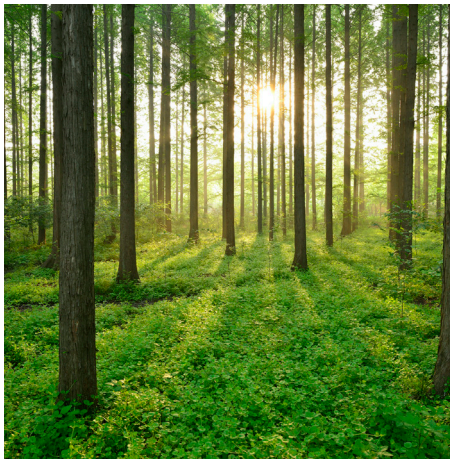
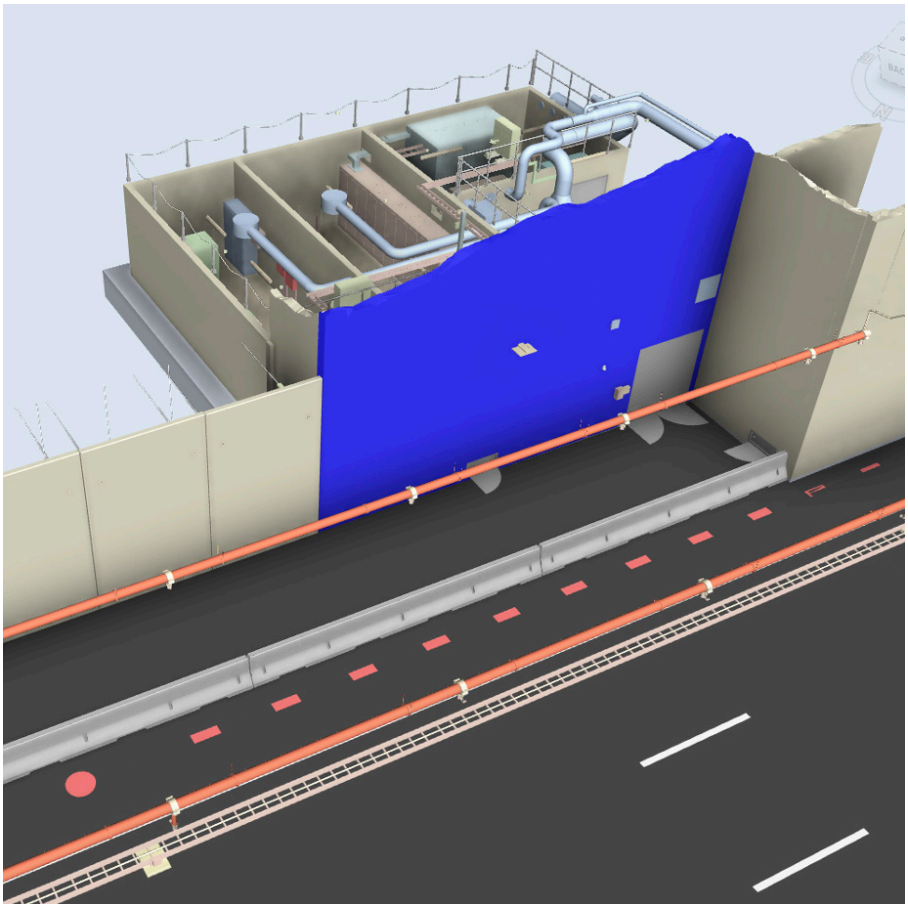
DIGITAL MODELS AND DIGITAL TWINS FOR NUCLEAR CONCRETE STRUCTURES

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NUCLEAR POWER CONCRETE PROGRAMME





Energiforsk

Digital models and digital twins for nuclear concrete structures

State-of-the-art and recommendations
for a first prototype

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Foreword

Nuclear power plants depend on long-lived concrete structures with high safety requirements. Connecting design information, inspection findings and structural assessments can support informed maintenance and ageing management, which is essential for long-term operation.

This study describes a useful classification of digital models of different sizes and levels of complexity and examines how they can support the management of nuclear concrete structures. It draws on selected case studies, interviews and standards to guide the development of a first prototype for Swedish nuclear power.

The findings point to the importance of defining needs and uses early in the process, instead of starting with the build-up of a comprehensive digital twin. The future use of this potentially powerful tool depends on defining the right complexity, features, ownership and uncertainties for the intended application.

This report forms part of the results of the project “Digital tvilling av reaktorinneslutningars betongkonstruktioner - Ett verktyg för teknisk förvaltning under långtidsdrift” which is financed by Energimyndigheten and the Energiforsk Nuclear Power Concrete Program. The Concrete program aims to increase the knowledge of aspects affecting safety, maintenance and development of concrete structures in the Nordic nuclear power plants and is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and SKB.

The study was carried out by Nerma Ceric, Miguel Prieto Rábade, Per Seltborg, Mariusz Kalinowski and Lena Sultan, RISE.

These are the results and conclusions of a project, which is part of a research Program run by Energiforsk. The author/authors are responsible for the content.

Summary

This study identifies three main lessons for developing digital twins for nuclear safety-critical concrete structures: start with a clearly defined decision, connect the information chain, and build trust through traceability, validation, ownership and user involvement. It provides an overview of digital models, digital shadows and digital twins and examines lessons from selected applications and relevant standards for the development of a first prototype for Swedish nuclear power.

The study combines a targeted review of terminology, standards and technical documentation with interviews and case studies from Slussen, E4 Förbifart Stockholm, the Port of Gothenburg and EDF's VERCORS programme. The review confirms that many required building blocks already exist, including object-based information models, inspection and monitoring data, physics-based modelling, validation procedures and decision-support workflows.

None of the reviewed applications is a full digital twin under a strict data-flow definition. Slussen is primarily an object-based digital information model, while E4 Förbifart Stockholm combines structured information, production data and information exchange for handover and maintenance. At the Port of Gothenburg, inspection findings and structural calculation models are used together to support decisions, but the information chain is not fully integrated and updates remain largely manual. VERCORS is the most developed digital-twin-oriented case reviewed, combining an instrumented physical mock-up with numerical models, calibration, validation and leakage prediction. However, the reviewed evidence does not demonstrate a continuously synchronized, bidirectional operational twin.

For Swedish nuclear power, a realistic next step is therefore a bounded, validated and traceable prototype focused on one concrete object or zone and one specific inspection, assessment, maintenance or life-extension decision. The prototype should connect relevant information, define ownership and update responsibilities, communicate uncertainty and be tested with its intended users. This provides a practical basis for demonstrating value and building confidence before broader implementation.

Keywords

Digital twin, digital model, digital shadow, nuclear, concrete structures, decision support, lifecycle information management.

Digital tvilling, digital modell, digital skugga, kärnkraft, betongkonstruktioner, beslutsstöd, livscykelinformation.

Sammanfattning

Denna studie identifierar tre huvudsakliga lärdomar för utvecklingen av digitala tvillingar för säkerhetskritiska betongkonstruktioner inom kärnkraft: utgå från ett tydligt definierat beslut, koppla samman informationskedjan och skapa tillit genom spårbarhet, validering, ägarskap och användarmedverkan. I studien ges en översikt över digitala modeller, digitala skuggor och digitala tvillingar, och lärdomar från utvalda tillämpningar och relevanta standarder sammanställs som stöd för utvecklingen av en första prototyp för svensk kärnkraft.

Studien kombinerar en riktad genomgång av terminologi, standarder och teknisk dokumentation med intervjuer och fallstudier från Slussen, E4 Förbifart Stockholm, Göteborgs Hamn och EDF:s VERCORS-program. Genomgången visar att många av de byggstenar som krävs redan finns, bland annat objektbaserade informationsmodeller, inspektions- och övervakningsdata, fysikbaserad modellering, valideringsmetoder och arbetsflöden för beslutsstöd.

Ingen av de granskade tillämpningarna är en fullständig digital tvilling enligt en strikt definition baserad på automatiska dataflöden mellan den fysiska konstruktionen och den digitala representationen. Slussen är i första hand en objektbaserad digital informationsmodell, medan E4 Förbifart Stockholm kombinerar strukturerad information, produktionsdata och informationsutbyte för överlämning och förvaltning. I Göteborgs Hamn används inspektionsresultat och beräkningsmodeller tillsammans som stöd för beslut, men informationskedjan, det vill säga hur information förs från konstruktionen till beslut, är inte fullt integrerad och uppdateringar sker till stor del manuellt. Av de granskade fallen har VERCORS kommit längst mot en digital tvilling. Där kombineras en instrumenterad fysisk modell med numeriska modeller, kalibrering, validering och prediktion av läckage. Underlaget visar dock inte någon kontinuerligt synkroniserad och dubbelriktad digital tvilling i drift.

