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Review

Analysis of Digital Twins in the Construction Industry: Practical Applications, Purpose, and Parallel with other Industries

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Abstract: Digital twins (DTs) have become a widely discussed subject, believed to have the potential to solve various problems across different industries, including Engineering & Construction (E&C). However, there is still significant misconception concerning the definition of DTs and their purpose within E&C. This study dives deep into identifying DT applications within E&C and the other prominent industries, i.e., Aerospace & Aviation, Manufacturing, Energy & Utilities, Automotive, Healthcare, Smart Cities, Oil & Gas, and Retail. The main challenges to the evolution of DT practical applications are also analyzed. A combination of a literature review, multi-case study analysis, and comparative analysis compose the deployed methodology. Standardization and a maturity level classification are proposed to drive progress of the adoption of DTs. The distinct aspects of the different industries and their assets are evaluated to the conclusion that DTs are better employed for maintenance of structures within E&C. DTs have become a well-worn topic, but the abundance of complex theoretical frameworks is met with simple or inexistent practical applications. Therefore, the novelty of this study lays in its comprehensive analysis of DT applications and real-world implementations—a departure from the often-theoretical discussions surrounding DTs.

Keywords: digital twins; practical applications; construction industry; Engineering & Construction; standardization; maturity level

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1. Introduction

Technology has been consistently trending in the last couple of years, especially towards greater connectivity, automation, and artificial intelligence (AI) integration. It is undeniable that this has exerted an influence over most sectors in the global economy. Terms such as artificial intelligence (AI), machine learning (ML), Building Information Modelling (BIM), and digital twins (DTs), for instance, represent contemporary technology trends that are currently experiencing notable popularity and discussion in both academic and mainstream media spheres. Concerning research papers, an investigation in a previous study showed that the number of publications containing the keywords "digital twins", "BIM", "management", and "maintenance" increased almost 4000% from 2010–2020 to 2021–2023 [1]. Such a commotion around these technologies was bound to reach the Engineering & Construction (E&C) industry, which is perceived as a very fertile ground for the digital transformation era.

Despite its economic significance, the E&C industry ranks among the least digitized sectors [2]. Other industries, such as Automotive, have already undergone radical and disruptive changes, so their digital transformation is now well under way [3]. However, going digital can be intimidating and discouraging for companies in more traditional, physical industries such as E&C, as it requires a high level of coordination and a new set of capabilities [2]. In addition to the sector's inherent resistance to change and transformation, its assets have longer lifespans, and its processes require specific standards due to safety concerns, which takes even more time. The main barriers to the digital transformation in this industry were identified by Wang et al. [4] as "lack of industry-specific standards and laws", "lack of clear vision, strategy and direction for digital transformation", and "lack of support from top management for digital transformation".

Successful adoption of modern innovative processes to improve productivity in E&C can have a huge monetary impact: a 1% rise in productivity worldwide could save $100 billion a year [3]. The International Monetary Fund estimated that if the public sector in advanced economies invested an extra 1% of GDP into infrastructure construction, they would achieve a 1.5% increase in GDP after four years [5]. All this potential is ready to be unlocked, but it requires that the industry actively embraces new opportunities and changes the way it has traditionally operated [3].

The development of DTs aligns with the increasing intelligence of products and systems in the era of Industry 4.0 [6]. Industry 4.0 is a complex and evolving field, which aims to achieve a higher level of operational efficiency, productivity, and automatization [7,8]. DTs are an enabling technology of Industry 4.0 because they allow machine-to-machine communication and contribute to the convergence of the physical and digital worlds, thus creating intelligent environments where machines and sensors are interconnected [9]. Thus, DTs are considered a potential solution to the main challenges faced by the E&C industry today: poor productivity and profitability, timing and budget issues, shortages of skilled labor, and sustainability concerns [10].

In this context of elevated trust in the potential of DTs combined with financial, societal, and environmental prospects, research on the topic has risen steeply. However, tangible examples of functioning DTs are still the minority, as most publications merely address what a DT "can do" to improve current processes. Furthermore, in the rush to join the conversation, the applicability of a trendy technology to the specific needs and assets of a segment is not properly evaluated, so relevant aspects remain unclear or left out completely. The main issues can be listed as follows:

i. The term "digital twin" is used as a catchphrase, with disregard to a proper definition.

Besides being a digital model that replicates a physical asset and its behavior, a DT requires a data flow from physical to digital, and vice versa. For example, Kritzinger et al. [11] present a straightforward definition differentiating digital models (manual data flow), digital shadows (automated data flow from physical to digital), and DTs (two-way automated data flow). Several publications claim to present a DT, but present a digital model calibrated with experimental results—if even that. This might be due to a lack of consensus concerning the concept of DTs for E&C, or the concept is overlooked altogether.

ii. Lack of clarity concerning the purpose of digital twins for E&C.

The concept of DTs first emerged in 2002 [12], but it started to be applied by the Aerospace industry in 2010 [13]. Unlike Aerospace, Automotive, and Manufacturing, industries which are also more advanced in DT applications, these are still the initial stages of DTs in E&C. The absence of standards, or of a widely adopted concept for DTs bespoke to this industry, leads to a lack of clarity regarding the purpose of DTs for E&C. In turn, this lack of clarity leads to a lack of focus when aiming for practical applications. Without a clear concept and purpose, it is not possible to properly assess if the DT is feasible, if it can be adopted by practitioners within the industry, and if that technology is overall necessary for the purpose it is being investigated.

iii. Unbalance between theoretical frameworks and practical applications.

DTs for E&C are still at their infancy, so not enough time has elapsed since most DT frameworks were conceived so they can be put into practice. However, the unbalance between the vast number of theoretical DT publications and the ones that seldom present practical, useful applications is undeniable. Diversity of research is essential, especially at these initial stages, but it is noticeable that many theoretical studies still lack focus on the purpose of DTs for E&C, which hinders their ability to move out of the theoretical realm. This field needs more focus so it can grow to collect the benefits of the technology and achieve the promised progress.

In this context, this paper proposes a discussion on the fundamental purpose of DTs within the Engineering & Construction industry. The sheer number of publications reviewing the benefits and potential of DTs is massive, so it is understood by this study that this is a well-established fact, supported by a saturated body of knowledge.

