety of structures as well. Reinforcement strain is at its highest at the location of cracks, which is not easily predicted before they occur. The use of continuous methods, such as FOS, offers significant benefits for structural health monitoring, especially in measuring reinforcement strain. FOS can provide continuous and distributed strain measurements along the length of reinforcement, offering detailed insight into tension stiffening and cracking behavior of concrete. Furthermore, it is free from corrosion, has long-term stability, allows continuous monitoring, is free from electromagnetic interferences, avoids undesirable noise, has a very low signal transmission loss enabling remote monitoring, and its sensors are small and light, making it possible to permanently incorporate them into structures (Casas & Cruz, 2003). This method is also cost-effective and labor-efficient, as demonstrated by studies such as those by Davis et al.

(2017) and Barrias et al. (2018), which showed good correlation with strain gauge measurements and highlighted the potential of FOS in reducing the costs and complexity of structural assessments.

The main conclusions from the FOS Beam experimental program indicated that the FOS embedded within the reinforcement bars offered greater reliability compared to those placed directly in the concrete, as cracks obstructed the accuracy of measurements. Furthermore, the assessment of crack detection by FOS demonstrated similar quality and reliability to that achieved by DIC methods. Lastly, the crack analysis using distributed FOS inside reinforcement bar presented good and reliable results, which was proved upon comparison with images from the crack propagation from the DIC system.

Figure 10 presents a schematic illustration of the FOS Beam test setup, Figure 11 shows a picture of the beam in the test frame with the DIC camera, and Figure 12 shows the BIM model. More information about the FOS Beam experimental program and detailed results from these analyses can be seen in the Licentiate dissertation (Saback, 2022), and in Saback et al. (2022).

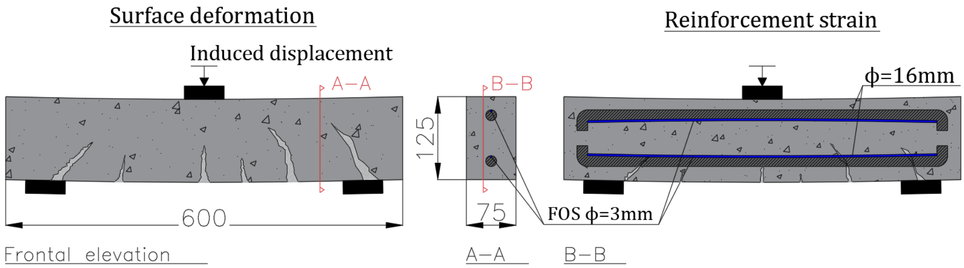


Figure 10. FOS Beam test setup: schematic illustration.

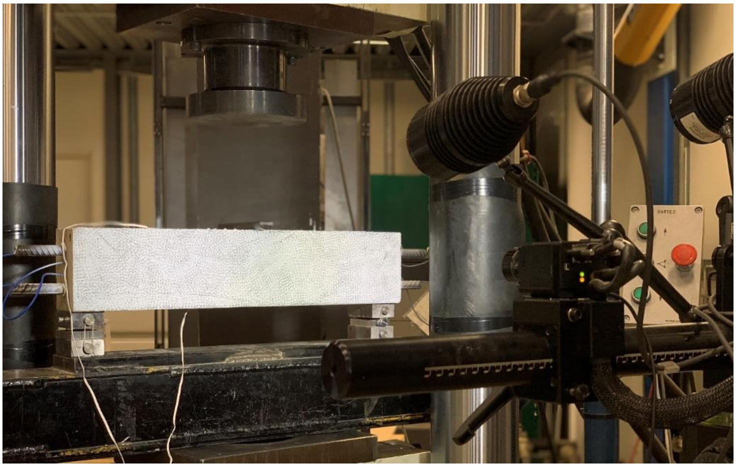


Figure 11. FOS Beam test setup.

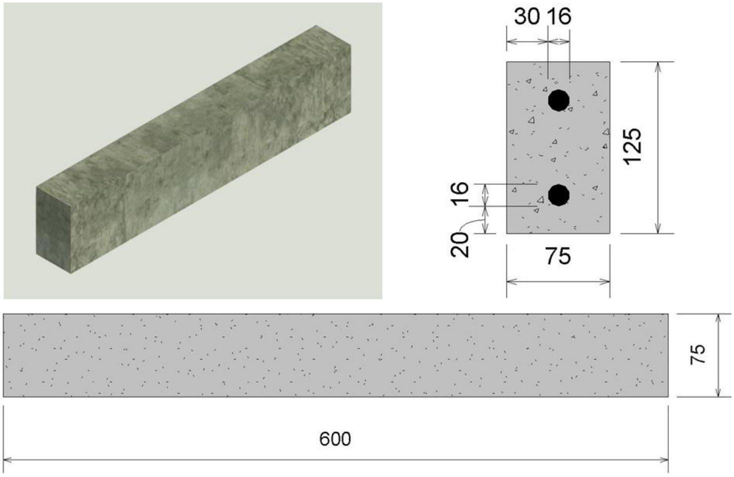
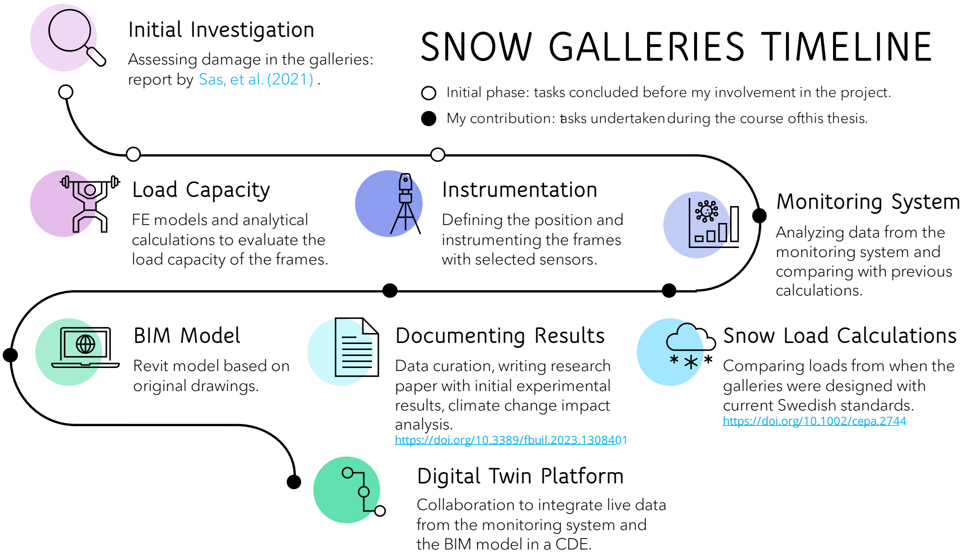


Figure 12. FOS Beam BIM model: 3D rendering (top, left), cross section dimensions (top, right), longitudinal dimensions (bottom).

