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Purpose-driven roadmap for digital twins in engineering & construction: case study

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The discussions on digital twins (DT) have greatly increased, and this technology is believed to solve many of the engineering and construction (E&C) industry's problems. However, there is a significant gap between this perceived potential and the maturity level of practical applications. The proliferation of context-specific frameworks for each DT project hinders the widespread adoption of DTs across the industry. This paper aims to shift the focus from individual DT frameworks to viewing DT as a tailored pack of existing technologies, chosen according to the purpose of the digitalisation initiative. A purpose-driven roadmap for DT adoption in the E&C industry is introduced to bridge the gap between perceived potential and practical applications. The methodology of this study comprises a literature review, DT investigation, and a case study analysis. The stages of the proposed roadmap stages include assessment, purpose definition, technology selection, implementation, and optimisation. The roadmap is validated, and its application is demonstrated through a case study of a reinforced concrete chimney in Sweden, where two longitudinal cracks had been previously identified. The conclusion highlights findings and future directions, emphasising the roadmap's role in fostering a flexible and impactful adoption of DTs in the E&C industry.

Keywords: case study/concrete structures/digital twins/framework/roadmap

Introduction

A digital twin (DT) is a digital representation of an asset which includes the distinctive feature of a data flow connecting both physical and digital entities. DTs are considered key enablers in implementing Industry 4.0 in the Engineering and Construction (E&C) industry and are believed to have the potential to solve some of its most pressing challenges, such as low productivity and poor technology advancements (Opoku, *et al*., 2021; Sepasgozar, 2021). The concept first emerged in 2002 (Grieves and Vickers, 2017) and the first application dates back to 2010, when NASA introduced DTs to replicate the life of air vehicles in its technology roadmaps (Shafto, 2010). Even though DTs have been around for more than 20 years in concept and for almost 15 years in practical development, actual DT applications are still scarce, particularly within E&C. In industries, such as aerospace and manufacturing, DT applications are more mature than in E&C, which is still grappling with different concepts for a DT and how to apply them (Saback *et al*., 2024a). Research shows that completed DTs in practice currently do not go beyond the third maturity level (Arup, 2019; Lazoglu, *et al*., 2023; MEED, 2021). Therefore, there is a gap between the perceived potential and the maturity level of practical applications of DTs within the E&C industry.

The propagation of DT applications within E&C is not being hindered by a lack of understanding of the benefits that the technology might bring, as these benefits have been well established. In fact, a previous study showed that the average number of publications per month containing the keywords 'digital twins', 'BIM', 'management' and 'maintenance' increased almost 4000% from 2010–2020 to 2021–2023 (Saback, *et al*., 2022b). With recognised benefits and a large growing body of research, a fundamental question arises: what is holding back progress? The main practical challenges when developing a DT application are navigating the technology options, the expertise required to operate them, and data-related complexities – such as data volume, continuous updates, multiple sources, and securing clean and complete data (Clark, 2022; Kwasniewski and Bjarnehed, 2018; Slind, 2022). Moreover, E&C as an industry is fragmented, complex, risk averse and slow to adopt technological changes. There is neither a common product nor a common consumer for the many branches of the industry, which complicates the propagation of DT even further.

To grapple with these challenges, many different DT frameworks have emerged – for example: Anon (2022), Boje *et al*. (2023), Hosamo Hosamo *et al*. (2023), Kosse *et al*. (2022), Pellegrino (2022) and Turk *et al*. (2022). The proliferation of scattered and decentralised DT frameworks also challenges the progression of DTs in E&C, as each initiative is forging a distinct path for themselves instead of building upon a cohesive foundation, since none exists. The absence of DT standardisation entails that each study might define DTs differently, which contributes to the lack of clarity in the applications and whether their definition corresponds to a DT or not. The frameworks are often context-specific or tied to specific technologies and, consequently, difficult to replicate. Then, the cycle of creating new, context-specific frameworks for each DT project is perpetuated. As a result, the field is further fragmented and overall progress is slowed down.

To break this cycle, the E&C industry requires recognised standards and strategic management to drive business models forward and bridge the gap between perceived potential and practical DT applications. To advance the implementation of DTs in E&C and address this gap, this study proposes two paradigm shifts illustrated in Figure 1. Firstly, it promotes a shift in the perception of a DT from a singular new technology, or a 3D model, to understanding it as a combination of existing technologies acting as tools to fulfil specific purposes. Secondly, it proposes a shift from promoting DTs through new frameworks to a more generalisable approach, focused on the purpose of a DT in a strategic roadmap. To apply these paradigm shifts, this study proposes a purpose-driven roadmap designed to assist in guiding E&C organisations in effectively adopting DTs. Then, the roadmap is validated by a demonstration of its application in a case study of a reinforced concrete (RC) Chimney in Sweden. The conceptual representation in Figure 1 thus makes conceptual sense within the context of the proposed framework, as it visually supports the central argument of the study.

This study aims to address the gap between perceived potential and practical DT applications in E&C to promote further dissemination. Besides the case study application, the novelty of this research is twofold. It brings forth a shift in perspective concerning DTs, a clarity only attainable after years of deep DT investigation in the E&C industry. Additionally, it introduces a purpose-driven roadmap; while several frameworks and reviews explore the benefits and challenges of adopting DT, this generalisable purpose-driven perspective sets this research apart. Independent of specific technologies or contexts, this outlook promotes reflection on why DT adoption is necessary for each situation. This study represents the culmination of extensive research in the field of DTs, consolidating key findings to propel the industry forward, enhance clarity in definitions, and share valuable lessons learned. This convergence aims to guide stakeholders, promote industry-wide progress, and contribute to the collective understanding of optimal DT implementation.

This article is organised in six sections. After the introduction, a brief review on strategic management and digitalisation is presented to contextualise the proposed roadmap – for full DT reviews previously published by the authors, see Saback *et al*. (2022a) and Saback (2022). The methodology for the study is presented in the third section, followed by the presentation and explanation of the proposed purpose-driven roadmap. The roadmap is then applied to the RC Chimney case study, which is also detailed in the fifth section. The last section presents the conclusions and indications to future research.