För svensk kärnkraft är ett realistiskt nästa steg därför en avgränsad, validerad och spårbar prototyp med fokus på ett betongobjekt eller ett avgränsat område och ett tydligt definierat beslut kopplat till inspektion, tillståndsbedömning, underhåll eller livstidsförlängning. Prototypen bör koppla samman relevant information, tydliggöra ägarskap och ansvar för uppdateringar, kommunicera osäkerheter och testas tillsammans med de avsedda användarna. Det ger en praktisk grund för att visa nyttan och bygga förtroende för den digitala tvillingen innan en bredare implementering.

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1 Introduction

Digital representations are increasingly used to support the management of long-lived structures. Managing concrete structures requires information from multiple sources. Design documentation, material data, inspection records, non-destructive testing (NDT), monitoring, operational history, structural calculations, repair records, and engineering assessments collectively contribute to understanding the condition of a structure and determining appropriate actions.

The terms digital model, digital shadow and digital twin are used inconsistently across research and practice. Kritzinger et al. define a digital shadow by automated one-way data flow and a digital twin by automated two-way data flow.[1] SS-ISO 23247-1:2021 allows synchronization to be event-based or time-based, but it was written for manufacturing.[2] Neither source on its own resolves how the terms should be applied to ageing civil structures or to decision-support systems that are updated periodically. In this report, the broader term digital representation is therefore used when discussing the reviewed cases, and the labels digital model, digital shadow and digital twin are applied strictly: a solution is not called a digital twin solely because it contains a 3D model, sensors, FEM analysis or prediction. The definitions used are presented in Chapter 4. The report title uses the term nuclear concrete structures. In the text, the more precise term concrete structures in nuclear facilities is used, with reactor containments as the main example.

This study is the state-of-the-art sub-project within Energiforsk's project on digital twins of the concrete structures of reactor containments as a tool for technical management during long-term operation. The purpose of this study is to show how digital representations are used in practice for long-lived, safety-critical structures and to identify a realistic first step for Swedish nuclear power. The report is guided by three recurring lessons from the reviewed material: start with a specific decision, connect the information chain, and build trust through traceability, validation, ownership and user involvement.

The objectives and scope are presented in Chapter 2 and the method in Chapter 3. The conceptual framework, the classification used in the assessment and a comparison with other classification systems are presented in Chapter 4. The four case studies are assessed in Chapter 5 and compared in Chapter 6, which also draws implications for concrete structures in nuclear facilities, including access and information security. Relevant standards are reviewed in Chapter 7, the specific characteristics of concrete structures in nuclear facilities are discussed in Chapter 8, and recommendations for a first prototype are given in Chapter 9. The

[1] W. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn, Digital Twin in manufacturing: A categorical literature review and classification (2018), IFAC-PapersOnLine 51(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474 (Accessed 2026-10-02).

[2] SS-ISO 23247-1:2021, Automation systems and integration - Digital twin framework for manufacturing - Part 1: Overview and general principles. Swedish Institute for Standards (SIS), Stockholm (2021).

conclusions are presented in Chapter 10, and the interviews are summarised in Appendix A.

2 Objectives and scope

2.1 OBJECTIVE

The objective is to provide Energiforsk and the Swedish nuclear industry with a practical overview of digital representations that can support the technical management of long-lived concrete structures. The report is intended to support knowledge transfer and future development, and has four specific aims.

Clarify the terminology. Distinguish between digital models, digital shadows and digital twins, so that the terms are used consistently (Chapter 4).

Learn from practice. Assess selected case studies and identify transferable lessons for inspection, condition assessment, maintenance and life extension (Chapters 5 and 6).

Review relevant standards. Examine standards that support information structure, exchange and traceability (Chapter 7).

Guide a first prototype. Provide recommendations for a realistic first digital twin prototype for Swedish nuclear power (Chapters 8 and 9).

2.2 SCOPE

The study provides a targeted review of digital models, digital shadows and digital twins for safety-critical structures, based on four selected cases: Slussen, E4 Förbifart Stockholm, the Port of Gothenburg and EDF's VERCORS programme. It focuses on static concrete structures with high safety requirements, such as bridges, tunnels and port structures, rather than technical systems or process equipment. The cases were chosen because they use digital representations for inspection, condition assessment, maintenance, service-life assessment or decision support.

The scope covers information models, inspection and monitoring data, structural models, validation, information exchange and lifecycle traceability. Access control and information security are discussed at a general level, based on the review and on what the cases showed (Sections 6.7 and 8.2).

Detailed design of a first prototype for a specific nuclear facility, software selection, cybersecurity architecture, detailed FEM methodology and regulatory qualification are outside the scope.

3 Method

3.1 STUDY APPROACH

The study combines three activities. First, a targeted review of terminology, standards and technical literature was used to establish a working conceptual framework. Second, practical use cases were selected to represent different levels of digital representation and different needs in the management of structures. Third, interviews were conducted with people directly involved in the selected cases. The analysis is qualitative and focuses on transferable implementation lessons rather than quantitative benchmarking.

3.2 SELECTION OF CASE STUDIES

The cases were selected because together they cover a progression from object-based information modelling and project handover to inspection-informed structural assessment and a research programme on concrete containment structures with extensive monitoring and predictive modelling. Three of the selected cases involve organisations suggested by Energiforsk as relevant contacts: the Port of Gothenburg, Trafikverket and EDF with the VERCORS project. Slussen was added to represent model-based design and production in a large urban infrastructure project. The cases are not presented as statistically representative of their sectors.

3.3 INTERVIEWS

Interviews were conducted with people directly involved in the selected case studies. The interviews were treated as qualitative sources and cross-checked against technical literature and standards where possible.

Slussen. David Möller, digital model representative for the Slussen project.

E4 Förbifart Stockholm. Martin Angbjär, unit manager for infrastructure systems in Trafikverket's maintenance organisation, previously involved in technical and project management on the project side. Lars Mattson, senior specialist in digital project management at Trafikverket and functionally responsible for digital project management within E4 Förbifart Stockholm. Aaron Hantler, representative of Trafikverket's maintenance organisation.

Port of Gothenburg. Martina Dawodi, technical project manager at the Port of Gothenburg. Hanna Schloenzig, design team leader at ELU. Henrik Wallerman, structural engineer at ELU.

EDF VERCORS. Jean-Philippe Mathieu, research engineer at EDF R&D and former project manager for the exploitation of the VERCORS mock-up. Jean-Luc Adia, EDF R&D, working on the characterisation and modelling of concrete behaviour in containment structures. Both are co-authors of the main publication used in Section 5.5, so the interview and the publication are not independent sources.

3.4 ASSESSMENT FRAMEWORK

Each case study was assessed using the same five questions. The resulting classification is a way to compare the cases. It is not a formal audit and should not be interpreted as a ranking of the organisations or projects.

Decision supported. What decision or work process does the digital representation support?

Information connection. What information from the physical structure is connected to the digital representation, and how is it updated?

Model types. Which model types are used: geometric, information, physics-based or data-driven?

Trust and governance. How are validation, uncertainty, ownership, versioning and traceability handled?

Classification. How should the case be classified according to the definitions adopted in this report: as a digital model, a digital shadow or a digital twin?

The answers for each case are presented in Chapter 5.

4 Conceptual framework

4.1 DIGITAL REPRESENTATIONS

Kritzinger et al. provide a useful data-flow classification, derived from a review of the digital-twin literature in manufacturing.[1] In a digital model, there is no automatic data exchange between the physical object and the digital representation. In a digital shadow, data flows automatically from the physical object to the digital representation, but not automatically in the reverse direction. In a digital twin, automated data exchange is bidirectional. This classification is strict and is particularly useful for avoiding the common practice of calling any detailed 3D model a digital twin.

SS-ISO 23247-1:2021 defines a digital twin as a "fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation".[2] The standard requires that the twin and the element are updated to each other's values and that data are collected from sensors. Its terminology cannot be transferred uncritically to concrete structures in nuclear facilities, although the standard notes that digital twins for building and construction may be modelled using the ISO 16739 series, Industry Foundation Classes (IFC), an open and vendor-neutral data model for exchanging building and infrastructure information between software.[3] The principles of fit-for-purpose representation, synchronization, reference architecture, information attributes and information exchange are nevertheless relevant when defining a prototype.

For the purposes of this report, digital representation is used as the umbrella term. A full digital-twin label is used only when the evidence supports a strong connection between the physical structure and the digital representation, systematic updating or synchronization, validated interpretation or prediction, and a defined decision-support function. Where a case is valuable but does not meet that threshold, the report describes the actual functionality rather than forcing it into a higher category.