3.2 Snow Galleries

The experimental work and digital modelling within the Snow Galleries project can be divided into two phases: an initial phase, consisting of investigation and instrumentation, and a second phase, including data analysis and digital modelling. The initial phase was concluded before I joined the project, so I have thoroughly reviewed and complemented the work that was accomplished before engaging in the second phase. Figure 13 illustrates a timeline for the project and the activities performed in each phase.

The objective of this case study was to apply the DT methodology to a structure that would benefit from live SHM data integrated in a CDE with a 3D model to improve decision-making in asset management. A snow gallery is a tunnel-like structure that protects roads, railways, and their traffic from heavy snowfall; it helps maintaining accessibility and safety during winter by preventing excessive snow accumulation and obstructions on transportation routes. To ensure efficient operation of this transportation route, the snow galleries go through routine inspections to evaluate snow accumulation and eventual obstructions. Therefore, remotely accessing snow load data in a DT might reduce the need for inspections under extreme weather conditions, minimize human error, facilitate data analysis, and help draw conclusions from historical data to prevent accidents.


SNOW GALLERIES TIMELINE

○ Initial phase: tasks concluded before my involvement in the project.

● My contribution: tasks undertaken during the course of this thesis.

Initial Investigation

Assessing damage in the galleries: report by Sas, et al. (2021) .

Load Capacity

FE models and analytical calculations to evaluate the load capacity of the frames.

Instrumentation

Defining the position and instrumenting the frames with selected sensors.

Monitoring System

Analyzing data from the monitoring system and comparing with previous calculations.

BIM Model

Revit model based on original drawings.

Documenting Results

Data curation, writing research paper with initial experimental results, climate change impact analysis.

https://doi.org/10.3389/fbuil.2023.1308401

Snow Load Calculations

Comparing loads from when the galleries were designed with current Swedish standards.

https://doi.org/10.1002/cepa.2744

Digital Twin Platform

Collaboration to integrate live data from the monitoring system and the BIM model in a CDE.

Figure 13. Timeline of snow galleries project.

Sas et al. (2021) reported that sixteen snow galleries in the Iron Ore Line, a crucial transportation route in Sweden, had been damaged over the years due to excessive snow loads. That triggered further investigation by Luleå University of Technology (LTU) and Swedish Transport Administration (TRV), to prevent similar occurrences in the future. The design snow load required by standards when these galleries were built was up to 60% lower than what is required by today's standards (Saback, et al., 2023). With time and technology, measurements of parameters comprised in snow load calculation became more frequent and accurate, and additional parameters have been included such as roof shape, thermal flow on roofs, and terrain exposure. Moreover, snow loads are predicted to increase in the future with climate change, due to higher precipitation and higher probability of extreme snowfalls.

In the first step of the investigation, the structural capacity of two snow galleries, SG9 and SG13A, was evaluated using finite element modelling and analytical calculations. The maximum load, displacement and stress supported by SG9 and SG13A before collapse were established, as well as the critical positions for instrumentation of the monitoring system. The monitoring system consisted of strain gauges to measure strains in the steel column, temperature obtained from nearby stations, and a laser beam to measure displacements on the top beam, which unfortunately did not yield reliable results and was disregarded.

Strain gauge measurements were used to calculate the snow loads as axial forces in the columns of the critical frames, which were then compared to the calculated capacities. Three snow load zones were established to facilitate interpretation of results: green, yellow, and red. In the green zone, snow load is below the capacity of all main frames and secondary beams. The capacity of the main frames in the yellow zone is still sufficient, but the secondary beams have reached their load-bearing capacity. In the red zone, load-bearing capacity has been reached for the main frames as well as the secondary beams. The results from the experimental campaign and monitored snow loads for SG9 and SG13A are presented in detail in Paper III.

For digital modelling the snow galleries, a BIM model of SG13A was created in Revit (Autodesk, 2024) from the original drawings, consisting of the steel frames that make up the gallery. Figure 15 presents renderings from the BIM model of SG13A (all frames) and from the frame in which the monitoring system was installed, i.e., frame 1535+420. Figure 15 presents measurements for frame 1535+420 as well as the cross sections of the steel beams which compose it, and Figure 16 contains two pictures of SG13.

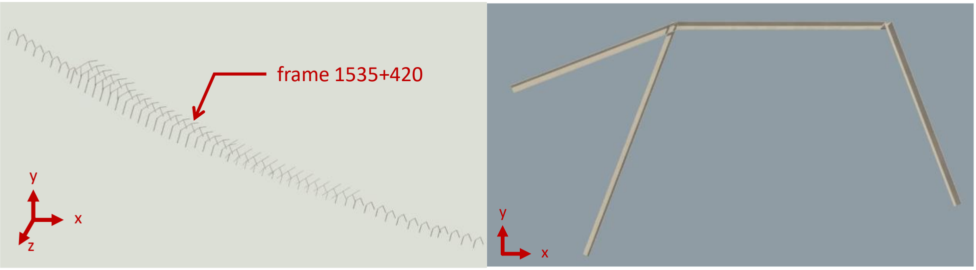


Figure 14. BIM model: rendering of SG13A (left) and instrumented critical frame 1535+420 (right).

