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Case Study IJCEP

Digital Twin-Enabled Structural Health Monitoring Framework for Real-Time Damage Detection in Civil Infrastructure

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Abstract

The paper discusses how Digital Twin-enabled Structural Health Monitoring (SHM) restyles civil infrastructure by finding damage in real time, decreasing costs, and increasing safety levels. As opposed to the traditional inspection methods, Digital Twins apply virtual models and sensors to observe structures, like bridges, dams, and buildings immediately, which reduces the repair costs by 30–50% and extends the project's lifespan by 20–30%. This research studies four real-world projects, namely, the Governor Mario M. Cuomo Bridge (USA, 2017), the Gordie Howe International Bridge (USA/Canada, 2024), the Site C Dam (Canada, 2023), and the One Penn 1 Building (USA, 2022), in a detailed manner. These projects help us know how small fixes controls errors from becoming big, how workers can inspect the project using their phones, instead of more physical checkups and no more higher climbing. Less inspection leads to less traffic and less pollution. We know how even simple training can help workers adapt to new technologies. Governments are seeing long-term saving capabilities and soon, newer projects will use Digital Twins technology more often, to stay stronger and safer, at the same time. Moreover, advancements, like AI and IoT, help to enhance the accuracy levels and scalability of Digital Twins. However, challenges, such as high setup costs, data integration problems, and regulatory issues, emerge and are a problem in the global implementation of digital twin technology. So, this study also assesses cost savings, time efficiency, and lifespan gains using data analysis and graphs and then suggests effective solutions, like cloud systems and worker training, to overcome obstacles for broader industry implementation.

Keywords: Digital twin, structural health monitoring, civil infrastructure, project, bridge

INTRODUCTION

The construction industry helps in constructing bridges, dams, and buildings but it faces issues such as repair costs, safety risks, and slow inspections. When workers do manual inspections, chances of missing small errors increase, which may become bigger, afterwards. So, a new technology, called Digital Twin-enabled Structural Health Monitoring (SHM), helps in providing a smart solution to such issues by making the infrastructure safer, economical to maintain, and durable, at the same time.

Virtual copy of real structures, such as bridges and buildings, is provided by the Digital Twin. Continuous information about cracks, rust, and shaking is collected through this technology. Engineers can fix the problems fast, as the data goes into a computer, and engineers can analyze it. In old methods, workers were needed to do site visits, but Digital Twin works automatically and saves time and keeps workers safer. Additionally, repair waste and fuel are saved, which were used while performing old inspections methods [1–3].

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Cities are growing, and more people are using civil infrastructure, so, Digital Twin enabled Structural Health Monitoring becomes more important than ever. This helps to keep the structures strong in urban and outside country areas. Our study explores how Digital Twins make projects faster, cheaper, and safer by looking at four real examples: a bridge in New York, a bridge between the USA and Canada, a dam in Canada, and a building in New York City. These projects help us to know how Digital Twin enabled Structural Health Monitoring helps to solve problems and improve infrastructure for better use [4–6].

BENEFITS OF DIGITAL TWIN-ENABLED SHM

Digital Twins help to check structures effectively, when compared to old ways, it helps to save money, increases workers' safety, and helps the environment. Below, points are mentioned which tell how they work and why it is great.

Instantly Spots the Damage

In old ways of checking, every few months, workers had to climb structures to detect cracks, and in which some minor cracks got missed, which later grew into major problems. Digital twins use sensors, which continuously measure bending, shaking, and cracks. The data are seen on computer screens, so engineers can notice it instantly and act accordingly [7].

A 2020 study found that digital twins can detect cracks, 40% earlier than worker's manual inspection. This enables faster checks, and engineers can solve the problems fast.

Saves Money

When Digital twins are set up, it costs about 10–20% more, as compared to old methods. But after installation, it catches problems early and saves the repair costs by 25–30%. A bridge in the USA saved $500,000 yearly, as Digital Twins helped to detect where and when to solve the issues [8].