4.2 COMPONENTS OF A DIGITAL TWIN

The reviewed literature treats a digital twin as a system rather than a single model. In their review of industrial applications, Tao et al. present a five-dimension model in which a digital twin consists of a physical part, a virtual part, data, services and the connections that link them.[4] For bridge management, Mousavi et al. identify the physical entity, the virtual model, data collection, data connection/integration and the user as the primary components. They also argue that decision support is a

[3] ISO 16739-1:2024, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema. International Organization for Standardization (ISO), Geneva (2024). SS-EN 17549-2:2023 is based on the previous edition, EN ISO 16739-1:2020.
[4] F. Tao, H. Zhang, A. Liu, A.Y.C. Nee, Digital Twin in Industry: State-of-the-Art (2019), IEEE Transactions on Industrial Informatics 15(4), 2405-2415. https://doi.org/10.1109/TII.2018.2873186 (Accessed 2026-10-02).

vital component of maintenance-oriented bridge digital twins, although it has rarely been integrated in practice, and their proposed framework therefore adds an intelligent decision-support layer (Figure 1).[5]

For safety-critical concrete structures, these components can be understood as an information chain: physical object → observation or measurement → transfer and quality control → structured storage → model or interpretation → validation and uncertainty → decision support → user feedback and controlled update. When the chain is closed by feedback to the physical structure, it forms a loop. The chain can contain several model types at the same time. Geometry answers where, an information model answers what and which documents belong to the object, an FEM model supports structural interpretation, and a data-driven model may support pattern recognition or prediction.

Data flow and information chain are related but not the same. Data flow describes how data move between the physical structure and the digital representation, and whether this happens automatically. It is the criterion used in the classification of Kritzinger et al. The information chain is broader. It covers every step from observation of the physical structure to a decision and a controlled update, including quality control, storage, interpretation and validation. A chain can be complete and useful even when the data flow is manual, as with periodic inspections. An automated data flow, on the other hand, does not give a complete chain if the data are not validated, interpreted and used for a decision. The data flow therefore determines how a representation is classified, while the information chain determines how useful it is for decisions.

[5] V. Mousavi, M. Rashidi, M. Mohammadi, B. Samali, Evolution of Digital Twin Frameworks in Bridge Management: Review and Future Directions (2024), Remote Sensing 16(11), 1887. https://doi.org/10.3390/rs16111887 (Accessed 2026-10-02).

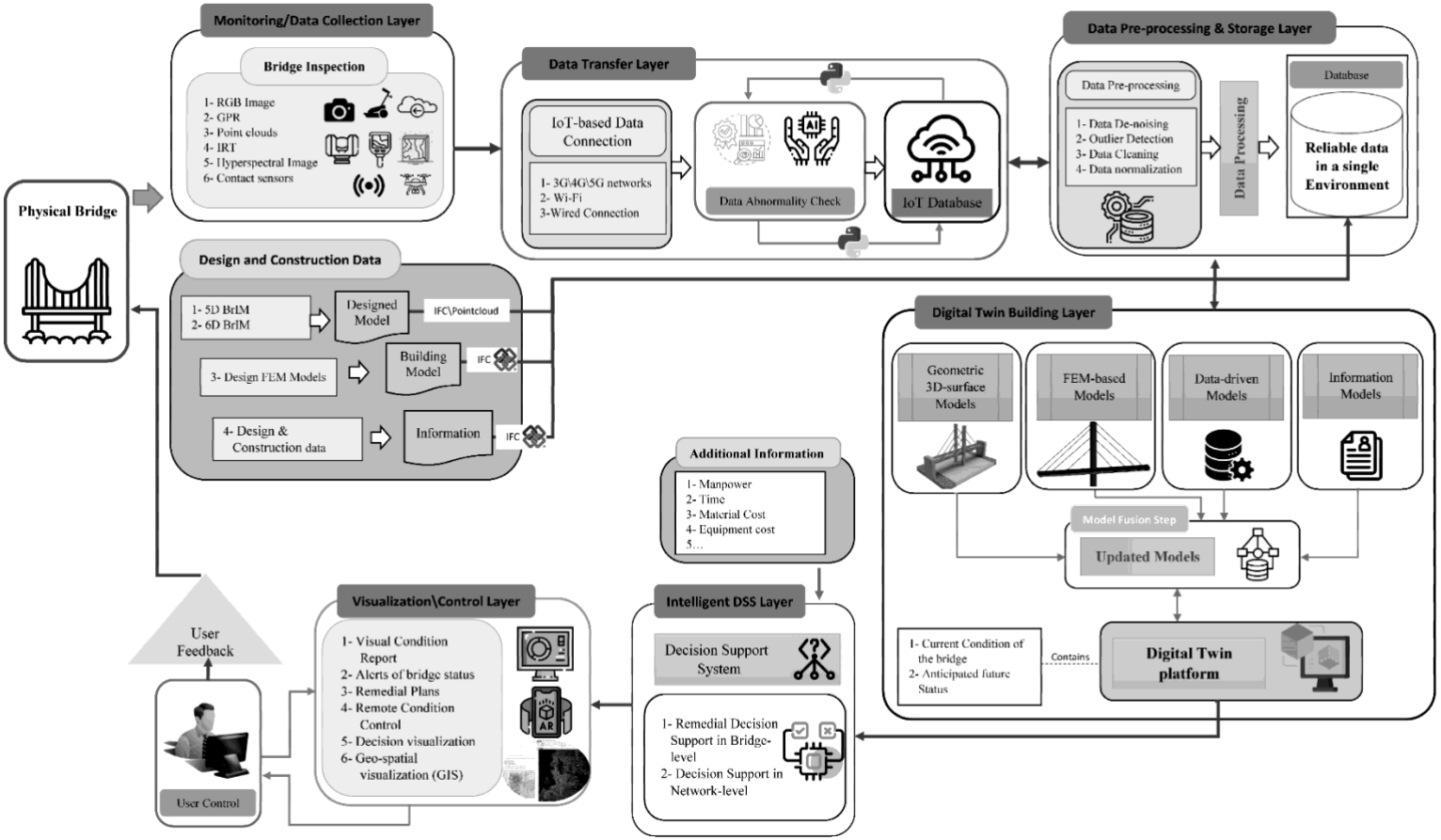


Figure 1 The evolved bridge digital twin framework, used as a conceptual reference rather than a prescribed architecture for concrete structures in nuclear facilities. Adapted from Mousavi et al. (CC BY 4.0).[5]

4.3 CLASSIFICATION AND DECISION-SUPPORT MATURITY USED IN THIS REPORT

The data-flow classification of Kritzinger et al. is used as the reference in this report, because it is explicit and can be applied directly to the reviewed cases.[1] It is compared with other classification systems in Section 4.4. A strict data-flow classification is useful but can be too coarse for civil structures that change slowly and are inspected periodically. The report therefore records two things separately: the strict data-flow category and the practical decision-support maturity. A manually updated but well-validated structural assessment may be highly valuable without being a digital shadow in the strict sense. Conversely, an automatically updated visualization may qualify as a digital shadow but still provide weak decision support. Table 1 summarises the three decision-support maturity levels used in the assessment, and each case is placed in both classifications (Table 3 and Section 5.6). In this report, classification refers to the categories digital model, digital shadow and digital twin, and maturity refers only to decision-support maturity. A higher category is not always better, the appropriate level depends on the intended use (Section 6.2). Figure 2 illustrates the difference between the categories.

Figure 2 Same rose, different representations. A physical object can be shown as a photo or a 3D model. It becomes a digital model, a digital shadow or a digital twin depending on how data flow between the object and its representation. Illustration: made with artificial intelligence

1	2	3	4	5	6
PHYSICAL ROSE	**PHOTO**	**3D MODEL**	**DIGITAL MODEL**	**DIGITAL SHADOW**	**DIGITAL TWIN**
					
The rose exists in reality.	Can show the rose.	Can show shape and dimensions.	We know more and can store information.	Updated automatically with data from reality.	Data can flow automatically in both directions.

Table 1 Decision-support maturity levels used in this report.

Level	Data connection	Main purpose
Digital model / information model	No automatic physical-to-digital update	Geometry, documentation, coordination and handover
Digital-shadow-oriented decision support	Inspection or measurement data are used to update or assess the digital representation	Condition assessment, comparison and inspection support, maintenance and life-extension decisions
Digital-twin-oriented decision support	Physical data and validated models are connected through a defined update process	Prediction, scenario analysis, maintenance and life-extension decisions

4.4 COMPARISON WITH OTHER CLASSIFICATION SYSTEMS

Table 2 compares the data-flow classification used in this report with three other frameworks, one from standards and two from the literature, and places the four reviewed cases in each of them. The frameworks differ in what they classify: the data flow between the physical and digital objects, the synchronization between them, or the components of a digital twin.

Table 2 Comparison of classification systems for digital twins and placement of the reviewed cases.