Strategic management for digital transformation in the E&C industry: challenges and opportunities

Digital transformation is not an objective state or a fixed destination, but rather a strategic choice made by executives from a range

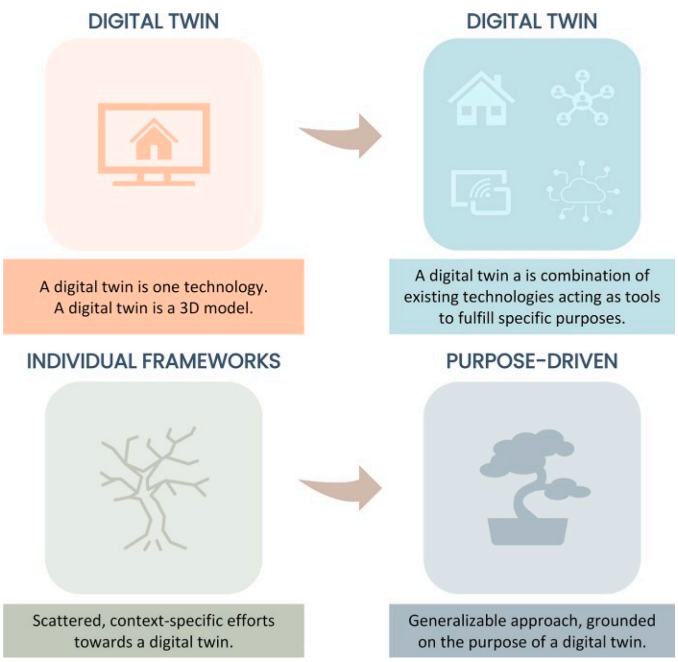


Figure 1. Proposed paradigm shifts for digital twins

of alternatives to improve current processes (Furr *et al*., 2022). As enablers of digital transformation, DTs should be tailored to reflect the specific needs of end users within an operation. Then, the first and most important step is to first identify those needs.

A roadmap is a valuable management tool that assists in setting strategic goals and estimating the potential of new technologies, products, or services (Carayannis *et al*., 2016; Vishnevskiy *et al*., 2016). Roadmaps that integrate technological development with market needs can significantly enhance strategic planning and management of an organisation (Vishnevskiy *et al*., 2016). This approach is essential for the E&C industry, which requires such strategic frameworks to effectively implement digital transformation and harvest the benefits of technologies such as DTs.

Even though the growing literature has improved the general understanding of digital transformation, a comprehensive portrait of its nature and implications is still lacking (Vial, 2019). Digital transformation involves managing the outcomes of disruptions caused by digital technologies, which trigger strategic responses from organisations. These responses include altering value creation paths, managing structural changes, and addressing organisational barriers (Vial, 2019). In construction firms, digitalisation can enhance business results and sustainability outcomes, but successful implementation requires a strategic-level change management protocol; without this, firms often fail to achieve the desired outcomes (Nikmehr *et al*., 2021). Therefore, E&C organisations need to consider several strategies to successfully implement DTs in their projects.

Key strategies include providing training and awareness programs for stakeholders, promoting collaboration among various professionals, and investing in technologies like building information modelling (BIM), data analytics, and machine learning (Arowoiya *et al*., 2024). Data management strategies to ensure data reliability, security, and accessibility, as well as guaranteeing regulatory compliance, pilot testing and validation, and evaluation mechanisms are crucial (Arowoiya *et al*., 2024). Furthermore, integrating DTs with existing systems and employing effective change management strategies to address resistance and challenges are essential for successful implementation (Nymark Ernstsen *et al*., 2021). Finally, embracing a culture of continuous improvement and innovation will help adapt to evolving technologies and market trends (Nymark Ernstsen *et al*., 2021).

Therefore, strategic management tools are crucial for the successful implementation of digital transformation in E&C since they align digital efforts with business objectives to ensure effective resource allocation. By monitoring performance and making data-driven decisions, construction firms can gain a competitive edge and adapt to evolving market conditions. Therefore, integrating strategic management practices enhances planning, decision making, and organisational effectiveness, helping construction companies navigate challenges, seize opportunities, and achieve sustainable growth (Nymark Ernstsen *et al*., 2021). This approach matches practices in other industries and is essential for keeping up with a rapidly evolving business environment accelerated by technology.

Methodology

This study builds on previous literature reviews, DT methodologies and case study applications focused on asset management of civil structures – see, for example, Saback *et al*. (2024b), Saback *et al*. (2022b), Saback *et al*. (2021) and Saback *et al*. (2022b). Therefore, the literature review presented is succinct and focused on strategic management for digital transformation implementation within E&C. The development of the proposed purpose-driven roadmap was based on the previous extensive research, and on a review of the literature accompanied by unstructured interviews.

The selected case study is a RC chimney structure that went through a structural assessment (Täljsten, *et al*., 2022) that identified the need for structural health monitoring (SHM) to ensure continued safe operation. The case study is presented in the fifth section, and complementary information was obtained from company reports and documents. The proposed roadmap was applied to the case study to simulate the development of a tailored DT architecture. From that simulation, the roadmap was validated and refined to promote generalisation and widespread adoption of DTs for civil structures.

Figure 2 illustrates the methodology for this study, and the roadmap is presented in the following section 4.

The proposed roadmap aligns closely with established project management frameworks such as PMBOK (Project Management Institute, 2025) and PRINCE2 (PRINCE2, 2025), particularly in the areas of planning, execution, and monitoring and controlling. For instance, in the Monitoring and Controlling phase, the roadmap promotes continuous performance assessment through key performance indicators (KPIs) defined during the Purpose stage. In the case study of the RC chimney, the integration of sensor data within the DT framework exemplifies this process: monitoring of crack width and thermal variations supports informed decision making and timely intervention. This alignment illustrates how the roadmap can serve as a complementary tool for project managers applying standard methodologies in digital transformation initiatives.

Purpose-driven roadmap

Introducing the roadmap

Following the methodology described in the previous section, a purpose-driven roadmap was developed, considering stages such as assessment, purpose definition, technology selection, implementation, and optimisation. The proposed roadmap is presented in Figure 3.