Increasing Worker Safety

Digital Twins help to detect minor cracks, and rust, before it becomes a bigger problem, and this way, structures are saved from breaking, increasing the workers' safety. In a dam project, Digital Twins helped to find the rust problem, before it caused trouble. Digital Twins can lower the chances of accidents by 30–50%. It is great technology, when used in busy places, and where lots of people use bridges and buildings, in routine [9].

Early Detection and Planning

Computer programs and data are used to know possible fixes; it's called predictive maintenance. Engineers do not wait for structures to break, and then fix, as happened in old ways. Predictive maintenance helps to increase the project's life by 20–30%, and as per a 2021 study, cuts downtime by 20%. This helps bridges, dams, and buildings to remain open more often [10].

Environment Friendly

Digital Twins are environmentally friendly, as they help plan repairs, cut waste by 15–20%, save fuel, and workers need to go, only when problems occur. This way, it helps fight climate change, making infrastructure projects greener.

CASE STUDIES

This section helps us to know about four different infrastructure case studies, their project overview, challenges faced, their solutions, benefits and the conclusion. The project consists of different types of structures, to help us understand better how Digital Twins perform, in different structure types.

Governor Mario M. Cuomo Bridge, New York, USA *Project Overview*

Completed in August 2017, this project is a 5-kilometer cable styled bridge, which crosses the Hudson River, and connects Tarrytown and Nyack, in New York. This $3.9 billion project replaced Tappan Zee Bridge, and now supports local businesses, and around 140,000 vehicles, daily. 200 sensors are deployed on its 192 cables, deck, and towers, and it uses the Digital Twin Technology for Structural Health Monitoring.

Sensors are used to measure errors such as bending, shaking, and rust. To provide engineers real-time data, a cloud-based platform is used, where engineers can see a virtual copy of the project, to find any damage at a fast speed. Engineers can check the data, around the clock, from anywhere, using the mobile app, and can make quick decisions. This helps to save repair time by 35% and annual savings of $420,000. In this project, the system lowered repair time by 35%, saving $420,000 a year.

Challenges

Data sent by sensors were in different formats, and Digital Twin could not combine it properly, which delayed real time monitoring by two weeks. Second, there were debates related to the initial cost, between the new and old inspection methods, as Digital Twin was costing, a $20 million extra, in the initial stages.

Setup got slowed by one month, as workers were not familiar with inspection methods, done using Digital Twin technology. Fourth, the American Association of State Highway and Transportation Officials (AASHTO) required three months of testing, where sensors can detect, even the small cracks.

Fifth, the fear of hackers stealing the cloud data, or shutting down the system, and at last, March 2017 power outage stopped the data collection work for two days.

Outcomes and Benefits

- *Faster Repairs:* The Digital Twin showed where exactly the repair is needed, and repair work was done, without wasting time. This saved 35% repair time, and $420,000 annually.
- *Accurate Monitoring:* IFC, a standard format, helped Digital Twin to display the problems in real time.
- *Cost Payback:* As per the New York State Department of Transportation, 2019 report, the extra cost of $20 million was paid back, as savings, in 4 years, due to less repair work.
- *Skilled Workers:* The two weeks of engineers training helped to increase their data analysis speed by 50%.
- *Safe Data:* Data are protected from hackers, using two step logins, and using strong encryption (AES-256).
- *Reliable Power:* During outage, backup generators kept sensors running and ensured no data gaps were available.

This project proves that bridge maintenance is transformed using Digital Twin-enabled Structural Health Monitoring. Digital Twins can catch the damage fast, ensure worker safety and save money. Training and standard formats helped to overcome challenges like high costs and data issues.

Gordie Howe International Bridge, USA/Canada ***Project Overview***

The Gordie Howe International Bridge is 2.5-kilometer-long bridge, which connects Detroit, USA with Windsor, Canada. This $5.7 billion bridge project was completed in July 2024 and was led by AECOM. The bridge helps an average of 12,000 vehicles commute daily and supports $2 billion daily trade between the two countries, USA and Canada.