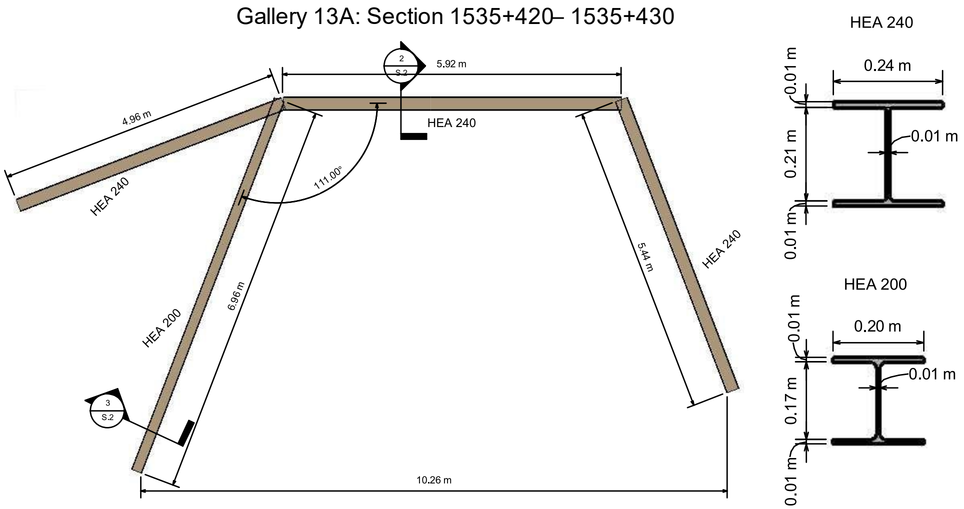


Figure 15. Measurements of SG13A (left) and cross section of steel beams HEA 240 (right, top) and HEA 200 (right, bottom).

Figure 16. Snow galleries view from outside (left) and inside (right).

3.3 Trough Bridge

In a railway concrete trough bridge, the bridge deck is supported between two vertical girders, forming a U-shaped reinforced concrete cross-section. This creates a trough or channel in which the railway tracks are laid. This design helps contain the ballast (crushed stone or gravel that forms the track bed), providing stability for the railway tracks, strength and durability to support railway loads and withstand environmental conditions.

The Trough Bridge project has a comprehensive experimental program with the goal of developing a procedure to evaluate the true structural capacity of bridges. Since many bridges are nearing the end of their design life, the premise behind the project is that a reliable evaluation of their true structural capacity could potentially extend their lifespans. This evaluation can avoid replacing these bridges, thereby prolonging their technical lifespans, which is a more sustainable solution both environmentally and financially.

A series of laboratory tests are planned for two real scale trough bridges, named TB1 and TB2, cast at Luleå University of Technology (LTU). The tests include serviceability and fatigue limit state capacity, reliability analysis, and static load pressure distribution analysis. Numerical models such as FE and deterioration models are also included in the Trough Bridge project scope. The project deploys a wide team of researchers to execute all the planned tests and respective digital models. Figure 17 illustrates a timeline for the project, differentiating the tasks I did and did not contribute to.

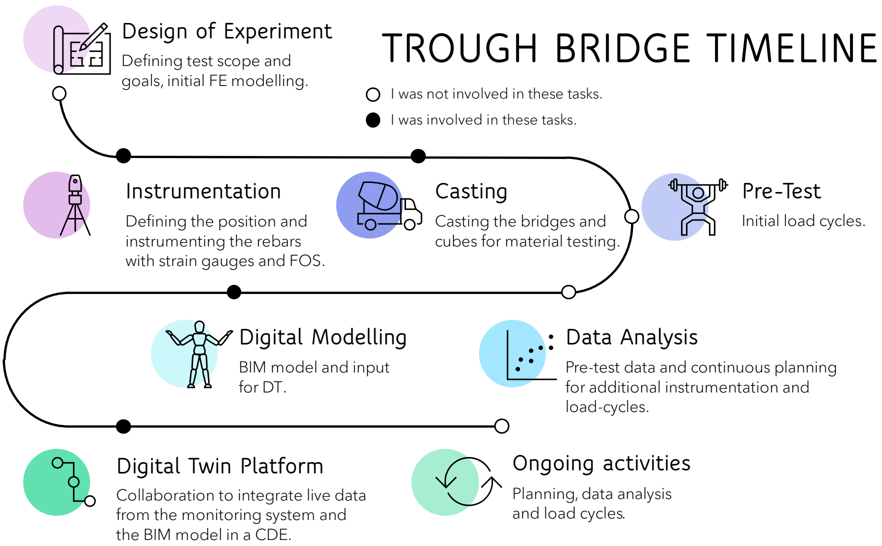


Figure 17. Timeline of the Trough Bridge project.

So far, both bridges have been instrumented and cast, and loading cycles have begun. The total length of the bridges is 7.20m, with 3.80m of width (Figure 18). Each bridge was instrumented with eight fiber optic sensors in selected rebars. The fibers were applied inside a groove carved into the rebars and bonded with an epoxy glue. The fiber optic system used was ODiSI 6, from Luna Innovations Inc. (Luna Innovations Incorporated, 2020), similarly to the FOS Beam. Besides FOS, some rebars were also instrumented with strain gauges to perform point strain measurements. Figure 19 shows an application of a strain gauge and a FOS into a rebar, and Figure 20 shows the rebars that were instrumented with the fibers and the position of the strain gauges. A BIM model of the trough bridge was developed in Revit (Autodesk, 2024) and is illustrated in Figure 21.

For this study, a pre-test of TB1 served as a demonstration for scalability of the proposed DT platform – discussed in chapter 5. Case Studies: Digital Twin Implementation. Furthermore, it represented practical work with FOS, strain gauges, data analysis, and digital modelling. More information about the trough bridge can be found in Paper V, in the Licentiate dissertation (Saback, 2022), and in upcoming publications from the Structural and Fire Engineering division at the Civil, Environmental and Natural Resources Engineering department at LTU, including the latest results in Sarmiento, et al. (2024)

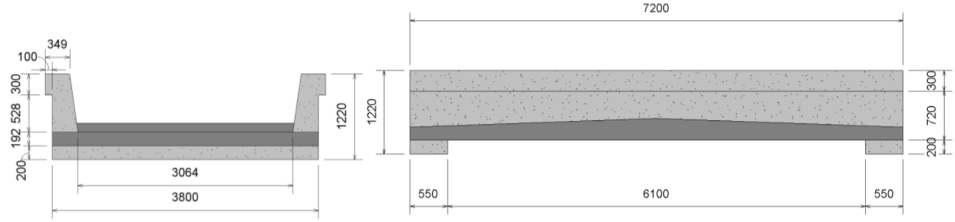


Figure 18. Trough bridge drawings: frontal elevation (left) and lateral elevation (right).