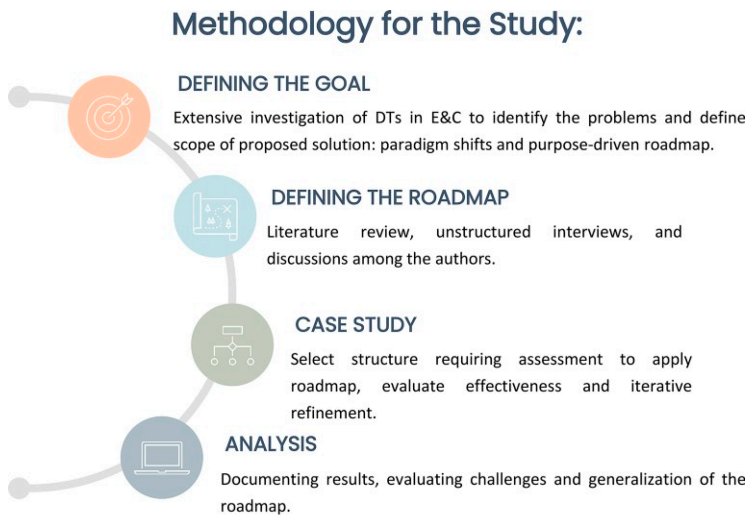


Figure 2. Methodology illustration

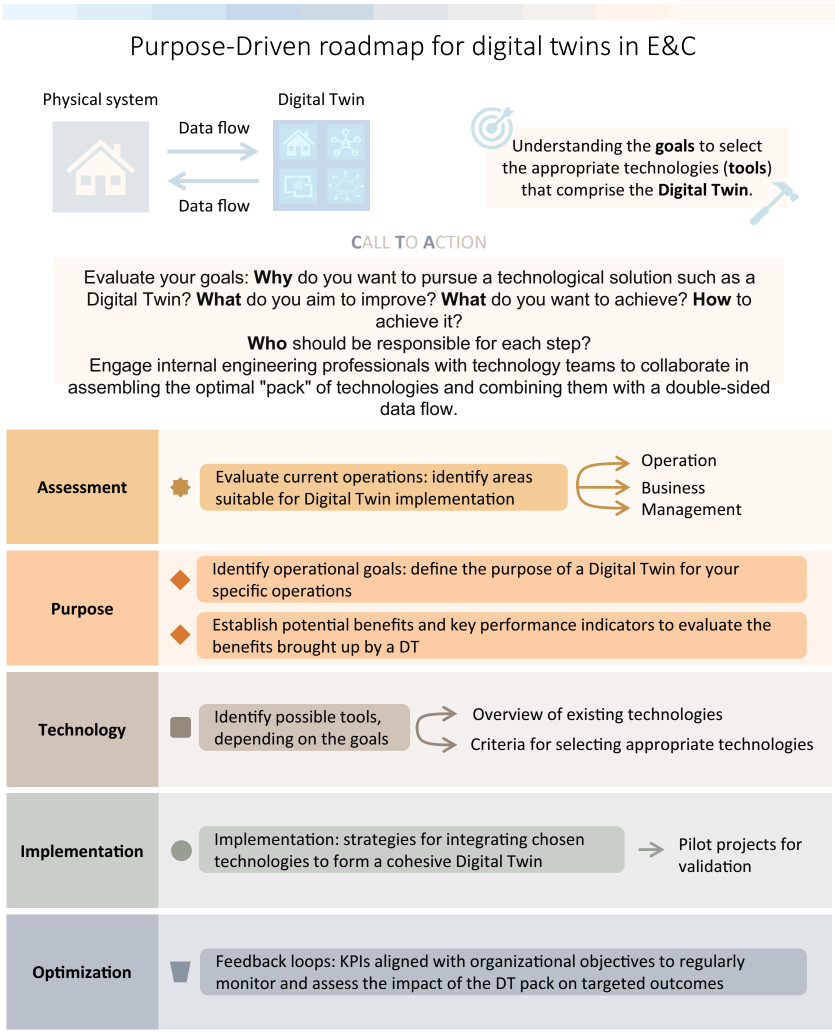


Figure 3. Purpose-driven roadmap for DTs in E&C

The overall objective of the roadmap is to promote the adoption of DTs across E&C by departing from context specific frameworks to a generalisable approach, grounded on the purpose of the technology and adaptable to different projects. The fact that it is not tied to specific technologies also allows for integration with future industry trends, accommodating the rapid evolution of AI and other technological advancements.

The proposed roadmap differentiates between Goals and Tools. Goals involve asset owner's intent of using DTs to optimise operations, business processes, or management. Based on these specific needs, appropriate tools (existing technologies) are then selected. The roadmap first promotes identification of needs and objectives for optimisation through DT, then, it encourages selection of suitable existing technologies to achieve those goals. Identifying end user needs is crucial but often overlooked in DT initiatives, so addressing this requires a deeper understanding of specific end user requirements and challenges.

The specific focus is to address the existing gap between the perceived potential and practical applications of DTs. The expected outcome is the development of a DT architecture for the asset owner including tools, concepts, and responsibilities. To achieve that, the roadmap aims to engage key stakeholders in its application, including engineers, construction managers, software developers and technology providers. The involvement of different areas, particularly engineering and technology, is necessary for the efficient implementation of a DT. Furthermore, the roadmap also aims to be aligned with industry goals to ensure that DT adoption contributes directly to industry advancement.

Roadmap stages

The roadmap should be employed when the organisation is aiming to employ a DT solution or wants to evaluate if a DT would be suitable for an asset. The first stage of the roadmap is Assessment. Its goal is to evaluate current operations to identify areas suitable for DT implementation, that is Operations, Business, or Management. The main question proposed in this stage is: Why do I need a Digital Twin? It might be so that, upon assessment, the conclusion is that a DT is not necessary and some kind of digital modelling or simulation suffices.

The second stage is Purpose Definition, aimed to guide the reader on defining the purpose of a DT for their specific operations. The first step is to identify operational goals, to clarify the purpose of the DT, then to establish potential benefits and key performance indicators to evaluate the benefits brought up by the DT. The question proposed at this stage is: What do I need this Digital Twin for?