This paper is divided into five sections. After the Introduction, the Section 2 explains the combination of a literature review, multi-case study analysis, and comparative analysis utilized in this research. In the following section, DTs are analyzed for Aerospace and Aviation, Manufacturing, Energy & Utilities, Healthcare, Smart Cities, Oil & Gas, Retail, and, of course, the Engineering & Construction industry. The progress of DTs in these industries is evaluated, comparing the similarities and differences: what can be applied to E&C, and how are the assets and their needs different among the industries. Lastly, a Discussion and Conclusions are proposed mainly regarding purpose and focus for future efforts on DTs to harvest the benefits for E&C, within the life cycle of the structure. By doing so, this paper acts on the main limitations identified by Wang et al. [4] by presenting a clear direction for digital transformation, which paves the way for industry-specific standards.

2. Methodology

A combination of a literature review, multi-case study analysis, and comparative analysis composes the research method adopted in this research. First, the existing literature was analyzed to provide a panorama of publications on DTs, both for the construction industry and others, and assess areas lacking in clarity. The literature was retrieved from Scopus as a scientific database for journal articles, as well as industry white papers, company reports, and conference papers, as they often contain the most up-to-date information, which is crucial for investigating DT applications. This study is also built upon a comprehensive literature review study previously conducted [14].

A multi-case study analysis was conducted for the DT applications identified across various industries, namely Aerospace & Aviation, Manufacturing, Energy & Utilities, Automotive, Healthcare, Smart Cities, Oil & Gas, Retail, and Engineering & Construction. In this approach, multiple cases were examined to provide a broader overview of how these industries have successfully implemented DTs and the outcomes they have achieved. Each application can be considered a mini-case within the multi-case study analysis, allowing an overview of the ways DTs are being employed without delving extensively into each individual case.

A comparative analysis is conducted to compare the progress of digital twins' applications in different industries with their progress in E&C. Similarities and differences in how DTs have been used and the challenges faced across these industries are evaluated to assess the ultimate purpose of DTs in E&C. Lastly, recommendations for future research and industry improvements, such as standardization, are proposed based on the insights gained from the analysis to drive progress and retrieve the potential benefits for E&C.

3. Digital Twins: Applications

Digitalization does not happen evenly across different industries, or even among companies within the same industry. Factors that propel some firms to go digital sooner than others are firm size, complexity of operations (long supply chains, several establishments), prospect of competition, and number of highly educated or specialized workers (productivity returns tend to be higher) [2]. This is true for DTs, so they have been reaching different industries at different paces. In the initial stages of practical implementation of a technology, which is currently the case for DTs, these varying speeds of adoption can represent significant leaps in progress from one industry to another. The difference in progress can be particularly steep when the technology is brought forward by companies through solutions developed in-house, tailor-made to their issues, and via protected intellectual property.

Besides the Engineering & Construction industry, the main industries that have been actively implementing, or looking into implementing DT technology are Aerospace & Aviation, Manufacturing, Energy & Utilities, Automotive, Healthcare, Smart Cities, Oil & Gas, and Retail. Different DT applications in these industries are discussed in the form of a multi-case study analysis in this section.

3.1. Aerospace & Aviation

Aerospace was the first industry to disseminate the concept and use of DTs through NASA in 2010 [13]. This sector employs DTs for real-time monitoring of aircraft performance, analysis of flight data for performance optimization, predictive maintenance, and simulation testing. By identifying patterns and anomalies, DTs facilitate predictive maintenance, i.e., early detection of maintenance requirements and potential failures, enabling preventive strategies that curb expensive breakdowns and unplanned downtime. This predictive approach to maintenance optimizes schedules, resource allocation, and overall asset maintenance costs and minimizes downtime [15].

As the pioneer and most advanced, the Aerospace industry has clearly defined purposes and established ways to use and benefit from DTs. Practical examples include Boeing, Airbus, and Lufthansa Technik. In Boeing's 787 Dreamliner, DTs were used to monitor the aircraft's battery system performance and real-time data analysis enabled potential safety hazards to be quickly detected, ensuring safety standards before the physical manufacturing phase began. [15]. Likewise, Airbus used DTs to monitor and optimize A350 XWB aircraft performance through simulations, again enabling informed adjustments before production [15]. Lufthansa Technik also created digital replicas of aircrafts to monitor real-time data from sensors used for predictive maintenance [15].

3.2. Manufacturing

The Manufacturing industry was one of the pioneers in the use of DTs. Improved asset efficiency could add $250 billion to $400 billion to annual GDP of the industry by 2025 [2]. The main purpose of DTs in Manufacturing is to improve highly manual, disconnected, and inefficient operational processes [16]. Examples of how DTs can be used include product prototyping and design, simulation and optimization of production processes, analysis of performance trends over time, and optimization of operations and production lines [17].

PepsiCo is using DTs to centralize management of distribution centers and to enhance supply chain efficiency by testing layouts, optimizing workflows, and preventing downtime across miles of conveyor belts [18]. In Rolls-Royce's "IntelligentEngine" program, DTs are created for each produced engine, gathering data across more than a dozen parameters from onboard sensors, which allows real-time monitoring of engines' performance during flights [17].

Automotive

The Automotive industry is a major adopter of DTs in manufacturing, mainly driven by the critical importance of time and cost efficiency in the production of cars, which justifies substantial investments in technology for optimization. Furthermore, the transition to electric vehicles brings added complexity and demands further optimization. DTs stand out as a powerful solution to meet these challenges. For example, the battery is a critical component of these vehicles, and DTs can provide a virtual live representation to improve its performance, safety, and cost-effectiveness [19].

BMW Group is at the forefront of this movement, with a new virtual electric vehicle plant set to open in 2025, and its factory of the future initiative, which is being expanded to include DTs at three additional factories [20,21]. This approach significantly reduces costs and production downtime, given the substantial expenses associated with factory shutdowns or assembly line disruptions: the plant produces new vehicles every minute, so every minute not building a car is the price of a car lost [20,21].

Volvo has also been reported to use DTs at their warehouses [22]. Ford Motor Company has integrated DT technology into its Dearborn Research and Engineering Campus Central Energy Plant (CEP), including virtual representation of the mechanical systems, real-time monitoring, and optimization by pairing virtual models with IoT data collected from sensors throughout the plant's lifecycle [23].

3.3. Energy & Utilities

Digital twins are applied by the Energy & Utilities industry to monitor and manage power plants, pipelines, and other infrastructure. The United Kingdom's Atomic Energy Authority (UKAEA) is using a DT platform (Omniverse by NVIDIA) to accelerate the design and development in their ongoing project of a full-scale fusion reactor [24]. SIEMENS Energy is developing a DT for its heat recovery steam generator, which uses hot gas exhaust to convert water into steam for turbines—the result is predicted to save the industry 1.7 billion dollars a year [25]. Shell uses DTs to represent the behavior of offshore platform assets throughout their life cycle and identify issues such as fugitive emissions and corrosion and report problems related to unsafe working practices [26]. In GE's Digital Wind Farm project, the DT of a 2 MW wind turbine has the potential to boost energy production by up to 20%, resulting in approximately $100 million in additional revenue over the wind turbine's operational lifespan [27]. DTs have also enabled the following outcomes, as reported by GE [28]: 93–99.5% increased reliability in less than 2 years; 40% reduced reactive maintenance in less than 1 year; 75% reduced time to achieve outcomes; and $11 M avoidance in lost production by detecting and preventing 3 failures.