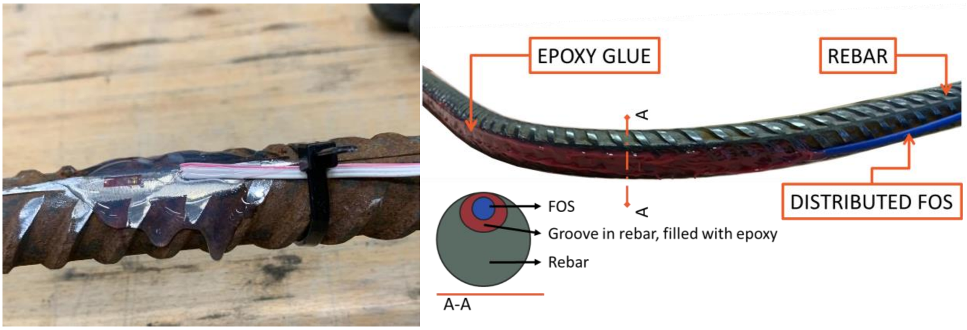
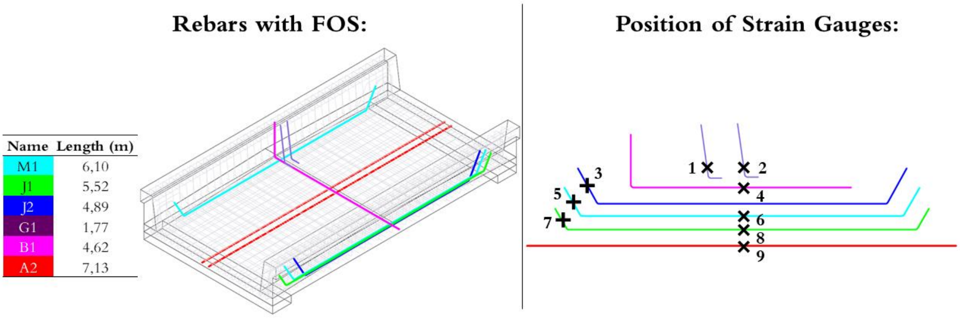


Figure 19. Trough Bridge instrumentation: strain gauge in rebar (left), FOS bonded into groove (right).



Rebars with FOS:

Name	Length (m)
M1	6,10
J1	5,52
J2	4,89
G1	1,77
B1	4,62
A2	7,13

Position of Strain Gauges:

Figure 20. Trough bridge instrumentation: rebars instrumented with FOS (left) and position of strain gauges in these rebars (right).

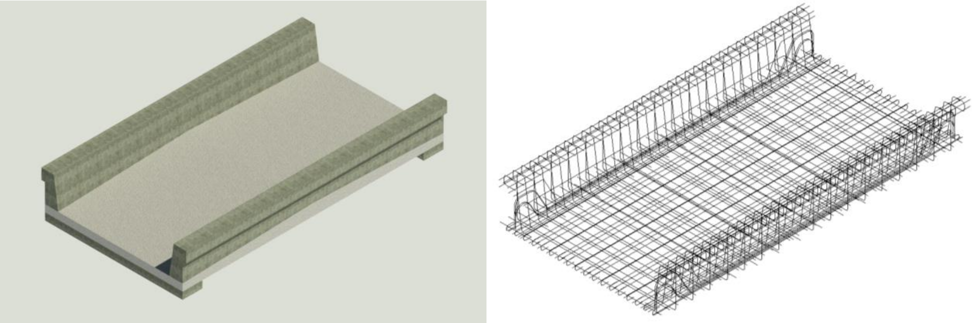


Figure 21. Trough Bridge BIM model: 3D rendering (left) and reinforcement (right).

Figure 22. Casting Day for the two trough bridges (left), transportation of TB1 (right, top), TB1 inside the laboratory (right, bottom).

Chapter 4

Digital Twin Platform

Building on the knowledge acquired from theoretical investigations, the following goal was to propose a methodology for developing DTs to improve asset management of civil structures. The aim of this methodology would be to integrate current condition information of the structure via live SHM data and an informed 3D digital model via BIM. This integration facilitates interpretation of results, improves decision-making, and stores relevant information for behavior analysis. This aim is previously illustrated in Figure 7, which shows a Venn diagram connecting BIM and SHM with a DT at their intersection.

While many other applications can theoretically be accomplished with a DT, as seen in the literature, the aim was to start small with a simple application, then gradually build on Technology Readiness Levels (TRL) to stay true to the DT concept. TRL are a systematic measurement system that supports the assessment of the maturity of a particular technology and the comparison of maturity between different types of technology (Conrow, 2011; Mankins, 1995).

Connecting live SHM data with a 3D model within a single CDE that can be accessed by interested parties would provide a way to monitor the current condition of a structure and assist in decision-making. This approach represents a significant step to build on existing knowledge and moving towards a more comprehensive DT platform.

DT frameworks were proposed from the literature (Saback de Freitas Bello, et al., 2022; Saback, et al., 2021; Saback de Freitas Bello, et al., 2021), then the study was directed towards assessing practical tools available to try and accomplish a functional DT for the intended purposes. Different methods and approaches were evaluated, such as Industry Foundation Class (IFC) (buildingSMART International, 2024), ACCA Software (ACCA, 2024), Power BI (Microsoft, 2024) and VCAD (Blogic s.r.l., 2024), ThingWave Reality (ThingWave, 2024), BIM 360 (Autodesk, 2024), Revit APIs (Autodesk, 2024), and Autodesk Platform Services (previously Autodesk Forge) (Autodesk, 2024), besides cloud computing platforms like Azure (Microsoft, 2024) and AWS (Amazon, 2024), and programming languages like Grasshopper, Python, Java, etc. The platform selection was based on its capabilities for data integration from various sources, representing its potential to house a DT, and complexity of programming requirements and licensing, since resources were limited.