500 sensors are placed on the bridge tower, deck, and cables, as Digital Twin Enabled Structural Health Monitoring technology is implemented in this project. The sensors help to track the vibrations, stress, and temperature effect, and the data are processed through the cloud based Digital Twin platform that provides a virtual bridge structure and provides real time updates.

The bridge handles difficult weather effectively like the –20° cold and heavy snow. The Digital Twins reduced the repair costs by 30% and helped to save $300,000 annually. Engineers are easily able to see the bridge data updates, which are accessible from both countries, with the help of Digital Twins. Its smart and cross border design helped the bridge in winning the 2024 Canadian Consulting Engineering

Award. Spotting damages instantly and correcting them helps in smooth functioning of the bridge, helping both traders and travellers move safely on the international route.

Challenges

The bridge project faced many challenges. Firstly, USA and Canada had different data rules, which delayed the sensor data combining process by 10 days, and slowed the Digital Twin's setup. Secondly, the cold winter temperatures (–20°C), led to some data missing, and made the data less accurate by 15%, which caused safety concerns. Third, budget planners were worried about the budget allocation, as Digital Twin cost $15 million extra, which is 12% more than already planned. Fourth, due to no clarity in rules for Digital Twins, the safety tests took two months more. Fifth, it was hard to analyze the data accurately, as the system slowed by 20%, when 500 sensors sent so much data. Finally, engineers are familiar with using old inspection tools struggled with the Digital Twin, delaying setup by three weeks, in a project needing fast results.

Outcomes and Benefits

- *Cost Savings:* Digital Twins helped in savings, by helping to plan repairs, before damages grew bigger, and saved $300,000.
- *Smooth Data:* Data syncing was fixed in one week, when the USA–Canada agreement set common data rules.
- *Better Sensors:* Adding the Cold-proof sensors took accuracy levels to 95%, overcoming the weather barrier.
- *Faster Approvals:* Safety check timing got improved, using ISO 19650 standards, and the time used to perform tests was lowered by 50%.
- *Quick Data Processing:* A stronger cloud system assisted in handling all 500 sensors and helped to speed up data by 40%.
- *Skilled Team:* Three weeks Digital Twins training provided to 30 engineers, helped in reducing errors by 60%.

The Gordie Howe International Bridge project demonstrates that Digital Twin-enabled Structural Health Monitoring can manage big and shared projects, across countries. It helps to save money, handles tough weather, and lets the trade flow between countries, in a smooth manner. Mutual agreements related to data rules, and training helped to solve the challenges, making this model a great fit for international infrastructure projects also.

Site C Dam, British Columbia, Canada Project Overview

The Site C Dam project was completed in October of 2023. And it is situated on the Peace River in British Columbia. Managed by BC Hydro, this $16 billion project generates 1,100 megawatts of power and supplies water to the farms. Using the Digital Twins technology, 300 sensors are continuously checking the spillway and base, for any damage like cracks and pressure changes. The digital twins help to establish a virtual model of the dam, which is used for detecting the damage, Fastly.The inspection time is lowered by 40%, which helps to save around $200,000 annually. Site C Dam can handle heavy rain (1,000 mm per year).For its green technology, the dam has won a 2023 Canadian Dam Association Award. The damage is visible to engineers, via their phones, and engineers can solve the issue quickly. So, Digital Twins helps in ensuring steady power and water supply, for communities and for agriculture purposes.

Challenges

Due to its remote location, weak internet caused delay, as data were sent 5 days later, which slowed the real time damage analysis. Secondly, the digital twins cost $10 million extra, which is around 8% more than planned, and this led to budget concerns. Thirdly, some data about cracks were missing, due to heavy rain. Fourth, to prove that the system works, Canada's strict dam rules required six months of tests. Finally, in 2022, a power line failure stopped the sensors and caused data gaps, for three days.