3.4. Healthcare

In Healthcare, digital twins' main focus is to enhance patient care through personalized medicine. Using DTs for diagnosis allows healthcare professionals to simulate scenarios and detect potential concerns without disrupting the patient's actual care [17]. The idea of a digital replica of the human body, called "digital patient", that provides a comprehensive understanding of a person's health has been around for more than a decade [29,30], but DTs might provide the technological leap to finally bring it into practice. Like the "digital patient", the DT of the human immune system is another plan to improve future healthcare, which has recently received substantial investment to build a working model [31].

DTs are also being used to represent medical devices, thus helping to predict maintenance needs and test new products through simulations [29]. There are a few examples of DTs used for healthcare applications; however, they seem to be in the early development stages. Although the concepts and business models seem well defined and robust investments have been made, the practical applications are still far from being in full operation.

3.5. Smart Cities

As the concept of DTs expanded to different assets which collectively form the foundation of a city, like buildings, bridges, and railroads, the natural progression was the digital integration of these assets as well. This evolution led to the emergence of the concept of the "smart city"—a dynamic ecosystem where smart assets are integrated and interconnected to improve urban management, infrastructure planning, and emergency response [17]. The main example of DTs in smart cities is Virtual Singapore, which first emerged after a series of flooding damage as a way to figure out the areas that are most at risk [32]. In 2012, a 3D map of the country started to be created and later developed into the plan for Virtual Singapore, completed in 2023 and recognized as the first DT of a country [32]. Furthermore, Ericsson plans to deploy 15 million 5 G microcells and towers globally within the next five years to create DT environments for optimizing network coverage and performance in highly detailed city-scale models [33].

3.6. Oil & Gas

IBM has performed a study on how DTs can improve the processes within the Oil & Gas industry, including predictive maintenance, asset and supply chain optimization, safety, and emergence preparedness, sustainability, drilling, reservoir management, training, and designing new systems [34]. A DT of an oil reservoir can help operators better understand reservoir behavior and plan extraction strategies more effectively for higher extraction rates; potential leaks or ruptures can be foreseen, thus increasing safety and emergency preparedness. Training can also be performed under safer conditions through realistic simulations in a risk-free, virtual environment. The Oil & Gas industry is considered a center of innovation and is under pressure for reducing its environmental impact [35]. The "key players" in DTs, measured by patent volumes, are Johnson Controls International, Honeywell International, and Siemens [35]. Honeywell uses a process simulation and modeling software, called UniSim Design Suite, for plant design, performance monitoring, troubleshooting, scenario analysis, decision support, and asset and operation management across a project's lifecycle [36].

3.7. Retail

In Retail, DTs help optimize supply chains and store layout, track inventory, and enhance customer experience through personalized recommendations, worker safety, and ergonomics [16]. Retailers can use DTs for inventory management, with real-time level tracking and early identification of potential stockouts, and to determine efficient shipping routes and potential bottlenecks [17]. The Retail sector is leading spending on AI across industries, reaching over $4.5 billion in 2021 and predicted to grow up to $31.98 billion by 2028 [37].

Amazon reportedly has full-scale, highly detailed DTs of their warehouses to perform simulations, trainings, tests, and layout optimizations before implementation in the physical warehouse [38]. Walmart uses DT technology to optimize store layout and inventory management [17]. It is difficult to identify specific retail DTs that are being used, as many companies do not publicly disclose information about their DT projects [39]. However, Home Depot and Target have reportedly implemented DTs for optimizing layout and placement of products, predicting demand, and managing inventory [39].

3.8. Engineering & Construction

The E&C industry is simultaneously very big and has significant untapped potential for digitalization. According to the World Economic Forum [3], the E&C industry accounts for about 6% of global gross domestic product (GDP); in parts of the developing world, such as India, it can account for more than 8% of GDP. In 2021, the size of the global construction market reached 7.3 trillion US dollars and is expected to grow almost 100% to 14.4 trillion US dollars by 2030 [40]. Furthermore, growth in construction in this decade until 2030 is expected to be higher than manufacturing or services [41].

Concerning digitalization, McKinsey Global Institute [2] ranked Construction as one of the least digitized sectors, considering digital assets, digital usage, and digital workers in each sector. In that same report, twenty-two sectors were ranked in terms of GDP share, employment share, and productivity growth in the US—all twenty-two sectors ranked, from highest to lowest productivity growth: Information and Communications Technology (ICT), Media, Professional Services, Finance and Insurance, Wholesale Trade, Advanced Manufacturing, Oil & Gas, Utilities, Chemicals and Pharmaceuticals, Basic Goods Manufacturing, Mining, Real Estate, Transportation and Warehousing, Education, Retail Trade, Entertainment and Recreation. Personal and Local Services, Government, Health Care, Hospitality, Construction, Agriculture and Hunting. The Constructor sector corresponded to 3% of the GDP share—the highest share was 16%, corresponding to the Government sector, and three sectors had the lowest GDP share, at 1% each: Entertainment and Recreation, Mining, and Agriculture and Hunting. Productivity growth was evaluated from 2005 to 2014, varying from −1.4% growth in the Construction sector to 4.6% growth in the Information and Communications Technology (ICT) sector. Therefore, Construction had the lowest productivity growth, which reflects the impact that digitalization can have on productivity improvement. In addition, since some of the least digitized sectors are the largest in terms of GDP contribution, the US economy as a whole is reaching less than 20% of its digital potential [2].

E&C is an extremely broad industry, which encompasses various sectors or segments based on the types of projects they focus on, and the type of work involved. Each of these segments will apply DT technology in a way that suits best their specific assets and needs. Common subdivisions within this industry include Building, Infrastructure, or Industrial Construction, Environmental and Sustainable Development, Specialty Trades (specialized tasks within the construction industry, such as plumbing, electrical work, HVAC installation, etc.), Renovation and Remodeling, Real Estate Development, Infrastructure Maintenance and Repair, and Demolition and Site Preparation. Figure 1 presents a schematic illustration of these different segments within the E&C industry and what each of them comprises. Tangible DT applications within the E&C industry are still mostly at the prototype stage, and this section presents a multi-case study analysis of DT applications within the various segments of E&C.