Some progress was accomplished on different fronts, but finally a collaboration was established for customizing a platform for 3D visualization to overcome overwhelming programming demands to integrate live sensor data and BIM in a CDE. The final architecture of the was shaped from my research, feedback, and close collaboration to convey the platform's needs and requirements to an external developer.

The final platform was then applied to the Snow Galleries and Trough Bridge case studies. BIM is represented by the models created in Revit (Autodesk, 2024) for both the galleries and the bridge, the SHM sensors were strain gauges for the galleries and FOS for the bridge, and a new application called DataConverterApp was created to integrate them in a customized CDE. ThingWave Reality is a tool with integrated data storage and processing capabilities for working with 3D models, the customized version was developed for this study to enable the program to manage and visualize the sensor data from the snow galleries. Figure 23 illustrates the general architecture of the final DT, described in detail for each case study in chapter 5. Case Studies: Digital Twin Implementation, in Paper IV for the Snow Galleries, and in Paper V for the Trough Bridge.

For the snow galleries, the DT platform enabled real-time visualization of snow load data derived from the strain gauges, offering facilitated interpretation due to the color-coded load zones. This feature can reduce the need for inspections under extreme cold weather by allowing for ongoing monitoring of load conditions within the system. As for the bridge, although the project is still ongoing, a demonstration was conducted during a pre-test to show the adaptability of the proposed platform to a different structure instrumented with different sensors. This flexible system architecture can be expanded, replicated, and classified based on maturity levels.

Before proper standards for DTs in E&C are established, it is possible to create proof-of-concept DTs, but developing fully operational DTs for complex applications remains more challenging. Following the application of the proposed DT platform to the case studies, the focus of this study shifted from further improving the platform. Although advancing the platform's maturity level or expanding the scope of SHM data would have been relevant, these efforts would primarily address technological and program development challenges, limited by available resources. Instead, the focus shifted to bridging the gap between perceived potential and practical DT applications and to how to promote widespread adoption to enable the industry to secure the benefits.

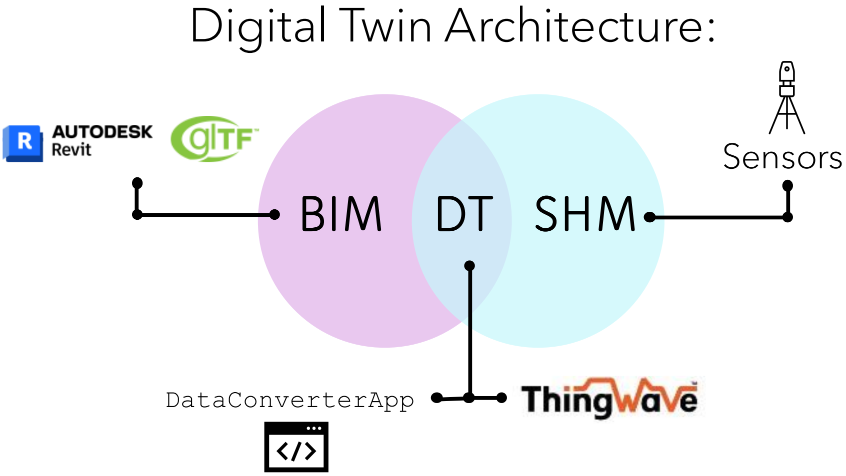


Figure 23. Digital Twin platform general architecture.

Chapter 5

Case Studies: Digital Twin Implementation

This chapter presents the DT implementation in two case studies: Snow Galleries, detailed in Paper IV, and Trough Bridge, detailed in Paper V. In Paper VI, a purpose-driven DT roadmap is proposed, and its application is demonstrated through a case study of a reinforced concrete chimney in Sweden. Since that case study is used to exemplify the steps of the roadmap and its data is not part of DT implementation, it is not detailed in this chapter.

5.1 Snow Galleries

The application of the proposed DT platform to the snow galleries case study was aimed at facilitating visualization of live snow load data from the monitoring system, thus reducing the need for routine inspections. Starting with a small sub application that can grow is an effective way to develop a DT. This approach allows for a focus on the specific purpose and evolve based on the results, demonstrating how it can benefit the project incrementally. In the case of the snow galleries, continuously monitoring axial column snow loads based on strains measured by strain gauges in a critical frame demonstrates the potential of a DT for asset management in such structures. This is particularly important due to the location of the galleries, on a critical transportation route and under extreme winter conditions, making their efficient functioning a priority.

For SG13A, a 3D model was created using Revit (Autodesk, 2024) and converted to glTF 2.0, and SHM data comes from strain gauges. The data flow from the physical asset (snow gallery) to the digital asset (digital twin) consists of the live monitoring data visualized in the 3D model in the digital environment. The physical-to-digital data flow is obtained through feedback from system intelligence, which triggers human intervention in the galleries. Then, predictive maintenance can be performed before more costly interventions are needed or there is any risk to safety. SHM data and the 3D model were integrated through the DataConverterApp, the MQTT (Message Queuing Telemetry Transport) protocol was added to enable live data. On the platform, the 3D model can be visualized and interacted with, and live snow load data can be seen in a graph in green, yellow, or red, following the pre-established color-coded scale. Based on ARUP (2019), the proposed DT of SG13A can be classified as a Level 2 DT in autonomy, intelligence, learning, and fidelity. Figure 24 illustrates the complete system architecture and Figure 25 shows the visualization of snow load data on the DT – both are thoroughly detailed in Paper IV, which also addresses the necessary steps to improve the DT's maturity level.