Framework	Basis of classification	Categories or levels	Placement of the reviewed cases
Kritzinger et al. (2018)[1]	Degree of automated data flow between the physical object and the digital representation	Digital model, digital shadow, digital twin	No case has automated data flow from the structure to the model, so all four are digital models in the strict sense. The Port of Gothenburg and VERCORS update their models manually or periodically (Table 1).
SS-ISO 23247-1:2021[2]	Fit-for-purpose representation with synchronization between a physical element and its representation (manufacturing)	Digital twin or not. Synchronization and sensor data are required	VERCORS and the Port of Gothenburg come closest through periodic or event-based model updates. Slussen and E4 Förbifart Stockholm have no synchronization after handover.
Tao et al. (2019)[4]	Components	Physical part, virtual part, data, services and connections	All cases have physical and virtual parts and data. Analysis services for decisions exist at the Port of Gothenburg and VERCORS. The connections between the physical and virtual parts are manual or periodic in all cases.
Mousavi et al. (2024)[5]	Components of bridge digital twins	Physical entity, virtual model, data collection, data connection and integration, user, and a decision-support layer	Same pattern as for Tao et al. A decision-support function is explicit at the Port of Gothenburg and VERCORS.

The data-flow classification is kept as the main reference in this report because it gives a clear test that could be checked against the interviews, and because it counters the tendency to call any detailed 3D model a digital twin. It is combined with the decision-support maturity in Table 1, which captures the decision-support function that is included as a component by Tao et al. and Mousavi et al.

4.5 RELEVANT STANDARDS

Three standards were selected for closer examination because they address different practical needs relevant to a first prototype: SS-EN ISO 23387:2025 for

structuring information,[6] SS-EN 17549-2:2023 for information exchange[7] and SS-ISO 23247-5:2026 for lifecycle traceability and the digital thread.[8] Their relevance is discussed further in Chapter 7.

[6] SS-EN ISO 23387:2025, Building information modelling (BIM) - Data templates for objects used in the life cycle of assets. SIS, Stockholm (2025).
[7] SS-EN 17549-2:2023, Building information modelling - Information structure based on EN ISO 16739-1 to exchange data templates and data sheets for construction objects - Part 2: Configurable construction objects and requirements. SIS, Stockholm (2023).
[8] SS-ISO 23247-5:2026, Automation systems and integration - Digital twin framework for manufacturing - Part 5: Digital thread for digital twin. SIS, Stockholm (2026).

5 Case study assessment

5.1 OVERVIEW OF THE REVIEWED CASE STUDIES

The four case studies illustrate different ways of using digital representations to support infrastructure and concrete structures. They range from object-based information models to validated predictive modelling for decision support. Table 3 provides a concise overview of their main purpose, information and assessed level of digital representation.

Table 3 Overview of the reviewed case studies: main purpose, information and models, and assessed level of digital representation.

Case study	Main purpose	Main information / models	Assessment
Slussen	Design, coordination, production	3D models with specified object information and linked documentation	Object-based digital information model
E4 Förbifart Stockholm	Coordination, as-built documentation and handover to maintenance	3D/IFC models, scanning and production data, links to documentation and BaTMan	Information model with as-built comparison and linked asset information
Port of Gothenburg	Capacity assessment, inspection targeting and maintenance decisions	Structural calculation models, inspection, damage and material data, sensitivity analyses	Decision-supporting, digital-shadow-like representation (manual updates)
EDF VERCORS	Prediction of ageing and leakage, repair and life-extension studies	Instrumented mock-up, pressure tests, finite-element models, calibration and validation	Digital-twin-oriented validated predictive model chain

5.2 SLUSSEN, STOCKHOLM

Classification. Slussen is an object-based digital information model used for design, coordination and production. It is neither a digital shadow nor a digital twin.

Reason for classification. The model is a 3D representation with specified information attached to each object. In practice, it is a BIM model of the kind commonly used in construction projects. It was updated by the project during design and construction, not from the physical structure, and it includes no condition monitoring or predictive analysis.

Evidence from the case. The project deliberately avoided digital-twin terminology and focused on design and production. The facility was built directly from models rather than drawings.[9] The guiding principle was to present the same information as traditional drawings in a new form, without losing anything. Object information was specified per object type, such as casting stage, BSAB code (from the Swedish classification system for construction information) and references to technical descriptions, while documents such as casting logs were kept alongside the model.

[9] Möller, D. Digital model representative, Slussen project [Interview] (2026-05-19).

The project's responsibility ends with the as-built model, which is divided into handover packages for the different future owners. Some of these owners are unsure how to manage 3D models. It also remains open how the models will be updated after modifications, and whether the file formats will still be usable in ten years.

Lessons and implications. A well-structured 3D model can create substantial value without being a digital twin. However, a good project model does not automatically become useful for long-term asset management. Information requirements, file formats and update responsibilities must be defined early, with the receiving organisation in mind.

5.3 E4 FÖRBIFART STOCKHOLM

Classification. E4 Förbifart Stockholm is an object-based digital information model used for coordination, production follow-up and handover to maintenance. It is linked to Trafikverket's document and asset-management systems, but it is neither a digital shadow nor a digital twin.

Reason for classification. The model gives a structured, system-independent picture of the facility, and its objects are linked to documentation and to the management system BaTMan. Laser scanning was used to compare the design with what was actually built. However, the model is not updated from the physical structure, and the interviewees describe it as an approximate rather than an exact copy.

Evidence from the case. Martin Angbjär described the handover model as an imperfect digital copy. It is good for orientation, but control measurements are needed before new design work. During construction, scanned excavations were compared with the theoretical tunnel model to check the excavated rock and verify contractors' quantities.[10] Model requirements were unclear when the contracts were signed, so models from different contracts had to be harmonised afterwards and converted to IFC before handover.[11] [12] Each object has an identity that links it to its documents and to BaTMan, so governed information is referenced rather than copied into the model (Figure 3). Maintenance was asked which information it needed, and attributes such as pipe material, dimension and slope were added to the model objects. All contractors reported rock production data continuously in a structured system covering the full 55 km of tunnel. These data include geological mapping, grouting and drill-rig data, and are presented in a GIS platform instead of drawings. From the maintenance side, Aaron Hantler stressed three needs: confidence that the model matches the facility, transparent handover processes and controlled access, since information on installations is sensitive.[13]

[10] Angbjär, M. Unit Manager, Infrastructure Systems, Maintenance, Trafikverket [Interview] (2026-06-05).
[11] Mattson, L. Senior Specialist, Digital Project Management, Trafikverket [Interview and demonstration] (2026-06-16).
[12] L. Mattson, J. Edmark, FRIDA - enhetlig leverans av 3D-modeller som relationshandlingar i IFC-format, Tisdagsföreläsning, Trafikverket (2026-05-19). Presentation material.
[13] Hantler, A. Maintenance organisation, Trafikverket [Interview] (2026-08-18).

Lessons and implications. Information requirements, object structure and exchange formats must be defined before contracts are signed. Adding them afterwards is costly. The model does not need to hold all information. It can act as an interface to established, trusted systems. The receiving organisation must be involved early. Since it may not yet know what it needs, this involvement requires dedicated funding and management support. Data quality is created when information is produced, not at the end of the project. Martin Angbjär also noted that, with hindsight, testing the approach on a sub-project first might have been better than applying it to the whole programme. This follows the same principle as starting with a bounded first prototype.

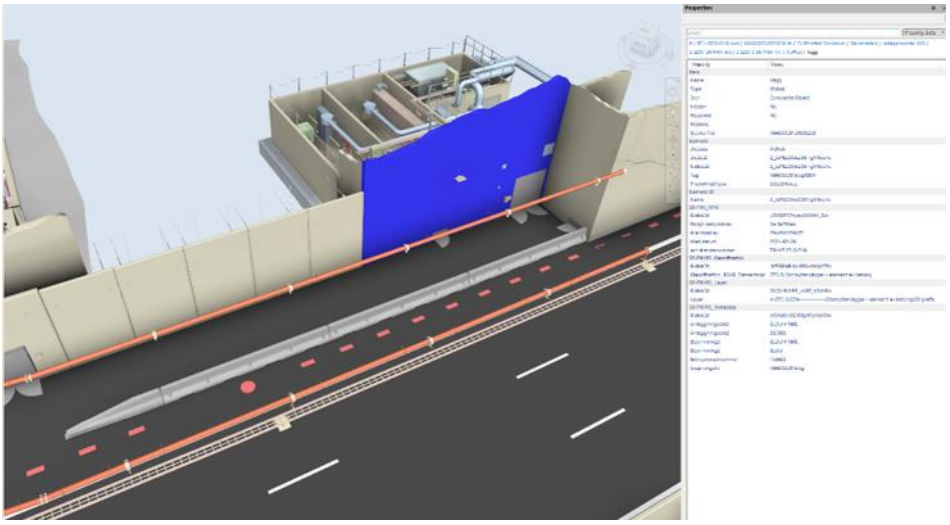


Figure 3 Object-based 3D model from E4 Förbifart Stockholm. The selected concrete wall carries properties such as IFC class, object identity, classification, approval information and references to the facility and structure numbers used in Trafikverket's asset-management system BaTMan. Source: Trafikverket, FRIDA presentation, published with permission.[12]

5.4 PORT OF GOTHENBURG

Classification. The Port of Gothenburg case is a condition-informed, decision-supporting digital representation. It is digital-shadow-like in purpose, but neither a strict digital shadow nor a digital twin.