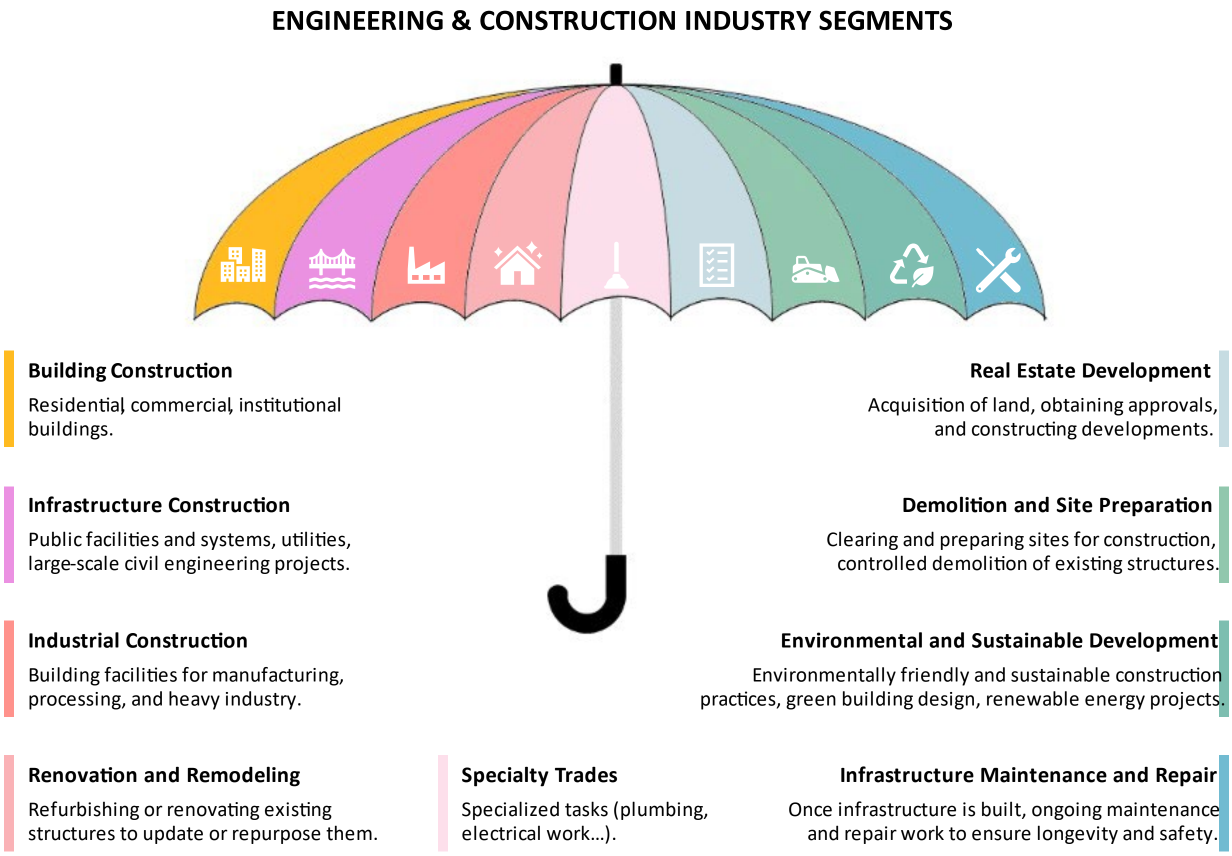

Figure 1. Engineering & Construction industry segments.

Digital twins have emerged as a valuable technique for enhancing project planning, execution, and management in the Construction industry, offering unprecedented opportunities for improved efficiency and productivity [42]. DTs can be employed by E&C in all steps of an asset's life cycle: project development and visualization, design optimization, monitoring construction progress, predictive maintenance, and simulation of scenarios—all without disruptions to the real processes.

A DT provides a comprehensive platform for the project and design stage. A virtual replica of construction sites and buildings offers a realistic view of the project and its potential flaws, so it allows for design scenarios simulations and feasibility assessment before construction begins. By concentrating access to all information in a single platform, it facilitates collaboration and clarity and avoids re-works. Harvesting these benefits results in enhanced efficiency and cost savings.

During the construction phase, real-time monitoring of progress and performance with a DT allows project managers to track construction milestones, identify bottlenecks, and ensure the project's schedule. Deviations can be detected early, so timely interventions can keep the project on track and within budget.

Predictive maintenance might be the most important contribution of DTs within E&C, due to the particularities of its assets. Unlike automobiles, for example, a construction asset's lifespan largely surpasses its development stage. While BMW produces one car per minute [20,21], a bridge might take a few years to be built and last for more than 50 years. Therefore, it is in the maintenance stage that the benefits from the DT will yield the greatest value. A predictive approach to maintenance, through continuous monitoring and simulation models, reduces downtime, prevents costly breakdowns, and might extend the structure's lifespan. Furthermore, ensuring proper functionality of a structure or infrastructure often impacts directly the safety of its users, i.e., society in general.

Figure 2 presents a general overview of the fabrication time and lifespan of the main assets produced by the industries addressed in this study. Provided that it represents a simplification of many layers associated with determining assets, companies, and notions of time, it still offers an overall insight into how and where DTs can be better employed in each industry. In the figure, E&C is the only industry to hold both very slow fabrication time and very long lifespans for its assets. Even though the costs associated to fabrication of assets in E&C are high, Figure 2 shows that it is the only industry that has even higher costs in the lifespan, i.e., maintenance costs. Therefore, this summary assists in further demonstrating the purpose of DTs in improving asset management and maintenance in E&C.

Industry	Main assets produced	Fabrication time of assets	Life span of assets
Aerospace & aviation	Aircrafts and components	$ Slow	Medium to Long
Manufacturing	Consumer goods	$ Very fast to Fast	Very short to Medium
Energy & Utilities	Energy generation and distribution	$ Medium to Slow	Long
Automotive	Vehicles and components	$ Medium	Medium
Healthcare	Pharmaceuticals and medical equipment	$ Slow	Long
Smart cities	Internet of Things (IoT) for urban infrastructure	$ Medium to Slow	Medium to Long
Oil & Gas	Natural gas and petroleum products	$ Slow to Very slow	Long
Retail	Consumer goods	$ Very fast to Fast	Very short to Medium
Engineering & Construction	Buildings and infrastructure	Slow to Very slow	$ Very long

Very fast: less than a day Fast: days to weeks Medium: weeks to months Slow: months to years Very slow: years

Very short: Weeks Short: Months Medium: Years Long: >Decade Very long: Many decades

$ Higher cost: Fabrication time or during Life span

Figure 2. Overview of different industries, the main assets they produce, the respective fabrication time and lifespan of the assets.