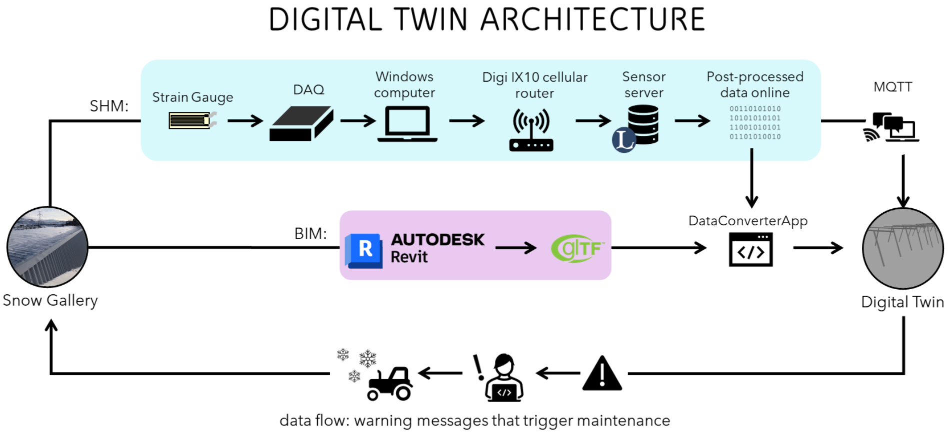
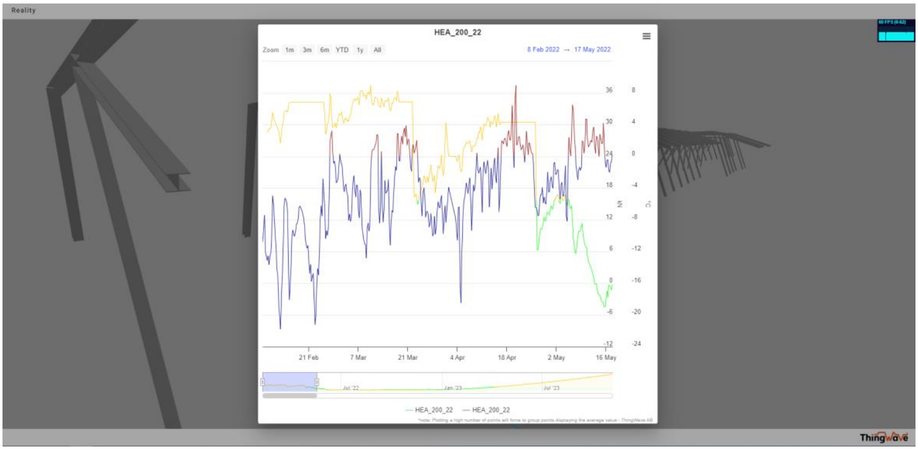


Figure 24. DT system architecture: Snow Galleries case study.



*note: Plotting a high number of points will force to group points displaying the average value - ThingWave AB

Figure 25. Visualization of the snow load data and the 3D model on the DT platform.

5.2 Trough Bridge

The benefits of DTs for asset management of bridge structures have been asserted at this point. Therefore, the specific objective of this case study was to demonstrate the proposed DT platform's adaptability to work with different structures and sensors, a concrete bridge instead of a steel frame from the snow galleries, and FOS rather than strain gauges. Since the Trough Bridge project is very comprehensive experimental program, which is still ongoing, it was not possible within the timeline of this thesis to have a full DT application for the bridge. Therefore, a demonstration of its functionality was performed during a pre-test. In the pre-test, load cycles were applied to the bridge in four axles, the values were established to ensure elastic behavior and that no permanent damage was inflicted on the bridge.

Similarly to the Snow Galleries case study, the basic architecture of the proposed DT, illustrated in Figure 26, consists of integrating a 3D model with real-time SHM data in a single, collaborative platform. To achieve this, a software plugin application was implemented to read data from the LUNA system, convert the data format used by LUNA into a JSON-based format, and forward it into the DT platform in real-time. Within the platform, the data stream from LUNA was mapped into digital representations of rebars and sensors to visualize the measured deformations. The sensor data can be visualized by visually changing the color of the digital representation of the physical elements, and by traditional signal plots to see current and historical data simultaneously.

Finally, as the bridge was loaded, the DT was showing the load detected by the sensors, which enabled the audience to visually see how the bridge was affected by the load cycles, all in real time. Although this is a prototype tested in a controlled laboratory environment, the potential scalability of the proposed solution can still be assessed. Through platforms such as this one, managers can improve the way data is visualized, stored, and shared.

Figure 27 shows the visualization of the 3D model and live data on the DT platform, a more detailed account of the DT platform for this case study can be seen in Paper V, and results from the pre-test are available in Sarmiento, et al (2024).

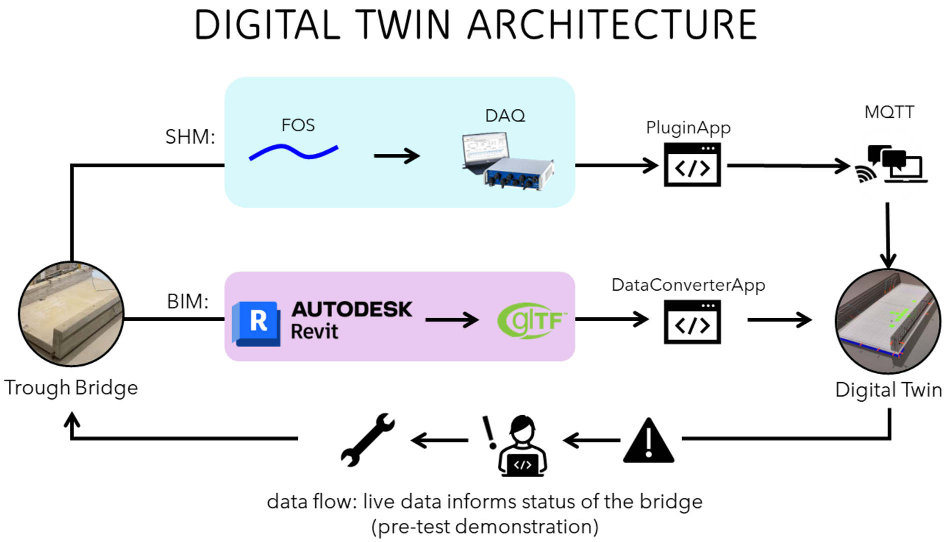


Figure 26. DT system architecture: Trough Bridge case study (pre-test live demonstration).