Reason for classification. Inspection results are used together with structural calculation models to assess the consequences of damage and to support operational decisions. However, the models are updated manually after inspections, damage information is kept outside the calculation models, and there is no real-time data flow from the structure.

Evidence from the case. The quay is described by three separate finite-element calculation models, one for each structural part, maintained by the consultant ELU (Figure 4).[14] [15] The models were first built from original drawings and later refined with site measurements, current loads, dredging levels and structural

[14] Dawodi, M. Technical Project Manager, Port of Gothenburg [Interview] (2026-06-12).
[15] Dawodi, M. Technical Project Manager, Port of Gothenburg, Schloenzig, H. Design Team Leader, ELU, Wallerman, H. Structural Engineer, ELU [Interview] (2026-09-22).

modifications. Each pile is assigned a capacity based on defined damage levels, which are updated and logged after every inspection. Not every combination of pile failures can be tested, so the sensitivity analyses focus on realistic scenarios, such as clusters of damaged piles. After an incident, damaged piles can be removed from the model and the consequences assessed within about an hour. This helps the Port target diving inspections and decide on load restrictions. The Port owns the deliverables, has used third-party review and has asked for more than one person at the consultant to know the model. The calculation models cannot easily be transferred between software tools.

Lessons and implications. Decision value can be created without a full digital twin by connecting inspection results to a calculation model that answers a recurring operational question. The approach grew from a specific need, not from an ambition to build a digital twin. For a nuclear prototype, model ownership, redundancy, change logging and the long-term exchange of calculation models need to be planned from the start.

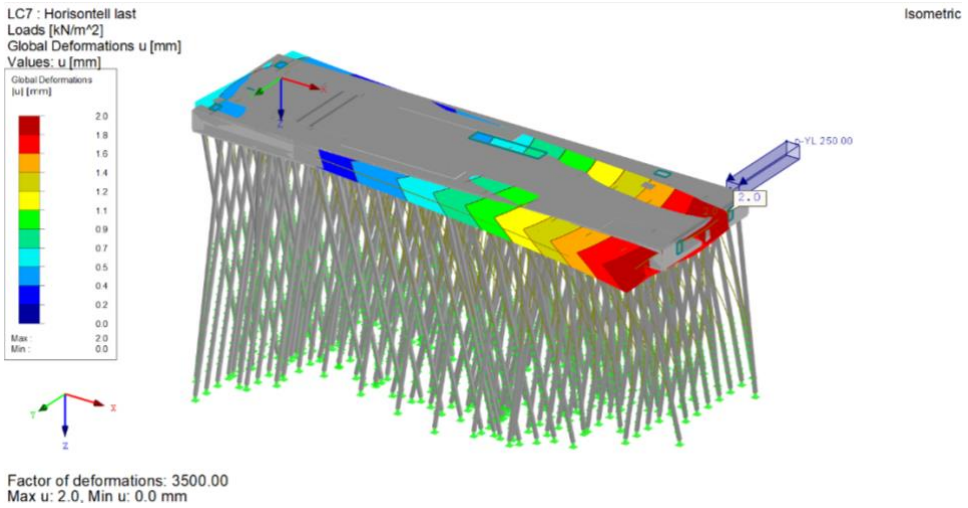


Figure 4 Structural calculation model of a quay structure at the Port of Gothenburg, showing calculated global deformation under horizontal loading. The deformation scale is amplified for visualisation. Source: Port of Gothenburg. Calculation model by ELU. Published with permission.

5.5 EDF/VERCORS

Classification. VERCORS is a digital-twin-oriented validated predictive model chain. It is the most mature and most relevant nuclear case reviewed, but it is not a full digital twin in the strict sense.

Reason for classification. Measurements from a representative physical structure are used to calibrate and validate finite-element models. These models predict ageing and leakage and support real engineering decisions. However, the models have been calibrated only a few times, updates follow the pressure tests rather than continuous data, and there is no automatic loop between the structure and the models.

Evidence from the case. VERCORS is a 1:3 scale mock-up of a double-wall containment without a steel liner, a design used in 24 of the 56 reactors in EDF's

fleet. Construction started in 2013, and the first pressure test was carried out at the end of 2015. Since then, the mock-up has been pressure-tested almost every year. The reduced scale makes the concrete dry about nine times faster than in a real containment, so about ten years of testing corresponds to roughly 90 years of operation. The mock-up is heavily instrumented for monitoring of temperature, water content, strain and displacement. Finite-element models in code_aster, EDF's open-source finite-element software[16], have been validated against these measurements, an approach EDF refers to as a digital twin, and the model chain is used to predict leakage before the yearly pressure tests (Figure 5).[17] The mock-up was built with concrete similar to that of the Nogent-sur-Seine containment, which is representative of average fleet concrete, and EDF is now working to apply the same approach to its fleet of containments. The models have been used to place costly polymer coating repairs only where they reduce leakage. They have also been used to predict the condition of containments up to 80 years of operation, for life-extension and severe-accident assessments. The interviewees also described limitations. Managing large volumes of sensor data, data security and shared data access were major early challenges, and an early prediction for a real containment was produced by hand rather than through an automatic loop.[18]

Lessons and implications. A digital twin for concrete structures in nuclear facilities should be built around a bounded problem that can be measured, modelled and validated. The interviewees stressed two further lessons. First, the measurements should match what can actually be measured in operating plants, because a model calibrated on the dense measurements from the mock-up may need more input than can be measured in an operating plant. Second, a data architect should be involved from the start to handle data storage, access and long-term responsibility.[18] The first lesson is also reflected in EDF's plans to test whether the same predictions can be made with the reduced set of monitoring data that is available on real containments.[17]

[16] EDF R&D, Code_Aster: Analysis of Structures and Thermomechanics for Studies & Research [Brochure]. EDF, Paris. https://www.edf.fr/sites/default/files/Lot%203/CHERCHEURS/Code_Aster/code_aster_brochure_presentation.pdf (Accessed 2026-11-03).

[17] L. Charpin, J. Haelewyn, A. Cherki El Idrissi et al., Predicting leakage of the VERCORS mock-up and concrete containment buildings - a digital twin approach (2022), Acta Polytechnica CTU Proceedings 33, 78-84. https://doi.org/10.14311/APP.2022.33.0078 (Accessed 2026-10-02).

[18] Adia, J.-L. EDF R&D, Mathieu, J.-P. Research Engineer, EDF R&D [Interview] (2026-07-06).

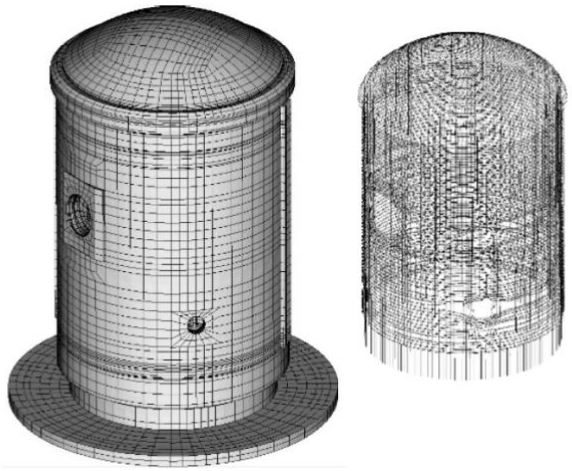


Figure 5 Finite-element mesh of the VERCORS mock-up. The prestressing cables are modelled individually, and the access hatch and other wall penetrations are represented. Source: Charpin et al. (CC BY 4.0).[17]

5.6 SUMMARY OF CASE STUDY CLASSIFICATION

The cases form a useful progression, but not a simple ranking. Slussen demonstrates the value of structured object information for model-based design, coordination and construction. E4 Förbifart Stockholm demonstrates handover, measured/as-built comparison, system-independent exchange, structured production data and links to governed asset-management information. The Port of Gothenburg demonstrates inspection-informed structural scenario analysis and rapid decision support. VERCORS demonstrates a validated measurement-model chain for an ageing problem in a concrete containment. What the cases have in common is that each grew from a concrete project or asset-management need, not from an ambition to build a digital twin. None of them fulfils the strict definition of a digital twin used by Kritzinger et al., which requires automated, fully integrated data exchange in both directions between the physical and digital objects.[1]

6 Cross-case analysis and implications for concrete structures in nuclear facilities

6.1 OVERVIEW OF THE ASSESSED USE CASES

Table 4 provides a comparative overview of the key features identified in the four reviewed case studies. The comparison highlights differences in digital representation, information integration, analysis, decision support and update processes. The assessment reflects what could be demonstrated from the reviewed material and interviews.

Table 4 Key features identified in the reviewed use cases.