Simulations of performance against fire, floods, or earthquakes enable engineers to identify potential vulnerabilities in a building's design or materials and make essential modifications to enhance safety and durability. The simulations can also help assess the effectiveness of safety measures, such as fire suppression systems or evacuation procedures, and ensure they meet the required standards. Therefore, the disaster preparedness and response planning data from the simulations can be vital for minimizing harm in the event of an emergency.

Simulation is also beneficial for transportation infrastructure, as it enables assessment of issues related to traffic congestion, weather conditions, and maintenance events before any construction or modifications take place [17] Real-time monitoring of transportation systems facilitates proactive maintenance, and as real-time information is provided to drivers, such as updates on traffic conditions, road closures, and weather alerts, they can make informed decisions, ultimately contributing to improved transportation efficiency and safety [17].

Modular construction with precast concrete elements allows for prefabrication and series production, resulting in shorter construction times, higher quality, flexibility, and lower costs [43]. Digitalization plays a crucial role in advancing automation within this production system, since the production processes remain manual, with limited automation [43]. In this regard, research efforts to integrate DTs into prefabricated concrete element production are still in the initial stages of development, mostly comprising conceptual applications and frameworks. For example, Kosse et al. [43] proposed a DT framework for industrialized production of precast concrete to identify production processes, derive information requirements, and create data models for precast concrete. Lee and Lee's [44] DT framework is based on building data modeling, IoT sensors, and GIS to enable real-time logistics monitoring and simulation of supply chain processes in precast construction. The DT-based approach by Tran et al. [45] focuses on geometric quality of prefabricated facade elements through automated matching between 3D as-designed and 3D as-built data based on a LIDAR point cloud. Lastly, Rausch et al. [46] proposed a framework for geometric DTs based on 3D scans to detect assembly problems. Consequently, current work particularly addresses accuracy in both design and fabrication of precast components [43].

"Crossrail" is the DT of the Elizabeth underground line in London, with over 250,000 models, from lightbulbs to cable trays, and real-time monitoring of temperature, humidity, and strain in tunnels, shafts, and stations [47] Deutsche Bahn's Digitale Schiene Deutschland (DSD) is constructing a DT of its extensive rail network to maximize transport efficiency and capacity without building new tracks [48] Lastly, the AI Factory at LTU is a concept for gathering research projects in the railway, mining, and construction industries [49]. For example, the goal of the ongoing project called "AI Factory for Mobile Machinery in Mines" is to enable a DT through development of an integrated platform for decision-making in mining asset management of mobile machines, empowered by AI and digital technologies [50].

Lastly, DT technology holds great potential in what regards higher education for architects and construction engineers as well. By integrating DT frameworks into educational settings, students can gain hands-on experience and a deeper understanding of how various technologies can visualize and optimize facilities throughout their lifecycle [51,52]. This technology can enhance the quality of online education by providing real-time interaction and data from on-site machinery and processes, ultimately improving the learning experience for students [52]. Additionally, incorporating DTs as a project-based learning objective can offer interdisciplinary expertise to students in architecture, engineering, and construction fields [53]. Overall, the adoption of DTs in higher education institutions presents new learning opportunities beyond the classroom, aligning with the digital transformation goals of higher education institutions post COVID-19 pandemic [54].

4. Discussion

4.1. Purposes of Digital Twins

The presented case studies show that different industries share some common purposes in their pursuit of digital transformation through DT technology to improve their processes and assets. Disregarding industry-specific goals, such as how "improving patient care through personalized medicine" is to Healthcare, the main purposes for DTs across different industries can be identified. Figure 3 outlines the top ten purposes for DTs reported by the surveyed industries and corresponding frequency of each benefit. For example, "optimization of operational processes" has been identified as a purpose of adopting DTs by the industries of Energy & Utilities, Manufacturing, Oil & Gas, and Retail.

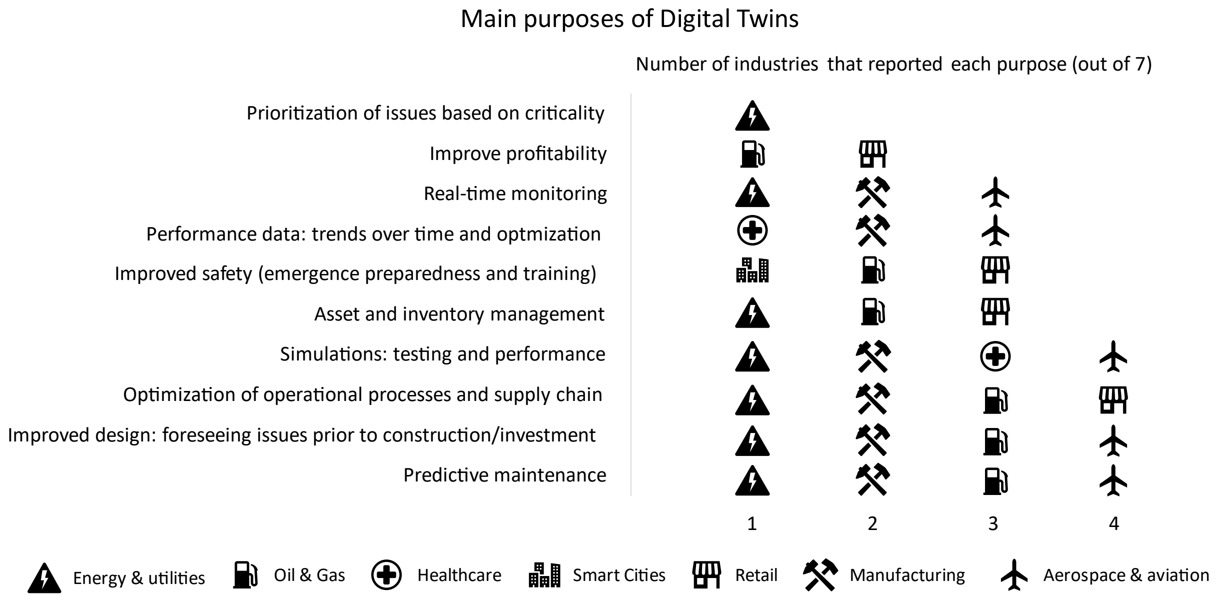

Figure 3. Main purposes of digital twins in other industries.