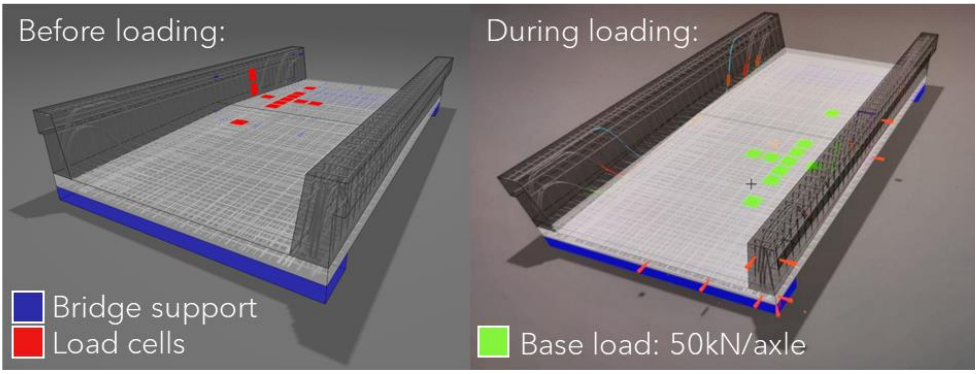


Figure 27. Visualization of the 3D model on the DT platform (left) and live data visualization (right).

Chapter 6

Conclusions

The E&C industry has vast potential to leverage technology for solving current asset management issues, there is plenty of options for technological tools, and the environmental and financial prospects of such changes are huge. Motivated by these prospects, this study investigated the use of DTs for asset management of civil structures. When diving deep into the subject, it became clear that there is a substantial gap between the perceived potential of DTs and the efforts to develop practical applications, largely due to misconceptions and lack of standardizations.

To address this gap, a thorough literature review on DTs, asset management in E&C, and related topics was conducted. Practical tools were then explored to propose a scalable and usable DT methodology. Experimental programs were planned and executed to establish a baseline for a practical application of this methodology. A proof-of-concept DT platform was developed and applied to two case studies: a real-life application involving snow galleries in a crucial transportation route, demonstrating how a digital tool could enhance safety by monitoring snow loads, and a laboratory demonstration on a real-scale bridge, showcasing the platform's versatility with different sensors and structures.

The proposed DT platform emerged as a flexible, scalable, and user-friendly solution for asset management in civil structures. It goes beyond theoretical frameworks by providing proof-of-concept case studies that illustrate how DT technology can enhance current structural management practices. The platform's flexibility allows it to be customized for various structures and sensor data types, while its capacity to manage large volumes of data effectively ensures scalability. Additionally, the user-friendly interface requires no prior programming knowledge, facilitating potential implementation by asset managers.

Beyond this point, further development of the platform would require addressing programming and technology challenges, which were beyond the resources of this study. The platform has potential to be improved and applied to real life situations but given the complexity of programming a comprehensive DT platform, collaboration with professionals from various fields, particularly programmers, is essential. Since improving the technology platform was not feasible within the resource constraints, the study shifted focus back to a structural engineering perspective on understanding the barriers to successful DT implementation in E&C and promoting widespread adoption. A purpose-driven roadmap was proposed to bridge the gap between the perceived potential and practical applications of DTs, aiming to facilitate industry-wide adoption and utilization of DT benefits.

The research questions posed in the first chapter of this thesis are addressed through the appended papers and summarized as follows:

RQI. What is the status of digital twins, in terms of both perceived potential and maturity level of practical applications, in Engineering & Construction compared to other industries?

Digital twins have gathered significant attention, leading to a surge in research that, up to some extent, translates to advancements in the E&C industry. However, this fast growth has also proliferated misconceptions. The perceived potential of DTs is evident in numerous publications highlighting what they "can do" to enhance processes across all lifecycle stages, from design to maintenance. All sorts of automation are described as possible; benefits and frameworks for DT applications from the literature are presented in Paper I. However, despite this optimism, the maturity level of practical applications lags behind.

Other industries began their digital transformations earlier than E&C and have thus made more progress in applying and evolving DT technologies. That progress manifests itself as time and investment dedicated to figuring out how to apply these technologies in ways that yield results, testing practical applications, and evolving them. These industries are also more likely to have standardized products, such as cars in the automotive sector, whereas products in the E&C industry are often unique. The E&C industry, starting later and known for slow technological adoption, continues to grapple with basic concepts. The literature review showed significant interest and potential in DTs, but their fragmented application in E&C, with varying definitions and low maturity level applications, hinders the development of standardized, scalable solutions.

RQII. What is the purpose of digital twins in the Engineering & Construction industry?

Assets in the E&C industry have many particularities. They require extensive time for planning and construction, but their lifespans are even longer. Consequently, while the initial costs of bringing these assets into existence are high, the maintenance costs over their lifetimes are even greater. This complexity raises questions about who should bear the costs of developing and maintaining a DT, given the different stakeholders involved throughout an asset's lifecycle.

Given these characteristics of the assets, along with considerations of a circular economy mentality, environmental and sustainability concerns, the lengthy lifespans, and the high maintenance costs, the purpose of DTs in the E&C industry is primarily for asset management and maintenance. The challenges with current inspection processes, particularly for infrastructure, and the critical importance of ensuring safe operation of these assets for society further underscore this purpose.

DTs should be integrated in a project from its earliest conception so all information about the asset can be managed throughout its lifecycle. Rather than a visualization tool that becomes obsolete after construction and as-built modifications are not incorporated, DTs should go beyond being just advanced 3D models and their potential lies heavily post-construction. Their application should focus on monitoring current conditions, automating inspections, reducing human error and manual knowledge transfer, facilitating access to digital environments, enabling predictive maintenance, and ensuring safety – all in an integrated platform. This approach can simulate future behavior and degradation, ultimately reducing costs and enhancing safety and efficiency. This purpose should be the primary consideration when investing in a DT application so the result is relevant, useful, and can survive outside the theoretical realm. Considerations of the purpose of DTs for the E&C industry are elaborated in Paper II.

RQIII. How can a digital twin improve asset management and maintenance in Engineering & Construction?