Component	Slussen	E4 Förbifart Stockholm	Port of Gothenburg	VERCORS
Physical structure represented	✓	✓	✓	✓
Structured digital information	✓	✓	Partial	✓
Inspection / condition data	–	Partial	✓	✓
Digital modelling layer	Partial	Partial	Partial	✓
Scenario / sensitivity analysis	–	–	✓	✓
Validation against physical behaviour	–	–	Partial	✓
Decision-support functionality	–	–	Partial	✓
Defined update process	–	Partial	✓	✓

Legend: ✓ = established, Partial = partly established, – = not demonstrated in the reviewed material

6.2 THE APPROPRIATE LEVEL DEPENDS ON INTENDED USE

The reviewed cases show that the value of a digital representation cannot be judged from visualization quality alone. As summarised in Section 5.6, each case creates value for a different purpose. The intended use determines which level of connection and model complexity is justified.

6.3 START WITH THE DECISION

A recurring lesson is to begin with the end in mind. The Slussen and E4 Förbifart Stockholm interviewees repeatedly stressed that projects need to know what the receiving organisation will use the information for. Otherwise, attributes and

models are created without a coherent purpose. The Port case shows the same principle from the opposite direction: the work is centred on a defined problem and the calculation models are kept alive because they answer recurring questions. VERCORS began from a defined engineering problem, ageing and leakage, and built monitoring and modelling around it.

For concrete structures in nuclear facilities, candidate decisions could include whether a detected change is significant, where to perform targeted non-destructive testing, whether a repair is required, how a degradation mechanism may develop, whether a repair has the intended effect, or what evidence is needed for a life-extension assessment. The decision should determine the data, object structure, model fidelity, update frequency, validation evidence and user interface.

6.4 TRUST AND VALIDATION

Trust can develop when users understand what the representation contains, where the data came from, how the model was checked and what uncertainties remain. The reviewed cases show different approaches to establishing this trust. VERCORS relies on a physical validation environment where model predictions can be compared with measured behaviour. The Port of Gothenburg has used third-party review of its calculation models. In the Trafikverket cases, trust is supported by known systems, stable object identities and transparent handover procedures.

Trust also depends on ownership. Someone must be responsible for updating information, approving changes, managing versions and ensuring that the digital representation does not drift away from the physical structure. The reviewed cases illustrate this from complementary perspectives. At the Port of Gothenburg, the calculation models are maintained by consultants, while the Port retains rights to the deliverables and has discussed redundancy, change logging and the need to avoid dependence on one individual. In VERCORS, managing large volumes of sensor data, data security, common data access and data architecture were major early challenges. In the Trafikverket cases, governed maintenance information remains in the established management system BaTMan, and the maintenance perspective emphasised the need for transparent processes when information is transferred from the project to maintenance.

Ownership keeps the representation up to date, but validation determines what it may be used for. For a safety-critical structure, validation should therefore be defined for a specific purpose. At the Port of Gothenburg, the calculation models are not used in isolation to verify load-bearing capacity. They are complemented by separate calculations and are also used for scenario and sensitivity analyses, such as load redistribution and the consequences of assumed pile loss. A geometric model can be accurate enough for orientation but insufficient for redesign. At E4 Förbifart Stockholm, control measurements are needed before new design work. The prototype should therefore state what it is allowed to support, what evidence supports that use and what additional checks are required before a safety-related decision is made.

6.5 INFORMATION GOVERNANCE AND LONG-TERM MANAGEMENT

The long service life of structures contrasts with the considerably shorter lifetimes of software, file formats, suppliers and organisational roles. The case studies repeatedly point to a common set of requirements: stable object identity, documented information requirements, versioning, export possibilities, clear ownership, links to governed source systems and sufficient organisational redundancy. Open exchange standards can reduce dependence on a single authoring tool, but they do not automatically solve exchange of every specialist model, particularly detailed structural calculation models.

Data architecture should therefore be treated as an engineering requirement rather than an IT afterthought. The first prototype should define which system is the authoritative source for each information type, how links are maintained, who can change data, how changes are approved, and how obsolete information is identified.

6.6 IMPLICATIONS FOR A FIRST DIGITAL TWIN PROTOTYPE FOR CONCRETE STRUCTURES IN SWEDISH NUCLEAR FACILITIES

The cross-case evidence supports a step-by-step approach, starting with a bounded prototype rather than a facility-wide twin. A bounded prototype makes it possible to test the complete information chain under controlled conditions: object identity, data quality, model assumptions, validation, uncertainty, ownership, update process and user value. It also reduces the risk of building a large integration platform before the decision-support benefit is demonstrated.

Based on the cross-case analysis, four lessons can be formulated for a first digital twin prototype. First, development should begin with a clearly defined engineering or asset-management problem. Second, the prototype should be limited to a specific object, zone and/or degradation mechanism. Third, the prototype should provide decision support rather than visualisation alone, with its output linked to a defined user and a defined decision. Fourth, validation and traceability should be built in from the start.

6.7 ACCESS AND INFORMATION SECURITY

Two questions are important for nuclear applications: what organisations do to keep a model and its information within a secure IT environment, and how access rights and division into layers are managed so that everyone who needs the model can use it without particularly powerful computers, while uncontrolled changes are prevented.

Separate sensitive information. At E4 Förbifart Stockholm, information on installations is handled at a different confidentiality level from the rest of the model.[11] Aaron Hantler noted that the model also contains power supply and operational systems, which raises the question of who should have access and who decides. In hindsight, installations could have been kept in a separate model, so that those working on the concrete structure do not need access to everything.[13]

Keep access control in governed systems. At E4 Förbifart Stockholm, the model links to documents and asset-management systems instead of copying their content, and users must log in to open a linked document. Changes are made in one place.[11]

Separate model users from result users. At the Port of Gothenburg, the consultant runs the calculation models and the Port uses the results. The Port owns the deliverables but does not hold the models itself. The working method has emphasised traceability through change logging and continuity through redundancy in model competence, so that the models and their underlying calculations are not dependent on a single person.[14] [15] Detailed models may also require high-performance computing: at EDF, a single simulation of the whole containment initially took more than a week on such systems.[18]

Plan data security from the start. At EDF, keeping large volumes of sensor data secure while making them available to all users was the main challenge at the start of VERCORS.[18]

For a nuclear prototype, access rights, update rights and information classification should therefore be defined together with the information requirements. Specific IT environments, cloud or on-premises solutions, network security, hardware requirements for users and the security protection requirements that may apply to Swedish nuclear facilities were not examined. These should be addressed with the facility's IT and security functions.

6.8 FROM BUILD-UP TO OPERATION

The interviews show that a model is used in operation only if the conditions for this are set during design and construction. Several interviewees described what they would do differently with hindsight (Sections 5.2-5.5 and Appendix A):

- Define information requirements, object structure and exchange formats before contracts are signed. At E4 Förbifart Stockholm, models from different contracts had to be harmonised and converted afterwards.
- Involve the receiving organisation early, with dedicated funding and management support, and ask what information maintenance actually needs.
- Test the approach on a sub-project before applying it to a whole programme.
- Keep sensitive information, such as installations, in a separate model from the concrete structure.
- Decide who updates the model after handover and how the file formats will remain usable.
- Plan model ownership, change logging and redundancy in model competence. At the Port of Gothenburg, more than one person at the consultant should be able to update the models.
- Involve a data architect from the start. At EDF, the people who specified the sensors were not those able to manage the resulting volumes of data, and the main early challenge was to bring all data together, keep them secure and make them available to all users. One EDF interviewee recommended a data architect, rather than a data scientist, as advice to others developing a digital twin.

These lessons point to five roles that should be in place from the start:

- **Receiving organisation (operation and maintenance)** states which decisions the model should support and which information it needs. This requires knowledge of its own maintenance processes and of the information it will actually use.
- **Data coordinator** translates these needs into information requirements. The data coordinator defines object identities, data templates, naming and exchange formats such as IFC, checks deliveries, and maintains the links to governed systems and the change log. This requires an understanding of the decisions to be supported, the asset-management systems, the relevant standards (Chapter 7) and how deliveries are regulated in contracts.
- **Data architect** designs the database and infrastructure for the data before they are collected. This includes discussing with specialists and technicians what data each sensor will produce and in what quantity, and deciding how the data are stored, kept secure and made available to all users. The data architect also plans who will take care of the data over the long term, and works together with the organisation's IT and security functions.
- **Model owner and structural specialists** maintain the calculation models, validate them for their intended use and document assumptions and uncertainty. This requires knowledge of the structure's design basis, the relevant ageing mechanisms and the software used.
- **Inspection and NDT specialists** make sure that inspection and measurement data can be linked to the right object and used in the model. This requires knowledge of the object identities used in the model and of the uncertainty of each measurement method.

For a nuclear prototype, these roles should be named before the prototype is built.

7 Standards and information requirements for digital twin development

7.1 INTRODUCTION

The purpose of this chapter is to examine how selected standards can support the information requirements identified in the reviewed case studies. Standards are important for long-lived, safety-critical concrete structures because information may need to be understood, exchanged and trusted for several decades, while software, data formats, suppliers and organisational responsibilities change much faster.