The applicability of these ten main purposes of DTs, as reported by other industries, can be evaluated to E&C and its assets as follows:

i. **Prioritization of issues based on criticality** contributes to all stages of E&C projects—design, construction, and operation for maintenance issues. The holistic approach that a DT provides, concentrating all data and access on a single platform, would improve how this prioritization is currently performed.

ii. **Improved profitability** is desired in any industry. For E&C, the DT can contribute to that end through enhanced efficiency, reduced downtime, and optimized processes.

iii. **Real-time monitoring** already exists for E&C but stressing the real-time aspect and the concentration of all data and access by all interested parties in one platform is a step forward from most current procedures. That facilitates data interpretation and ensures that project managers have up-to-date information on the health of the structure, improving decision-making.

iv. **Performance data: trends over time and optimization**, similarly to real-time monitoring, exists but could be improved by the holistic DT platform. Analyzing performance data helps in identifying trends, optimizing processes, and making informed decisions for ongoing and future projects.

v. **Improved safety (emergence preparedness and training)** is particularly important for accessing remote or hard to reach assets, such as bridges and towers. In addition, DTs enable safety simulations, emergency response planning, and training programs in a virtual and realistic environment, enhancing overall safety in construction, buildings, and infrastructure assets.

vi. **Asset and inventory management** using DTs could improve existing asset management systems by consolidating inventory control in a single platform. It streamlines inspections and centralizes data accessible to all parties, facilitating data interpretation and efficient resource allocation.

vii. **Simulations: testing and performance** are already performed in E&C using existing software such as finite element (FE)-based, but this is also a potential improvement that can be provided by the DT. A DT offers a wider scope of simulations, especially considering the entire life cycle of the structure and the connection with the physical asset once the operational phase begins.

viii. **Optimization of operational processes and supply chain** has general applications in E&C, given the complexities of its projects, so streamlining workflows, resource allocation, and supply chain management through DTs enhances overall efficiency. However, this is particularly impactful in manufacturing-oriented segments of engineering, such as prefabricated concrete factories.

ix. **Improved design** is achievable in E&C projects through DTs by enabling visualization and testing of designs to identify and rectify issues prior to physical construction, thus reducing costs and delays. However, considering the existing effectiveness of software like BIM and FE-based tools in design, the impact of DTs is more distinct in later stages, given the long lifespan of structures.

x. **Predictive maintenance** by monitoring the current health of E&C assets enables early detection of maintenance needs and potential failures. This preemptive approach limits expensive breakdowns and unplanned downtime, ultimately enhancing safety of critical structural assets. As seen in Figure 2, the operation stage of these assets is both longer and more expensive than earlier life cycle stages, which reinforces the importance of improving predictive maintenance through DT in E&C.

4.2. Maturity Level

The presented DT applications in other industries demonstrate a higher maturity level when compared to those in the E&C industry, not only in the volume of examples, but in clarity of purpose and stage of development as well. While the other industries seem to speak the same language and walk towards a known direction, E&C is still grappling with concepts and how to apply them, and each DT initiative is forging a separate path for themselves. For example, Pregnolato et al. [55,56] proposed a replicable framework for DTs for civil infrastructure, demonstrated by applying the framework to Clifton Suspension Bridge in Bristol (UK). The authors also conclude that more case studies are needed to demonstrate the viability of DTs within E&C [55] Zinke et al. [57] proposed a DT framework for a stand-alone project of a single asset operator but stressed that an application that covers a wider range of infrastructures requires generally accepted and standardized regulations [57].

Digitalization in these industries began sooner than in E&C, so the financial investments came first, the business models evolved, and it was possible to adapt prior digitalization initiatives into DTs once the technology evolved. However, even those more mature DTs are not all in operation yet. Although seemingly well defined, projects are still presented in terms of projections of what the DT can or will do, instead of how it currently operates to benefit the companies. It is easy to become lost in the sea of information about DTs and sustain the wrong impression of progress; it is only through a deeper dive that the different levels of actual development become clearer—although, even then, they are not always utterly clear. In that sense, DTs are not a novel topic in terms of discourse, it might even become mainstream soon, but it is still definitely novel in terms of tangible applications.

This surge in popularity of the term "digital twin" has made it challenging to discern the instances that thoroughly obey the concept and to evaluate their maturity level. This issue would be mitigated by classifying the DT into different maturity levels according to the development of their different aspects. Different classifications have been proposed by several institutions, but there is not one that is widely accepted. Even the different aspects that compose a DT are not yet under consensus. Establishing a universally recognized classification system would be the first step towards standardization, which has been acknowledged as a prerequisite to drive progress of DTs in the field.

There are now many alleged DTs, which, whether they represent something concrete, a plan for the future, or not a DT at all, can only be distinguished after further investigation. A universal classification of DT maturity levels could provide much-needed clarity to this matter. Then, instead of allegations of a "digital twin," there would be, for example, a "digital twin—level 2", accompanied by a clear set of criteria and future research goals to advance to level 3. In this section, a classification system is proposed based on different level definitions. The main challenges hindering the progression of DTs within E&C are also discussed.

4.3. Challenges in Engineering & Construction

It has been established that the benefits of DT are known to the E&C industry, as they have been discussed ad nauseam. Therefore, the slow progress of DTs in E&C is not due to lack of knowledge of how they can be an asset to the industry. Then, it is important to understand what are the perceived challenges that hinder the adoption of this technology.

Generally, the biggest challenges in developing a functional DT are navigating the technology options and choosing the best one available, high-level expertise needed, and data-related complexities: data accuracy, volume, integration, and interoperability, continuous updates, multiple sources, and securing clean and complete data [58–61].

The construction industry traditionally has been slow at technological development, and, as stated by the executive director of an American multinational engineering company, "clients do not want to be guinea pigs" [3]. Therefore, the wariness towards embracing innovative technologies come from both the corporate and the client sides. That, associated with the industry's inherent complexity and risk-averse nature, creates a discouraging scenario for the advancement of DTs.

DTs rely extensively on data and, even though infrastructure data are unlikely to contain personal data, they can still be sensitive, so robust data management and sharing policies are required to address privacy concerns and establish secure data standards [55]. E&C is one of the most fragmented industries in the world, which in itself is a challenge to data sharing, data flow, threats to cybersecurity, and vulnerability that comes with a DT [3].