After the theoretical investigation outlined the benefits and potential of DTs and laid out the grounds for a DT methodology, a practical application was proposed and tested. Paper III introduces the first case study, detailed in Paper IV, while Paper V presents the second case study demonstration. The first case study demonstrated how live monitoring of snow loads via DTs could enhance the assessment of a snow gallery, a critical structure protecting an important transportation route. This application showed that real-time snow load monitoring in a DT could reduce the need for manual inspections under extreme weather conditions, improving safety and efficiency. By further developing this DT application, additional benefits could include predictive maintenance, reducing unplanned downtime, optimizing resource allocation, and providing more accurate data for long-term planning and decision-making.

There is extensive literature on how DTs can enhance asset management and maintenance of bridges. In the demonstration presented in Paper V, it shows how live sensor data is visualized on the DT of a bridge. In a real situation involving an instrumented bridge, using a DT to monitor loads offers numerous benefits: it facilitates the interpretation of data by providing real-time insights into the structural performance, eases access to critical information for stakeholders, reduces human error by automating data collection and analysis, and improves safety by enabling proactive maintenance and early detection of potential issues.

Both case studies illustrated the practical applications of DTs, showing their potential to enhance asset management through real-time monitoring and data integration. By developing a flexible, scalable, and user-friendly DT platform, the study demonstrated how DTs could improve safety, operational efficiency, and decision-making in the E&C industry.

RQIV. How can the Engineering & Construction industry bridge the gap between perceived potential and practical applications and effectively implement digital twins to leverage the benefits of this technology?

The E&C industry faces significant challenges in advancing adoption of DTs, primarily due its unique complexities. The industry is characterized by fragmentation into different segments, each with distinct assets, production/supply chains, and stakeholders. These challenges are aggravated by the lack of clear ownership, established business models, and defined transition plans and agreements on data management. These challenges give rise to the proliferation of scattered and decentralized DT frameworks. Each DT initiative often forges its own distinct path, lacking a cohesive foundation and standardization. This diversity results in varied definitions of what constitutes a DT, leading to unclear applications and difficulties in replication. These frameworks are frequently context-specific or tied to particular technologies, further fragmenting the field, and impeding overall progress.

To bridge the gap between perceived potential and practical applications of DTs in E&C, two paradigm shifts are proposed in Paper VI:

Reconceptualizing digital twins: shifting the perception of a DT from being seen as a singular new technology or merely a 3D model to understanding it as a combination of existing technologies that act as tools to fulfill specific purposes. This broader view emphasizes the integration and interaction of various technologies to achieve the objectives of a DT.

Generalizable Framework Approach: moving away from the propagation of new, context-specific frameworks for each DT project and adopting a more generalizable, purpose-focused approach instead. This is the objective of the roadmap proposed in Paper VI, which aims to guide E&C organizations in effectively adopting and implementing DTs.

This strategy aims to demystify DT technology and encourage its adoption by showcasing clear, practical benefits. Therefore, the proposed approach to bridge the gap between potential and applications, effectively implement DTs, and leverage their benefits can be summarized as follows: shift the view of DTs from a singular technology to an integrated assembly of existing technologies, maximizing their combined potential throughout the entire life cycle. Build on existing knowledge and progress to promote standards, mindful of the fragmented production chain and the particularities of E&C assets. Foster collaboration among different skills, e.g. structural engineering and software development, with a purpose-focused approach to clearly understand the benefits of a DT application.

In conclusion, this study provides a foundational framework and proof-of-concept applications for using DTs in E&C asset management. By addressing both theoretical and practical aspects, it lays the groundwork for future research and development aimed at overcoming existing challenges and realizing the full potential of DTs in the industry.

Chapter 7

Future Research

Technology will continue to advance, with the rapid evolution of AI playing an unpredictable role in this progress. Whether the gap in E&C between technology potential and development will close or widen further, both within the industry itself and compared to other sectors, remains uncertain. Given that civil structures are a critical matter within the public interest, they should remain a focal point of study. As the practical applications progress, a new challenge emerges in developing technology that withstands the test of time in a fast-paced environment. Furthermore, standardization is an issue that will remain essential for the progress and widespread dissemination of DTs in the E&C industry.

For future research addressing the technical challenges of the proposed DT platform, collaboration with specialists from various fields, particularly software development, is crucial to elevate its maturity level. Engaging in interdisciplinary efforts can enhance the platform's functionality, making it more robust and reliable. Rounds of real-time monitoring should be implemented to gather data, assess the platform's performance, and identify areas for improvement. This foundational DT platform, with adequate resources, focus, and professional input, could be presented to stakeholders for refinement based on their needs, ultimately resulting in a valuable tool for the future.

Integrating data analytics and machine learning tools can significantly boost the DT’s autonomy, intelligence, and learning capabilities. Specifically, incorporating feedback loops to FE simulations, structural analysis software, cost estimation and management tools, and geographical information systems (GIS) can expand the scope of the DT. The fidelity of the DT can be enhanced by updating the 3D model using advanced methods such as autonomous scanning to create a point cloud model. Additionally, for the Snow Galleries case study, improving the robustness of the current SHM system to include more frames within SG9 and SG13, more galleries in the Iron Ore Line, and other sensors can ensure comprehensive monitoring and data collection. Furthermore, the scope of DT applications can be expanded beyond the initial Snow Galleries and Trough Bridge case studies to other types of civil structures.

For the theoretical contributions and the purpose-driven roadmap proposed, future studies should aim to validate them with real applications in collaboration with companies facing needs that DTs can address. Engaging in a process where the roadmap is applied to industry case studies will provide valuable feedback on its practical utility and effectiveness. This iterative process will not only enhance the roadmap itself but also aid in developing DT applications that promote widespread adoption. Continuous refinement and application of the roadmap can drive standardization across the industry, helping to disseminate accurate information and prevent future misconceptions.

Even though civil engineering processes may take longer to adapt to modern technologies, envisioning a future for infrastructure management without tools like BIM and DTs seems almost inconceivable given the extensive array of technology already available. However, it may still take time before these technologies become more widely adopted within the industry and investments yield clearer returns. Additionally, due to safety concerns and to facilitate dissemination, processes in construction require standardization, which further extends the timeline for widespread adoption. Therefore, these are the anticipated next steps in the future of DTs in the construction industry.

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