The review is targeted rather than comprehensive. No single standard provides a complete method for developing a digital twin for concrete structures in nuclear facilities, and several of the reviewed standards were developed for other contexts, such as manufacturing or building information modelling. Their relevance is therefore assessed by analogy.

The three standards were selected using three criteria. First, each addresses one of the three information needs that recur in the reviewed cases: structured object information, interoperable exchange and lifecycle traceability (Section 7.2). Second, they are current editions adopted as Swedish standards (2023–2026). Third, they can be applied to a first prototype without a complete digital-twin platform. Other relevant standards are listed in Section 7.7 as starting points for further work.

The review focuses on requirements that are relevant to a first, bounded prototype rather than on a complete digital twin implementation. The aim is to identify how standards can help structure, exchange and trace information for one selected object and decision.

7.2 INFORMATION REQUIREMENTS IDENTIFIED FROM THE REVIEWED USE CASES

Three information needs recur across the case studies: structured object information, interoperable exchange and lifecycle traceability. These are not sufficient to create a digital twin, but they are prerequisites for keeping information understandable and usable over time. Table 5 summarises how the three selected standards address these needs.

Table 5 Role of the three selected standards in a first prototype.

Standard	Main focus	Relevance to a first prototype
SS-EN ISO 23387:2025	Structured, machine-interpretable information	Helps define properties, units, definitions and references for the selected concrete object
SS-EN 17549-2:2023	IFC-based exchange of object data and requirements (no geometry)	Supports exchange of property data, data sheets and requirements between systems, using definitions from data dictionaries

Standard	Main focus	Relevance to a first prototype
SS-ISO 23247-5:2026	Digital thread and traceability	Provides a concept for linking digital representations across life-cycle stages, with identifiers, versions and timestamps*

**** SS-ISO 23247-5:2026 is developed for manufacturing. Its relevance to concrete structures in nuclear facilities is therefore considered by analogy.***

7.3 SS-EN ISO 23387:2025 - STRUCTURED OBJECT INFORMATION

SS-EN ISO 23387:2025 states that machine-interpretable data are important for reliable and sustainable information exchange across the asset life cycle and defines a standardized data-template structure for object characteristics.[6] It also provides relationships between object types, data templates, properties, groups of properties and reference documents.

7.4 SS-EN 17549-2:2023 - INTEROPERABLE EXCHANGE STRUCTURES

SS-EN 17549-2:2023 is more specific than the phrase "system-independent information exchange" suggests.[7] It describes an IFC-based Model View Definition intended to store and exchange construction-object data, link objects and properties to semantic definitions, express requirements and configurable objects, and support construction workflows. Its relevance is therefore interoperability and structured exchange, not a guarantee that every model can be opened unchanged in any software.

7.5 SS-ISO 23247-5:2026 - DIGITAL THREAD AND TRACEABILITY

SS-ISO 23247-5:2026 defines the digital thread as "bidirectional, dependable and trustworthy information that links digital twins with multiple data dimensions, including structure, behaviour, space, time, and lifecycle stages".[8] In practice, the thread consists of links between digital twins at different life-cycle stages, such as design, engineering, manufacturing and testing, each carrying metadata such as link type, identifiers, timestamp and version. For concrete structures in nuclear facilities, the transferable principle is to preserve the relationship between observations, models, assumptions, validation evidence, versions and decisions. The standard should be treated as a conceptual reference because its formal scope is manufacturing.

7.6 SYNTHESIS OF FINDINGS

Taken together, the three standards address complementary parts of the same information chain: what information belongs to an object, how it is exchanged between systems and how it is traced over time. None of them, however, defines what a digital twin for concrete structures in nuclear facilities must contain, how its models should be validated or which decisions it may support. These questions must be answered for the specific application. The standards are therefore best used as tools for making information structured, exchangeable and traceable,

rather than as a framework that in itself creates a digital twin. This is consistent with the reviewed case studies, where recurring difficulties concerned late definition of information requirements, harmonisation of models before handover and exchange of specialist calculation models between software tools.

7.7 ADDITIONAL RELEVANT STANDARDS

In addition to the three standards examined above, several standards were identified as relevant but were not reviewed in detail in this study. They are listed here as starting points for further work. Besides SS-ISO 23247-5:2026, the SS-ISO 23247 series includes parts on overview and general principles,[2] reference architecture, digital representation of manufacturing elements and information exchange.[19] The technical report SIS-CEN/TR 18077:2025 collates 34 European case studies of digital twins in the built environment, including bridges, ports and two nuclear-related cases.[20] According to its introduction, there is currently insufficient information to establish good practice in the development of digital twins. SS-EN ISO 22057:2022 applies the data-template approach of ISO 23387 to environmental product declarations.[21] Finally, ISO 16739-1 (IFC),[3] ISO 12006-3 for data dictionaries[22] and the ISO 19650 series for information management[23] are referenced by the standards reviewed above and are likely to be relevant for a prototype. A closer review of these documents is recommended before they are applied in a nuclear context.

7.8 IMPLICATIONS FOR A FIRST DIGITAL TWIN PROTOTYPE

The first prototype should not begin by implementing standards for their own sake. It should begin with an information requirement for one decision and then use standards where they solve a real lifecycle problem. In practice, this leads to three recommendations:

Structure the information. Use the data-template structure in SS-EN ISO 23387:2025 to define the properties of the selected object or zone, each with a definition, unit, data type and reference document. Add project-specific properties for provenance, such as source, date, method, uncertainty and responsible owner.

Plan for exchange. Specify early which information must survive software changes. Use IFC for models and the IFC-based structure in SS-EN 17549-2:2023 for

[19] Remaining parts of the SS-ISO 23247 series, Automation systems and integration - Digital twin framework for manufacturing: SS-ISO 23247-2:2021 (Part 2: Reference architecture), SS-ISO 23247-3:2021 (Part 3: Digital representation of manufacturing elements) and SS-ISO 23247-4:2021 (Part 4: Information exchange). SIS, Stockholm (2021).
[20] SIS-CEN/TR 18077:2025, Building information modelling - Digital twins applied to the built environment - Use cases. SIS, Stockholm (2025).
[21] SS-EN ISO 22057:2022, Sustainability in buildings and civil engineering works - Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM). SIS, Stockholm (2022).
[22] ISO 12006-3:2022, Building construction - Organization of information about construction works - Part 3: Framework for object-oriented information. ISO, Geneva (2022).
[23] ISO 19650 (all parts), Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling. ISO, Geneva (2018-).

exchanging object data, data sheets and requirements. The latter does not cover geometry. Specialist calculation models need a separate preservation strategy.

Ensure traceability. Link observations, models, assumptions, validation evidence, versions and decisions, using the digital-thread concept in SS-ISO 23247-5:2026 as a reference.

8 Relevance for concrete structures in Swedish nuclear facilities

8.1 CHARACTERISTICS OF CONCRETE STRUCTURES IN NUCLEAR FACILITIES

Safety-critical concrete structures in nuclear facilities, such as reactor containments, have long service lives, high requirements on documentation and verification, limited inspection access and sensitive information. Digital twins therefore need stronger control of information, validation and access than many conventional infrastructure applications. Although the reviewed infrastructure cases cannot be transferred directly to nuclear applications, the challenges they highlight are equally relevant in a nuclear context.

8.2 REQUIREMENTS FOR DIGITAL REPRESENTATIONS IN A NUCLEAR CONTEXT

Based on these characteristics and the reviewed case studies, a digital representation of concrete structures in nuclear facilities should meet the following requirements:

Traceability. It is vital to understand where information comes from, when it was created, how it was checked, which version is valid and whether it is still relevant for the decision being made.

Long-term usability. Information should be structured so that it is adaptable to changes in software, personnel, contractors, data platforms and organisational responsibilities.

Visible uncertainty. Inspection results, NDT data, monitoring data and simulations all contain uncertainty, which the digital representation should communicate.

Validation for the intended use. A model that is useful for visualisation is not automatically valid for structural assessment, and calibration for one degradation mechanism does not make it valid for another.

Controlled access. Information sensitivity should be considered from the beginning, for example through role-based access, information classification and separated information layers, rather than one open model containing all information.

Usefulness to the receiving organisation. The representation must be understood, trusted and used by inspection, maintenance and safety assessment personnel.

8.3 IMPLICATIONS FOR DIGITAL TWIN DEVELOPMENT

A prototype for concrete structures in nuclear facilities should therefore separate three questions that are often mixed together. First, what is the physical object, and which ageing or degradation mechanism is of interest? Second, what decision

should be supported? Third, what digital connection is necessary to improve that decision? Only after these questions are answered should the project decide whether the solution needs a static information model, periodic condition updates, continuous monitoring, predictive modelling or a bidirectional data flow.

The evidence also argues against treating real-time updating as a universal requirement. Concrete ageing processes may evolve slowly, while inspections, pressure tests, repairs or new assessments create discrete events that justify a periodic condition update. The update process should also be flexible enough to handle unexpected events, such as incidents or new findings. The update frequency should follow the physical process and the decision need. What matters is that the current state, assumptions and validation status are controlled and visible to the user.