Outcomes and Benefits

- *Faster Inspections:* Digital Twins helped in analyzing the problems early, and inspection time was cut by 40%, saving $200,000 annually.
- *Better Internet:* To solve internet problems, satellite data transfer methods were used, which made monitoring instant, even in the remote areas.
- *Cost Payback:* $10 million were paid back, in 5 years, using the smart repairs.
- *Rain-Proof Sensors:* To handle heavy rains, waterproof sensors helped to raise the accuracy levels to 90%.
- *Trained Workers:* 20 workers were trained for one week, which increased their work speed by 50%.
- *Stable Power:* Solar panels provided power stability and ensured no data gaps occurred.

The Site C Dam proves that the Digital Twin enabled Structural Health Monitoring, works well in remote areas also, and supports the power and water supply for communities. Satellite systems and waterproof sensors implementation, helped during poor internet and heavy rains. By studying this project, we know that Digital Twins helps in protecting civil infrastructure, even in difficult environments.

One Penn 1 Building, New York, USA *Project Overview*

Located in Manhattan, New York City, One Penn 1 Building, is a 57-story office tower, which was renovated for $2.1 billion, in December month of 2022. It helps to host major companies, houses 5,000 workers, and is managed by Vornado Realty. This building uses Digital Twin technology and has 200 sensors to check the facade and base, for any cracks and shaking issues. The virtual building model provides error updates Fastly, which can be seen through a tablet app, has cut repair costs by 25%, and saves around $150,000 yearly. It won the 2023 LEED Platinum award for its green design, as it uses 10% less energy, because of the Digital Twins monitoring system. The tablet app provides instant information about the building, which helps to keep the workers, visitors, and the building infrastructure safe.

Challenges

Due to the busy streets and crowded city, the sensor’s delivery and setup were slowed by one week. Secondly, budget concerns were raised when Digital Twin cost $8 million extra, in the initial stages, which was 10% more. Third, the data from 200 sensors slowed the system real time updates by 20%. Fourth, the project faced a 10-day delay, as some engineers were new to this technology. Fifth, the regulatory bodies needed three months of tests to finally approve the system. And finally, data quality of sensors was reduced by 5%, due to dust and noise from nearby construction activities.

Outcomes and Benefits

- *Faster Delivery:* Deliveries were made at nighttime to overcome traffic barriers, and this reduced the delays to 3 days.
- *Quick Data:* Using a strong cloud system, helped to process the data speed by 30%.
- *Skilled Team:* Workers were provided with training classes, which increased their work speed by 50%.
- *Rule Compliance:* Delays were cut by 50%, as early tests helped, and qualified the rules.
- *Dust Protection:* As dust was a problem, filters were applied on sensors, which were able to increase the data accuracy to 90%.

The One Penn 1 Building project proves that Digital Twin helps to monitor tall buildings successfully, even in busy cities, simultaneously keeping the workers safe, and saving money.

DATA ANALYSIS

This section shows the benefit of Digital Twin enabled Structural Health Monitoring (SHM), when compared with the old inspection methods (Figures 1–3).

Graph Overview

Three graphs, each focusing on one key benefit, are drawn to compare Digital Twins with old inspection methods.

- *Maintenance Cost Savings:* This graph shows the amount of money saved by using Digital Twins, in comparison with old inspection methods. Here, all projects saved money, with the Cuomo Bridge saving the most and One Penn 1 saving a bit less. It's because in old methods, some errors were found when they became bigger, but in Digital Twins, even small problems are found instantly.
- *Setup Cost Increase:* This graph shows how much more is paid, meaning the increased cost spent on implementing the Digital Twins, as compared to the old method's implementation. The data show that all projects spent more at the start, with the Gordie Howe Bridge spending the most and Site C Dam spending the least. So, old methods cost less at the start but could not save any money afterward.
- *Lifespan Gain:* In this graph we saw that the Digital Twins help structures last longer than old methods. All projects have longer-lasting structures, where the Gordie Howe Bridge gained the most and Site C Dam gained a little less.