The elevated fragmentation of E&C also poses additional challenges. For instance, unlike some other industries, E&C lacks a well-defined type of customer, and its diverse segments (illustrated in Figure 1) cater to different customer types. This diversity complicates process standardization and the establishment of unified goals across the industry, as the varied interests of stakeholders may lead to conflicting priorities. There is also not a definition of a common product across the E&C industry. E&C projects do not revolve around tangible products in the way the automotive industry, for instance, produces distinct vehicles. Instead, E&C deals with complex structures and systems, making it challenging to define a standardized product. Furthermore, E&C projects are carried out by many parties, each working towards improving their own part of the work, and not necessarily the entire project/product. For example, in a building project, the workflow can include the commissioner of the building, the architect, the designers, the construction company, and the property manager. This approach often leads to lack of collaboration and shared objectives, which hinders the potential for some improved solutions. Therefore, the challenge in promoting digital transformation lies in aligning the interests of diverse stakeholders towards a common, project-wide goal. These additional challenges due to fragmentation accentuate the importance of strategies that transcend traditional project boundaries and promote collaboration and a shared vision for the entire project life cycle. The principles behind DT technology are particularly effective in addressing these issues.

Besides the aforementioned standardization, strategy and support barriers identified by Wang et al. [4], the World Economic Forum [3] has listed the main internal challenges to the digital transformation within E&C, presented in Figure 4. The difficulties are mostly related to the industry's intrinsic characteristics, such as project-oriented practices, conservative culture, informal processes, and dependence on individual expertise.

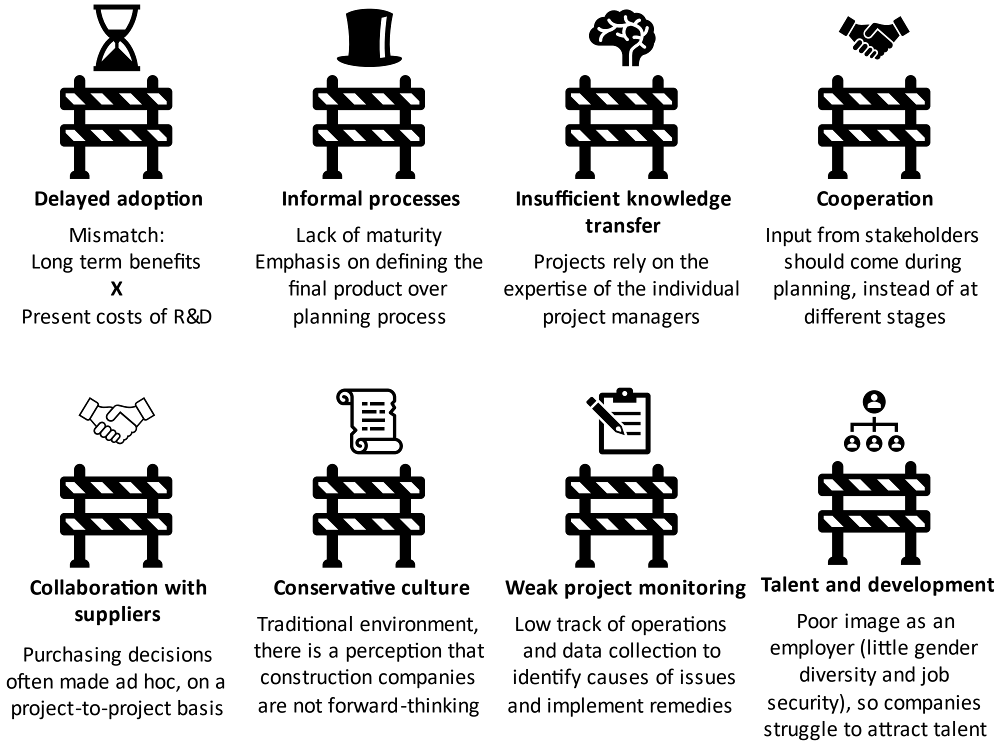

Figure 4. Internal challenges: digital transformation in E&C.

The extensive discussion on the potential of DTs can have a backlash effect. Once E&C joined the discussion, there was already a significant body of knowledge on the subject. The promise that DTs can be used for risk management, inspections, operation management and maintenance, monitoring, simulation, forecasting... creates a pressure to develop a single solution that encompasses everything. This, in turn, can be prejudicial to the development and evolution of a more focused solution that can effectively be applied to one or a few issues. Therefore, clarifying the purpose of DTs in E&C is the first step to establish a clear roadmap to achieve step-by-step progress.

4.4. Levels of Development and Standardization

Due to their complexity, DTs are often divided in different levels of development, for example, Lazoglu et al. [62], ARUP [63], MEED [64], Evans et al. [65], and a compilation of level divisions by B&N, AFRY, IBM, and Autodesk are presented in Saback et al. [1]. There have also been focused E&C efforts, such as the Federal Highway Research Institute in Germany, which began a concept study for the unification of DT bridge components [66].

ARUP [63] proposes five different levels based on fidelity, learning, intelligence, and autonomy capabilities. Autonomy is defined as the ability of a system to act without human input, while intelligence is the ability of DTs to replicate human cognitive processes and perform tasks. Learning is the ability of a twin to automatically learn from data to improve performance without being explicitly programmed to do so. Finally, fidelity is the level of detail of a system, the degree to which measurements, calculations, or specifications approach the true value or desired standard. Figure 5 presents the characteristics of the digital models on each level proposed by ARUP [63], also adopted by Lazoglu et al. [62].