9 Recommendations for a first prototype

9.1 DEFINE THE DECISION TO BE SUPPORTED

Define the decision before selecting technology. State the user, the decision threshold or question, the evidence required and the consequence of an incorrect result.

9.2 DEFINE THE SCOPE OF THE PROTOTYPE

Choose a limited concrete object, zone or degradation mechanism that can be measured, modelled and reviewed. Avoid a whole-facility model as the first prototype.

9.3 ESTABLISH THE INFORMATION CHAIN

Do not duplicate governed information unnecessarily. Link to established document, inspection or asset-management systems where possible and define which source is authoritative.

Link each relevant observation to object/location, time, method, source, version and uncertainty. Include inspection, non-destructive testing, monitoring, material, repair and assessment data only when they support the defined decision.

9.4 SELECT THE MODELLING APPROACH

Use the lowest model complexity that is sufficient. A structured information model may be enough for some decisions. Predictive decisions may require FEM or other physics-based models.

9.5 DEFINE VALIDATION, UNCERTAINTY AND UPDATE RESPONSIBILITIES

Specify how the model is checked, which data are independent validation data, what uncertainty is acceptable and what the model is not allowed to conclude. Assign responsibility for new data, model changes, approval, archiving and superseded versions. Decide whether updates are periodic, event-based or continuous.

9.6 TEST AND EVALUATE WITH USERS

Evaluate whether intended users understand the information, can trace the result to its evidence, understand uncertainty and can use the output in the real decision process.

9.7 RECOMMENDED PROTOTYPE ARCHITECTURE

A practical first prototype can be expressed as the following controlled chain: decision → object/zone → required information → data collection → quality

control → model/interpretation → validation and uncertainty → decision support → user feedback → controlled update. Every link should have an owner and a traceable source.

Export requirements, object identifiers, access rights and information classification should be defined early (see Sections 6.7, 7.8 and 8.2).

10 Conclusions

10.1 MAIN FINDINGS

The reviewed evidence supports three main conclusions, which correspond to the three lessons introduced in Chapter 1. First, development should start with a clearly defined decision, not with a complete digital twin. Structured object information, measured/as-built comparison, inspection-linked analysis and validated predictive models can all create value at lower or intermediate levels when they answer a defined question, and the decision determines which data, model fidelity, update frequency and validation are needed. Second, the information chain is more important than the visual model: value depends on connecting the right physical evidence to the right object, model and decision with controlled traceability. Third, trust is an engineering and organisational property. Traceability, validation, uncertainty, ownership, versioning, long-term information management and user involvement are as important as sensors, FEM models or databases.

Terminology must be used carefully. None of the reviewed cases meets the strict automation criteria of Kritzinger et al., although several of them are useful for decision support.[1] The report therefore recommends describing actual functionality before applying a classification label.

10.2 RECOMMENDED NEXT STEP

The recommended next step for Swedish nuclear power is a bounded pilot focused on one concrete object or zone and one inspection, assessment, maintenance or life-extension decision. The pilot should use existing trusted data where possible, define a structured object information model, connect relevant physical observations, use a model of appropriate complexity, establish independent validation and uncertainty communication, and test the result with the responsible users. If the pilot demonstrates value and can be maintained under controlled governance, the architecture can then be expanded to additional objects, degradation mechanisms and decisions.

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Appendix A: Interview summaries

A.1 SLUSSEN, STOCKHOLM / DAVID MÖLLER

Purpose. The interview examined how digital representations are used in the Slussen project, how information is structured, how models support production and coordination, and communication.

Main observations. The project has not relied on the term digital twin. The working concept is a 3D representation with relevant information attached to objects. The model has supported coordination, design, production planning, communication, cost estimation and documentation. A key principle has been that the new digital representation method should not lose information that would traditionally have been delivered through drawings and documents.

Transferable lessons. A digital model can be highly valuable without being a digital twin. The important foundation is structured, quality-controlled information that can be understood.

A.2 E4 FÖRBIFART STOCKHOLM / MARTIN ANGBJÄR

Purpose. The interview focused on the transition from project delivery to maintenance, system-independent handover, measured/as-built information and organisational lessons.

Main observations. The project has used 3D models extensively, but Martin Angbjär described the handover model as an imperfect digital copy. Scanning has been used to compare excavated geometry with the design model, and large amounts of production data exist. The maintenance organisation requested system-independent information, leading to harmonisation and conversion for handover. The interview repeatedly returned to the principle of "begin with the end in mind": project information should be defined from the needs of the receiving organisation.

Transferable lessons. The receiving organisation must be involved early. Information requirements should be defined before production, not reconstructed at handover. A prototype should focus on information that the future owner will actually maintain and use.

A.3 E4 FÖRBIFART STOCKHOLM / LARS MATTSON

Purpose. The interview and presentation examined digital project management, object identity, IFC exchange, production data and links to asset-management systems.

Main observations. The model is used as a visual and information interface rather than as the sole repository for all asset information. Object identities link users to documents and to BaTMan, where governed maintenance information is stored. Production data, such as geological mapping, grouting and drill-rig data, cover the

full tunnel length. They are stored in a separate structured system and presented in a GIS platform. Lars Mattson emphasized consistent requirements, the use of IFC for exchange and the need to define the final information product before the project starts.

Transferable lessons. Do not duplicate governed information across systems. Use stable object identities and links to authoritative sources. Open exchange structures can improve portability, but they require explicit information requirements and quality control.

A.4 TRAFIKVERKET MAINTENANCE / AARON HANTLER

Purpose. The interview focused on what maintenance needs from digital information, what creates trust and what would make a digital approach acceptable in daily work.

Main observations. Maintenance needs confidence that the digital information corresponds to the physical facility and that changes are transparent. Existing management systems and work processes matter because users already know and trust them. The interview also supported the idea of starting with a limited maintenance problem rather than a complete digital twin.

Transferable lessons. User acceptance depends on clear responsibility, transparent updates and a demonstrable maintenance benefit. The first prototype should be built with the receiving users, not handed to them after development.

A.5 PORT OF GOTHENBURG / MARTINA DAWODI, HANNA SCHLOENZIG AND HENRIK WALLERMAN

Purpose. The interviews examined how structural models, inspections and sensitivity analyses are used to manage an existing quay and how the information is governed over time.

Main observations. The case uses several structural calculation models rather than one integrated BIM model. The models were initially based on original drawings and have been refined using inspections, measurements, structural changes and current loading. Damage information and inspection results are used to modify assessment scenarios, including the removal or reduction of pile capacity. Sensitivity analyses help target inspections and support rapid responses to incidents or new findings. The Port has used third-party review and has discussed redundancy, change logging and ownership because the models are maintained by consultants. A follow-up interview with the Port and ELU described how the models are built and updated, and confirmed that the purpose of the information is controlled management of ageing and operational decisions.

Transferable lessons. A strong case can begin with a recurring decision. The model should remain alive because it is repeatedly used, but governance, redundancy and exchange of specialist calculation models must be planned explicitly.

A.6 EDF VERCORS / JEAN-LUC ADIA AND JEAN-PHILIPPE MATHIEU

Purpose. The interview examined why VERCORS was created, how the mock-up and numerical models are connected, how calibration and validation are performed, and what EDF learned from developing a digital-twin approach.

Main observations. VERCORS was created to understand and predict the long-term mechanical and leak-tightness behaviour of concrete containment structures. The mock-up is heavily instrumented for temperature, moisture, strain and displacement and is subjected to periodic pressure tests. Numerical models are calibrated and validated against measured behaviour and used to predict ageing, leakage and the effect of repairs. The project also exposed major data-architecture challenges: sensor data from many disciplines had to be stored securely, made accessible and managed consistently. Calibration is periodic rather than continuous, and the interview explicitly noted that the ambition of a fully realised digital twin was not completely achieved in the early project phase.

Transferable lessons. The strongest element is the validated measurement-model chain around a defined physical problem. A Swedish prototype should emulate that logic, while limiting the first scope to measurements and model parameters that can realistically be maintained and validated in an operating plant.

DIGITAL MODELS AND DIGITAL TWINS FOR NUCLEAR CONCRETE STRUCTURES

This project reviews how digital models, digital shadows and digital twins can support the management of nuclear safety-critical concrete structures and what can be learned for Swedish nuclear power.

The reviewed case studies show that there is no single digital-twin solution. Useful applications range from structured information models to models that combine inspection, monitoring and structural analysis to support decisions. The appropriate level of digitalisation depends on the decision to be supported, and continuous real-time updating is not always necessary.

For concrete structures in Swedish nuclear facilities, the recommended next step is to start with a clearly defined decision and develop a limited prototype around the information, models, validation and users required for that purpose.
The key is not to digitalise everything, but to connect the right information in a traceable and reliable way to support better-informed decisions.

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