After the assessment of current operations and establishment of the purpose of the DT, the next stage is the technology selection. This stage is about understanding end user needs and how to address them with the best 'technology pack'. Different technological tools that can compose a DT are currently available at market. It is one of the paradigm changes proposed by this study to shift the view of DT as a technology to an assembly of existing tools integrated to perform at their full potential in benefit of a structure throughout its lifecycle. Therefore, based on what the DT aims to achieve, possible technologies can be selective to fulfil specific tasks, such as design, modelling, simulation, SHM, non-destructive testing (NDT), budget analysis, inspection, and so on The question posed here is: Which tools do I need to compose the DT and achieve each intended goal?

The fourth stage, after selecting the appropriate tool for each need, is Implementation. This stage comprises integration strategies to combine all selected tools in a cohesive DT, remaining faithful to its concept to collect the benefits of employing a DT. At this point, the collaboration between different stakeholders is again highlighted, since the integration of different data sources relies on technical knowledge that should be aligned with the engineering expertise required to maintain the structure. At this point, the main question is: How can the selected tools and data sources be integrated into a cohesive DT? Pilot tests are recommended to ensure functionality of the solution, for example, by starting with small tasks that can later be scaled up to the entire system.

After the fourth stage, the DT should be functional and operating. The fifth and last stage is Optimisation, intended for continuous improvement of the DT. Feedback loops play an important role in ongoing optimisation of the DT, as well as KPIs aligned with organisational objectives to regularly monitor and assess the impact of the DT on targeted outcomes. This stage should answer the question: How can this Digital Twin be improved?

Case study analysis

The proposed roadmap was applied to a case study for demonstration, validation, and refinement. The goal of the application was to demonstrate its usability, gather feedback on the clarity, feasibility, and relevance of the roadmap stages. The case study consists of a RC chimney in Sweden. The RC chimney is about 90.5 m tall, built in 1963 using the gliding-formwork casting in an open field terrain (Täljsten *et al*., 2022). The diameter of the chimney is 4.0 m on the inside and 4.34 m on the outside, so the thickness of the concrete wall is 170 mm. The structural assessment performed on the chimney that identified the need for SHM is presented in subsection 5.1, while the following application of the roadmap to the RC Chimney, in the following subsections, simulates how the asset owner could proceed if they wished to follow up asset management of the structure using a DT to ensure its continued safe operation.

Structural assessment

Upon detecting two vertical cracks along the height of the chimney, a structural assessment was ordered by the asset owners. Then, a thorough structure assessment, performed according to current best practices, was performed including analytical calculations, numerical modelling, as well as various advanced non-destructive techniques, shortly presented in this section. Figure 4 shows aerial images of the RC Chimney, including south, north, east, and west faces. In the north face it is possible to see the vertical crack patched in white. The cracks had been repaired before, but the repair method was not satisfactory. The structural analysis, reported by Täljsten *et al*. (2022), considered wind and thermal loads to generate the highest bending moments and calculations revealed that the horizontal reinforcement found in the concrete was indeed not sufficient.

The holistic assessment that was carried out included a 3D model obtained through drone-based photogrammetry to point cloud, used to obtain the as-is geometry and to support crack detection (Figure 5). It also comprised a 3D BIM model that can be updated with information about the structure, materials, and so on shown in Figure 6. The internal geometry, that is the reinforcement, was identified from original drawings and located using ground penetrating radar (GPR). Results from the GPR scanning for the horizontal reinforcement, vertical reinforcement, and full length of the chimney are presented in Figure 7.

A dynamic analysis evaluating different vibration modes was conducted, seen in Figure 8. NDT and semi-destructive testing were performed for material characterisation, such as material properties, quality assessment regarding concrete carbonation, thin-section analysis, and so on Figure 9 shows the GPR scanning, core sampling, and ultrasonic inspection conducted on the external wall of the chimney. Surface cracks were also identified using a cover-meter, as illustrated in Figure 10. The figure also shows a point where a substandard previous repair was identified, where cracking occurred in the repair mortar. Furthermore, ultrasonic scanning

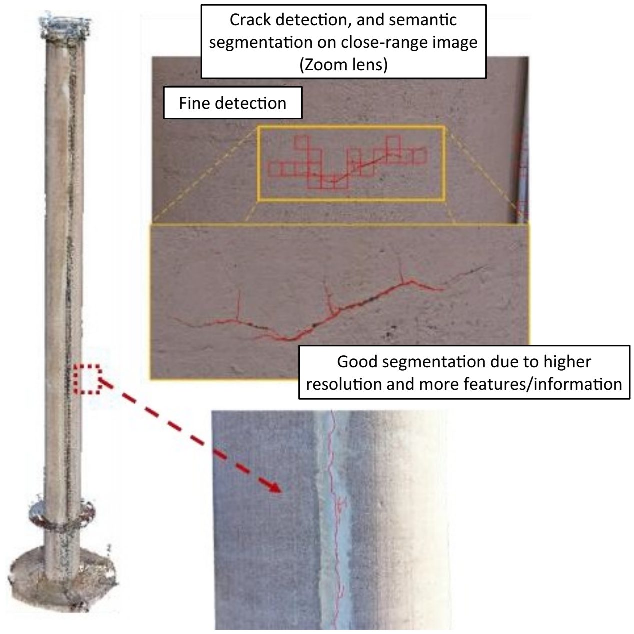


Figure 5. Photogrammetry and crack detection images of the RC Chimney

was used to track concrete cracking; a vertical continuous crack is shown in an ultrasound scan in Figure 11.

The main objective of the FE analysis was to demonstrate the applicability of the proposed roadmap. AXISVM12 was selected for being well suited for the intended analyses – namely, crack simulation, comparison between damaged and undamaged states, and vibration mode evaluation. The FE model utilised material