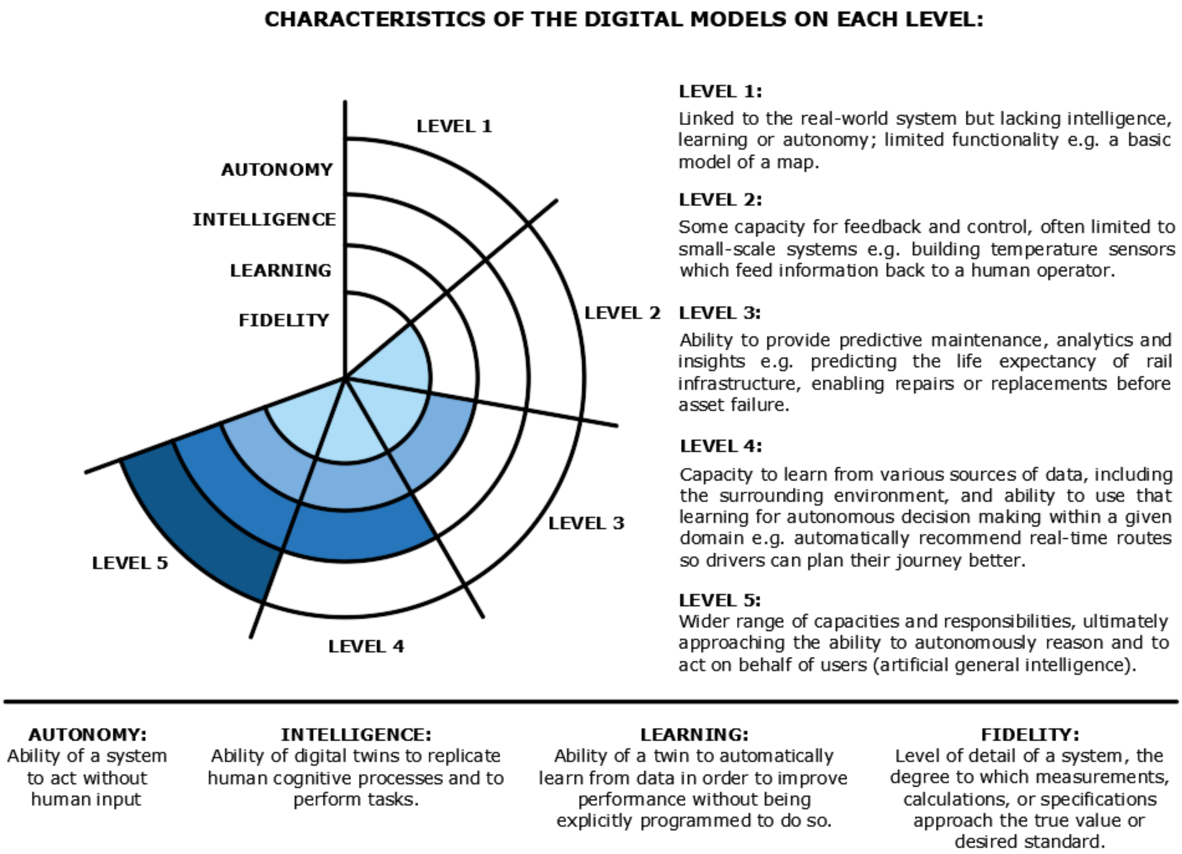

Figure 5. Different levels of digital twins in terms of autonomy, intelligence, learning, and fidelity. Adapted from ARUP [63].

Research shows that completed DTs in practice currently do not go beyond the third maturity level [62–64]. As seen in this section, the different maturity level classifications in use are similar amongst themselves. However, a universally recognized standard is still lacking, which would be essential to the proper dissemination of DTs. Establishing standardized documentation for DTs, including level classification, is essential for organizing information and sharing progress and knowledge. Furthermore, adopting a standard level nomenclature is crucial to prevent confusion and propagation of misinformation. It has become increasingly common for digital and BIM models to be erroneously referred to as DTs, only to benefit off the popularity of the term. Besides, it can be confusing to come across one source that refers to a BIM model as such, while another identifies it as a DT. Therefore, an official level classification system could rectify this issue, for example, by allowing a BIM model to be classified as a DT level 1 proceeded with an outline of the steps intended to elevate it to a higher DT level.

5. Conclusions

The constant rise of different technologies has culminated in several promises of technological advancements as the solution to several issues faced by most industries. DTs are seen as one of those solutions, able to improve many issues at once in a single platform. They have been evolving for years in different industries, but E&C, a late bloomer in terms of adopting technology, has been playing catch up to understand how DTs would best suit their assets and needs. There is significant untapped potential in E&C, but other industries are still more advanced in DT maturity level. In E&C, there is no consensus concerning the definition of DTs, a lack of clarity of their purpose, and an unbalance between complex theoretical frameworks and simple practical applications. Through a combination of a literature review, multi-case study analysis, and comparative analysis, this paper presented an investigation of DT purpose and applications in the most advanced industries as well as in E&C. The main conclusions drawn from this study are presented in this section.

Digitalization progresses at different paces, accelerated or slowed down by factors such as firm size, complexity of operations, and specialization of workers. As a result, DTs have different maturity levels in diverse industries. If progress is tied to intellectual property of companies that developed DTs for their specific issues, the progress can be even more uneven.

Research and development of DTs is more prominent in Aerospace & Aviation, Manufacturing, Energy & Utilities, Automotive, Healthcare, Smart Cities, Oil & Gas, and Retail. E&C is behind on DT maturity, as a consensus on its definition and purpose have not yet been widely reached, and most applications remain theoretical or at the prototype stage. E&C is a broad and fragmented industry, where each stakeholder and segment seek to advance DTs in a way that aligns with their specific assets and requirements.

The analyzed applications of DT in other industries are more mature than in E&C in number, clarity of purpose, and stage of development—but not all applications are already in operation. Since DTs are a widely discussed, trendy subject, distinguishing real applications and their level of maturity is usually not straightforward.

Particularly to the E&C industry, fragmentation poses significant challenges to the widespread adoption of digital transformation solutions, such as DTs. A lack of a cohesive product definition, a unified customer profile, and the fragmentated involvement of different stakeholders throughout the lifecycle of a product limit standardization and the vision of collaborating towards a common goal. DT technology can be an enabler to transcend traditional boundaries and foster collaboration in a unified platform.

Also particular to the E&C industry is the lifespan of its structures. As illustrated in Figure 2, assets in E&C have extremely long lifespans compared to those in other industries. Therefore, it is even more significant that digital solutions track the complete life cycle of these assets, especially post-construction when they fall under the administration of the entity responsible for their management. During this period of many years, the costs of maintaining the asset begin, and the benefits of using digital technologies for optimization become particularly valuable.

Standardization is essential to drive progress forward on DTs. This involves establishing clear concepts and different maturity levels concerning fidelity, learning, intelligence, and autonomy capabilities. Several institutions have proposed different classifications, but none have widespread acceptance yet. Standardization and a universally recognized classification system are paramount to the proper evolution of DTs in all fields, but especially in E&C due to its characteristics. With this classification system, one would refer to a DT level 1, 2, 3. . ., accompanied by well-defined criteria and plans to advance levels, which would bring the much-needed clarification.

The biggest challenges in developing a functional DT are technology- and data-related. Both construction companies and clients are often resistant or slow to technological change, which further complicates matters, in addition to the aspects presented in Figure 4. Therefore, a clear purpose of the DT is the first step to establish a clear roadmap to achieve step-by-step progress. Due to the characteristics of the industry and its assets, DTs in E&C are better employed to maintenance and asset management. DTs directed to infrastructure assets, such as bridges, are more frequently found. These assets have longer construction times, significantly long lifespans, and usually the same entity bearing the cost of maintenance would be the one covering the expenses of the DT, so the return of investment is clearer.

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