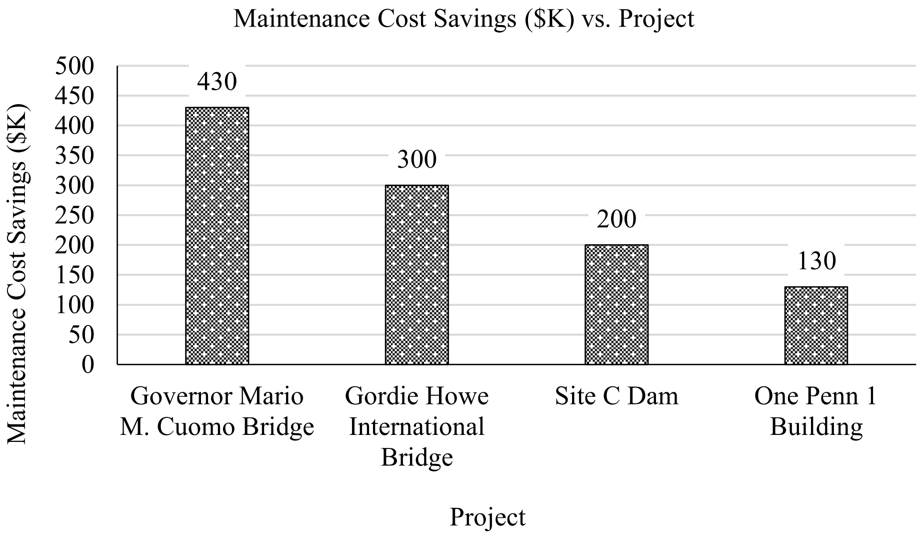

Figure 1. Graph showing savings in maintenance costs as compared to old methods.

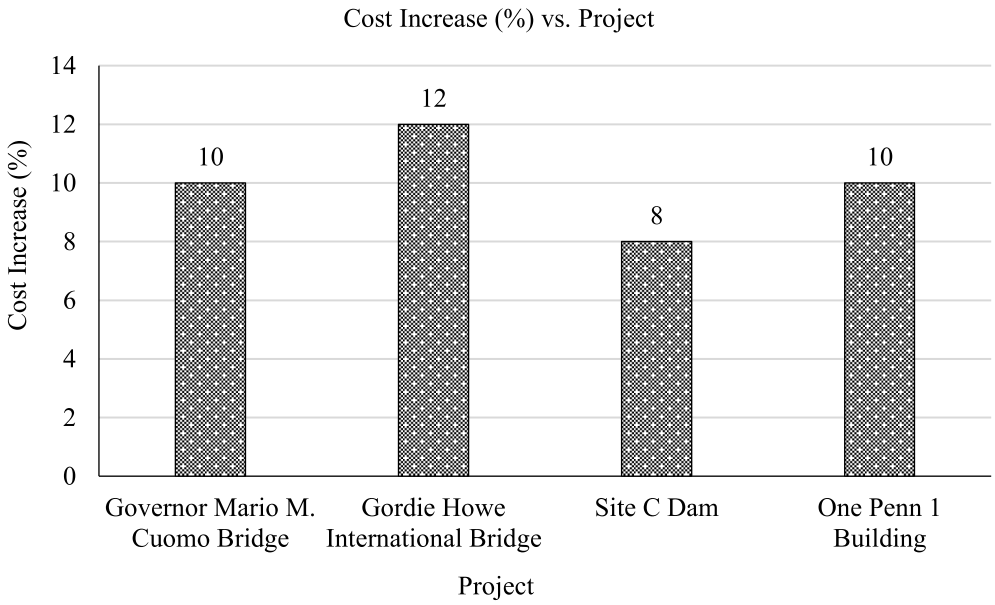

Figure 2. Graph depicts increased starting cost while implementing digital twins.