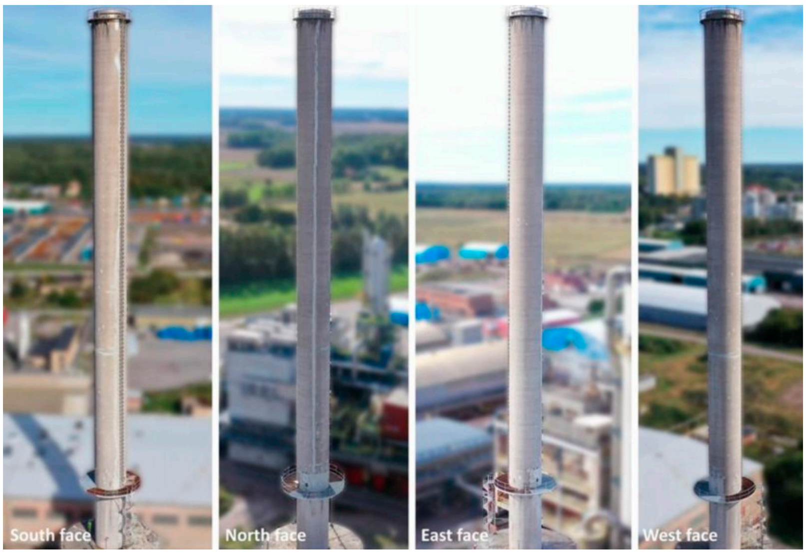


Figure 4. Aerial images of the RC Chimney case study

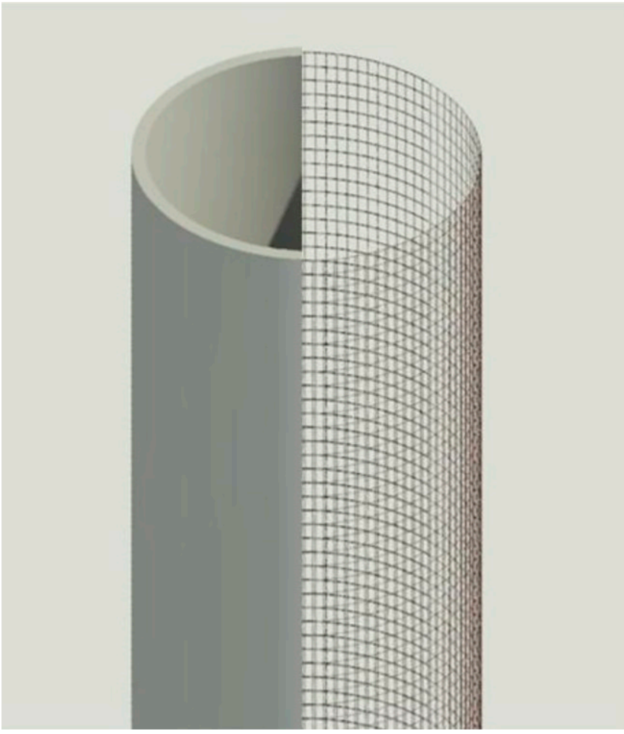


Figure 6. BIM model of the chimney; left half showing surface view and right left showing internal reinforcement

properties for concrete class C35/45 for the entire chimney, with a reduced Young's modulus (E) to simulate reduced stiffness due to cracking in the damaged model. A mean E-modulus value of 29,000 MPa was considered for the uncracked/undamaged chimney, based on laboratory cylinders tests. In the vicinity of the cracks, the E-modulus of the finite elements was reduced to 10 MPa. A FE model-updating method was used to calibrate the chimney's stiffness, aligning it with data from the monitoring programme. Two main load cases were considered in the FE-updating analysis: self-weight and global wind. The displacements at the top of the chimney increased from 174 mm in the undamaged model to nearly 300 mm in the damaged model, exceeding the service limit state of H/250 = 280 mm. Consequently, the maximum displacement of the cracked chimney model did not meet the service limit state requirements. The analysis was performed at the global structural level, with the cracked regions evaluated within the context of the overall chimney behaviour rather than through isolated element modelling. The undamaged and damaged FE models are presented in Figure 12.

The main outcome from the analysis was that the chimney requires strengthening and follow up via SHM. While the identified cracks did not pose immediate danger to the overall structural safety of the tower, a series of actions were recommended to limit the progression of damage. The actions included field monitoring of the crack widths, monitoring of site-dependent wind loading, thermal loading due to temperature differences between inner and outer wall surface considering flue gas and the outside temperatures. FE modelling was used to design the fibre-reinforced polymer (FRP) wrapping repair solution, illustrated in Figure 13. Lastly, the analysis report also stated that failure to follow the recommended actions may result in serviceability problems, accelerated deterioration, and reduced service life.

Assessment: Why do I need a digital twin?

The goal of the first stage, called Assessment, is to evaluate current operations and identify areas suitable for DT implementation, in operations, business, and management. The previously performed structural evaluation (Täljsten, *et al*., 2022) identified concerns about structural integrity due to cracks, which can be identified as an operational challenge. The evaluation also recommended continuous monitoring of crack width progression to detect changes in behaviour, such as tracking possible crack width growth relative to the temperature and wind action. Early detection of those changes allows for prompt intervention, which helps to limit further damage. This presents an opportunity for optimisation through the DT by integrating SHM into a single, collaborative platform with the 3D model. This integration facilitates interpretation of results, improves the selection of repair methods and the timing to implement them based on the chimney's response as measured by the installed sensors and visualised/analysed through the DT, thus enabling predictive maintenance.

Data from continuous SHM can be updated into digital models displaying the current condition of the RC Chimney, such as FE models or other simulation software. Then, future behaviour simulations can be performed to evaluate the effectiveness of different repair methods before implementation. Optimised schedules for predictive maintenance and repair strategies can reduce unplanned downtime and ensure safety, thus enhancing business value, reducing costs, and improving decision making. Asset management in a centralised DT platform can enhance management processes, communication, and strategic planning by improving coordination and enabling integrated data management. Therefore, since clear roles for optimisation through DT have been recognised to target the main issue identified by the structural analysis, it can be concluded that a DT is appropriate for this case study.

Purpose: What do I need this digital twin for?

After the initial assessment of current operations has been concluded, the purpose of the DT should be established. The assessment of the RC Chimney identified the main issue as structural integrity concern due to cracks and pointed out the respective opportunities for optimisation through DTs. Then, the first step of the Purpose stage is to identify clear, specific operational goals for the DT, presented in Table 1.

Then, the purpose of the DT in the context of the identified operational goals should be clearly articulated. In this case study, the purpose of the DT it to provide real-time monitoring of crack

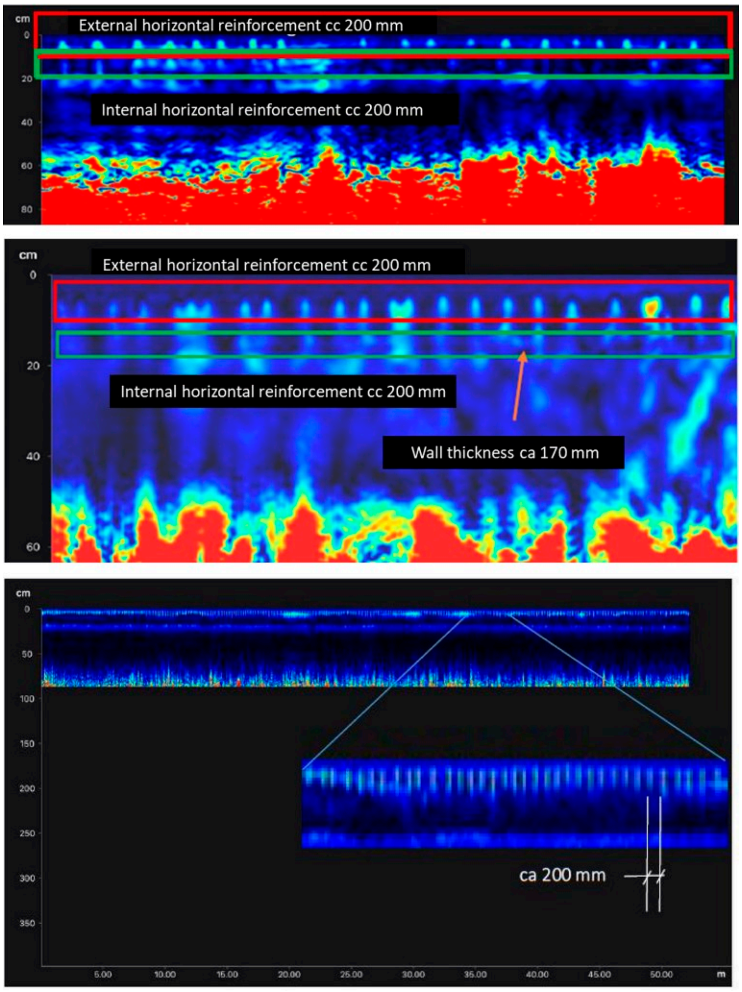


Figure 7. GPR scanning: horizontal reinforcement (top), vertical reinforcement (centre), full length (bottom)

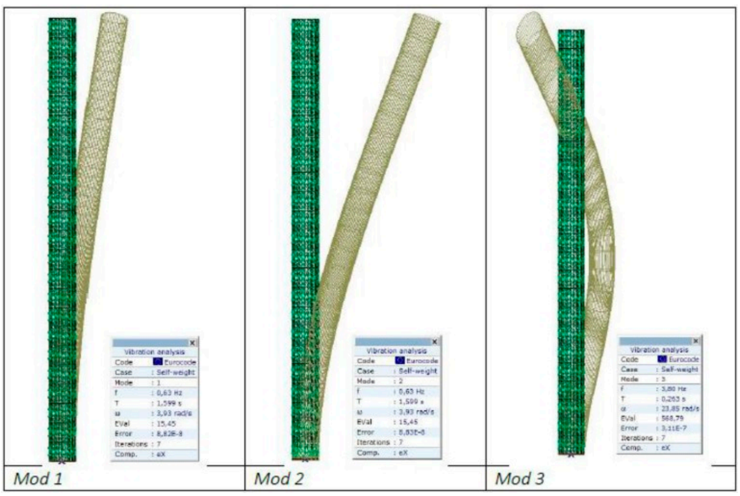


Figure 8. Vibration mode analysis

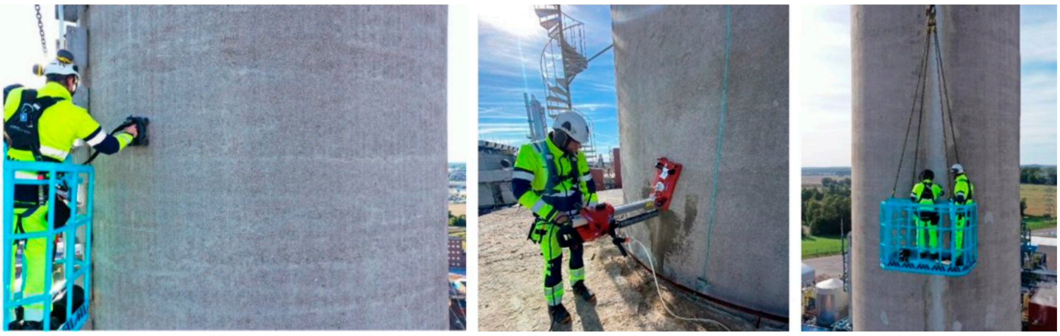


Figure 9. GPR scanning (left), core sampling (centre), ultrasonic inspection (right)

Figure 10. Surface crack detected and covermeter measurement (left), substandard repair where cracking occurred in the repair mortar (right)

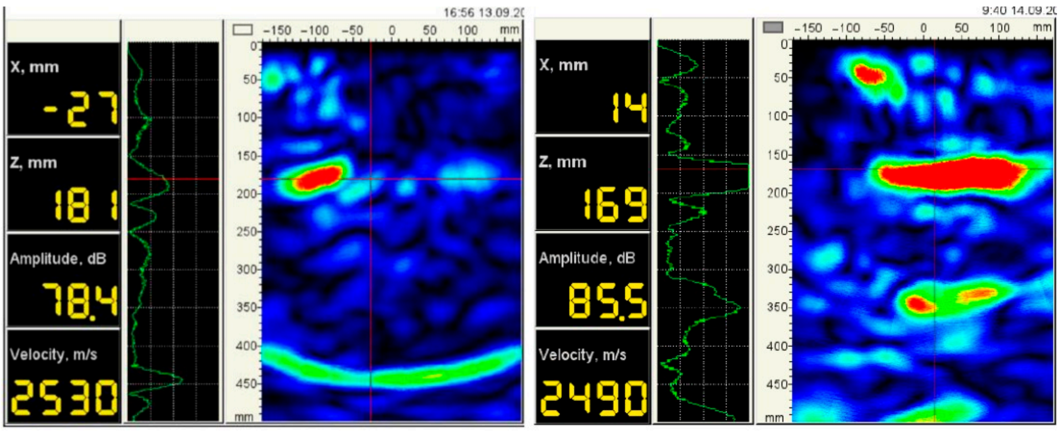


Figure 11. Ultrasonic scanning: vertical continuous crack (left), example of thickness measurement without a crack, the entire back is visible at 170 mm (right)

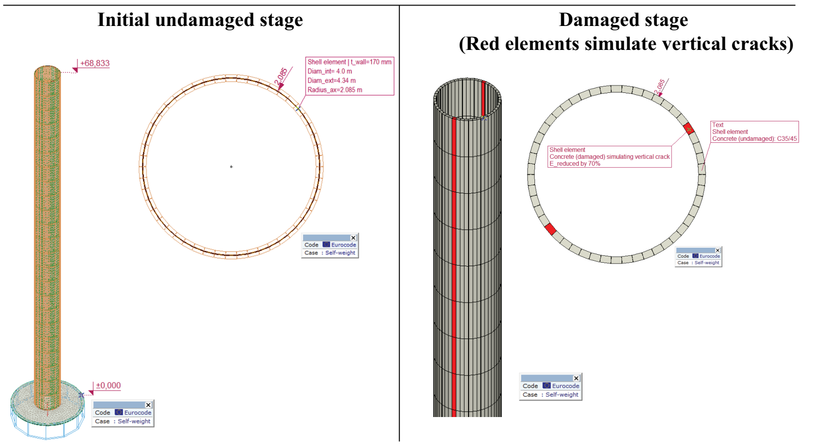
widths and crack behaviour before and after strengthening the RC Chimney to improve visibility into its structural health, predict and prevent potential failures, thus improving decision making and ensuring structural safety.

Last within the Purpose stage is the definition of KPIs to identify measurable benefits to evaluate the effectiveness of the DT implementation, presented in Table 2.

Technology: Which tools do I need to compose the DT and achieve each intended goal?

This stage aims to select the 'technology pack' that composes the DT, that is define an architecture for the system to fulfil the operational goals defined in the Purpose phase. It comprises an overview of existing technologies, presented in Table 3, and criteria for selecting the most appropriate options.

FE model: overall geometry and material properties



Name	Type	Model	E_x [N/mm^2]	E_y [N/mm^2]	ν	σ_T [1/°C]	ρ [kg/m^3]
C35/45	Concrete	Linear	29 000	29 000	0.20	1E-5	2500
C35/45 (cracks)	Concrete	Linear	10	10	0.20	1E-5	2500

Figure 12. FE model showing overall geometry and material properties in initial undamaged stage (left) and damaged stage (right)

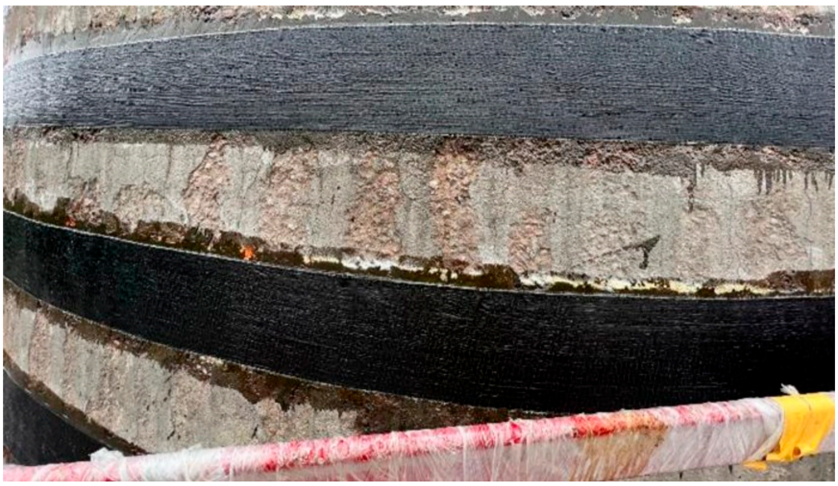


Figure 13. FRP strengthening

Then, the criteria for selecting the appropriate technologies for the DT architecture from the options in Table 3, among others, involve several key factors. Firstly, compatibility and integration are essential; the technology must be compatible with existing systems and able to integrate with other selected tools to ensure seamless data flow and cohesive operation of the DT. Scalability is necessary so the technology can accommodate future expansion and increased data volumes, supporting long-term analysis and adaptation to project needs. Reliability and accuracy are vital, as the data provided by the technology must be reliable and accurate to ensure the integrity of the DT and the validity of the insights derived from it. The technology should be user friendly, at a level proportional to the expertise of those who will be trained to operate it within the asset management team. Vendor support and community can also be considered to facilitate access to technical support and shared knowledge, enhancing problem-solving capabilities. Similarly, cost-effectiveness is a factor that should be considered in relation to the means of those responsible for financing the DT to ensure it is financially viable.

Implementation: How can the selected tools and data sources be integrated into a cohesive DT?

The goal of the Implementation step is to develop strategies for integrating the chosen technologies into a cohesive DT and outline

Table 1. Operational goals for the RC chimney DT

Operational goals	Aim	Purpose
Operational safety	Ensure structural integrity and safety of the RC Chimney	Use DT to continuously monitor crack progression and efficiency of repair solution (crack response, displacements, natural frequency, new damages), and set thresholds to predict and prevent potential failures
Maintenance optimisation	Optimise maintenance schedules and repair methods	Implement predictive maintenance based on real-time data and simulations to extend the service life of the chimney and reduce maintenance costs
Cost efficiency	Reduce the costs associated with monitoring, repairs, and unplanned downtime	Use automated DT monitoring to minimise the need for manual inspections and reduce overall maintenance costs
Data-driven decision making	Improve decision making processes related to SHM	Provide accurate, real-time data and predictive insights to support strategic planning and resource allocation

Table 2. KPIs for operational goals

Operational goals	KPIs
Operational safety	▪ Frequency of crack increase detection ▪ Severity of crack width increase ▪ Efficiency of repairs
Maintenance optimisation	▪ Maintenance cost savings ▪ Number of unplanned downtime due to maintenance ▪ Time between maintenance actions
Cost efficiency	▪ ROI from DT implementation
Data-driven decision making	▪ Decision making time ▪ Accuracy of predictive maintenance and repairs ▪ Satisfaction of stakeholders with decision outcomes

pilot projects for validation. One of the most significant challenges in creating functional DTs currently is establishing a common data environment for different data sources. Other data related challenges, such as data cleaning, storage, and security, also hinder DT development. Therefore, this stage is critical for transitioning from theoretical potential to realising tangible benefits from the technology. Then, it is highly recommended that this process be supported by individuals with software development or programming backgrounds, as well as engineers, emphasising the importance of a multidisciplinary team in DT projects.

To integrate the chosen technologies into a DT effectively, a detailed system integration plan should initially map out the data flow between sensors, IoT platforms, data storage, analytics tools, and visualisation software. This plan should ensure compatibility and establish communication protocols between different components, while also defining roles and responsibilities for team members involved in the DT project. Implementation can be carried out using external software platforms, custom in-house software development, or a combination of both through the customisation of existing platforms. Examples of integration platforms include Siemens MindSphere, GE Predix, ThingWave, and PTC ThingWorx.

Establishing a centralised data management protocol is essential for securely storing data and developing data processing pipelines to clean, preprocess, and organise data for analysis. Implementing

Table 3. Overview of technologies for RC Chimney DT

Category	Tools and devices	Objective
Sensors: Cracks	Strain gauges, optical methods (drone scanning, photogrammetry), FOS, LVDT, GPR, ultrasonic tomography	Structure scanning, crack detection and monitoring measuring crack widths and detecting structural changes
Sensors: Temperature	Temperature sensors	Monitoring thermal loading and environmental conditions
Sensors: Wind and dynamic loads	Vibration sensors, wind stations, accelerometers, geophones	Detecting structural responses to wind and other dynamic loads
Data collection	IoT platforms	Collecting and transmitting data from sensors in real time
Data storage	Cloud storage solutions	Securely storing large volumes of data
Data analytics	Predictive analytics tools	Analysing historical data and predicting future maintenance needs
Machine learning	Machine learning algorithms	Filtering, identifying patterns and anomalies in structural data
Visualisation	BIM software	Creating a digital representation of the physical structure
Simulation	Simulation and FE software	Running structural simulations and stress tests
Reporting	Dashboards, Business Intelligence and Reporting Tools	Visual and interactive reporting

robust security measures to protect data integrity and ensure compliance with relevant regulations is equally crucial. This involves establishing data encryption protocols, implementing secure access controls for cloud storage, conducting regular security audits, vulnerability assessments, and ensuring alignment with industry standards and regulations related to data privacy and security.

Pilot projects for validation should follow the proposed roadmap but beginning with a less comprehensive task to validate DT implementation, gather feedback, and refine the implementation process. For the RC Chimney, a suitable pilot project could start by focusing on a specific section of the chimney that offers potential to demonstrate DT benefits and test the process flow. During the pilot testing phase, it is crucial to identify any integration issues, data inaccuracies, or usability concerns that arise. Based on feedback and observations from this initial testing, the DT model and integration strategies should be refined accordingly. Lastly, the performance of the DT system can be evaluated using the predefined KPIs, as well as assessing the accuracy of predictive models and the effectiveness of real-time monitoring throughout the pilot project.

Optimisation: How can this digital twin be improved?

The objective of this last step is to establish feedback loops, aligned with the previously defined KPIs, to regularly monitor and assess the impact of the DT pack on targeted outcomes. Feedback loops are essential for ensuring the DT's effectiveness, as they involve regularly monitoring and assessing its impact on the operational goals. By continuously evaluating these KPIs, DT progress can be tracked, areas for improvement can be identified and adjusted from data-driven input. This iterative process fosters a dynamic and responsive approach, ensuring the DT consistently delivers value and aligns with strategic goals. Therefore, the system can include automated reporting tools to provide real-time insights and alerts based on KPI performance. Furthermore, periodic reviews with stakeholders for the RC Chimney can be scheduled to discuss findings, gather feedback, and make necessary adjustments.

Conclusion

This study presents a purpose-driven roadmap to promote the widespread adoption of DTs in the E&C industry. The issues hindering progress of DTs in E&C are not due to the lack of new technologies or frameworks – both of which are already available – but rather due to a lack of strategic integration. The proposed roadmap was created from two paradigm shifts to addresses this, viewing DTs not as a single technology or digital model but as a combination of existing technology tools integrated into a single platform. This approach ensures that data from various sources are connected and utilised to their full potential throughout the asset lifecycle. If a DT is presented as one technology or as a digital model, it might lack the important definition of how to integrate data from the different sources in a collaborative platform. The second shift is departing from context-specific frameworks, and instead offering a generalisable approach that begins with questioning the purpose of the DT.

The application of the proposed roadmap was demonstrated through a case study of a RC chimney in Sweden. Technological endeavours often fail due to a lack of added value, insufficient investment, or unprofitability. Therefore, it is crucial to assess these factors thoroughly before committing to a DT investment, which is a fundamental concern of the roadmap. The study aims to address the gap between the perceived potential of DTs and the current maturity level of their applications in E&C by providing a strategic management tool. This tool, in the form of a roadmap, assists in developing a DT system architecture that is generalisable and independent of specific contexts, encouraging a focus on the purpose of the DT solution to avoid common pitfalls. Rather than focusing on the technology barriers, this approach proposes a strategy in terms of the frontlines of the industry. The goal is to contribute to move digital transformation forward in E&C by promoting the adoption, scalability, and replicability of DT technology. By following this purpose-driven roadmap, organisations can systematically implement DTs in a way that directly addresses their unique goals and operational needs.

The novelty of this study lies in introducing two paradigm shifts for DT in the E&C industry – redefining DTs as an integrated pack of existing technologies rather than a single digital model, and proposing a generalisable, purpose-driven approach instead of context-specific frameworks. Building on these insights, the paper presents a five-stage roadmap that bridges strategy and technology, guiding organisations in aligning DT implementation with operational and business objectives. The roadmap's practical value is demonstrated through a real case study of a reinforced concrete chimney in Sweden, integrating finite element modelling and structural health monitoring. Together, these contributions provide both conceptual and practical advancements, offering a replicable approach to support digital transformation in the E&C sector.

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