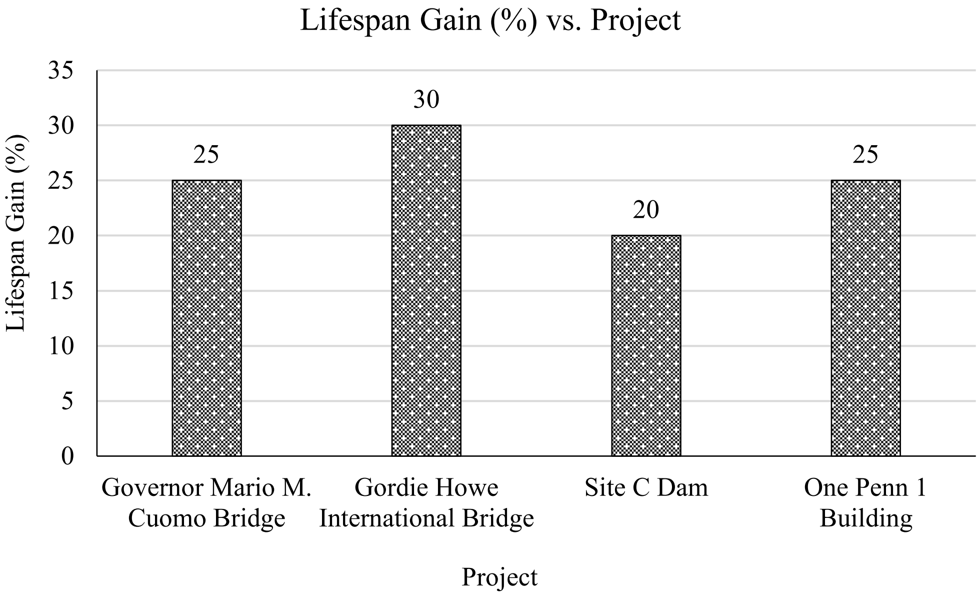

Figure 3. Graph showing increased lifespan of projects, using digital twins' technology.

DIGITAL TWINS: CHALLENGES AND SOLUTION

Digital Twins have proved that it is successful in monitoring structures like bridges, dams, and buildings. But implementing the Digital Twins comes with challenges. In this section, we will study six main challenges faced in the four projects, namely the Governor Mario M. Cuomo Bridge in New York, Gordie Howe International Bridge between the USA and Canada, Site C Dam in Canada, and One Penn 1 Building in New York City. After that, we will study the solutions to these problems, so that Digital Twins can be used more widely to keep the civil infrastructure stronger and safer.

Uneven Data Sharing

Getting data from the sensors and letting the data work together is hard, as each sensor might send the information differently. As in the case of the Gordie Howe International Bridge, there were different rules for sharing the data, and as a result, it slowed down the Digital Twin setup. Same, in the case of the Cuomo Bridge, there was a problem combining the sensor data, which made it difficult to instantly monitor the problems. This causes delays in monitoring, and engineers might not be able to see the damage early.
Solution: Use standard formats to combine sensor data, like the format used in the Cuomo Bridge and cloud systems, helped at the Site C Dam project.

Costly Setup

In the start, implementing Digital Twins is costly, as compared to the old inspection methods. In tight budget projects, builders get worried, while implementing costly Digital Twins technology, as seen in the Site C Dam and One Penn 1 Building project.

Solution: To solve this issue, show how Digital twins save money in the long run, by lowering the repair costs, and save time too. The government also provides help, like in the Site C project, and using affordable systems, help too, like in the One Penn 1 project case.

Strict Rules

Building rules don't necessarily always support the Digital Twins technology, because in some areas, longer tests are needed to get the Digital Twins approved. While in some places, rules are not clear enough, which causes delay in getting approvals, and this discourages the teams which use this technology.

Like in the Site C Dam, long tests were needed to meet Canada's safety rules, and in the Cuomo Bridge and One Penn 1 Building projects, the Digital Twins rules were not clear.

Solution: Updating the building rules and standards to include Digital Twins, helps to speed up the approval time.

Untrained Workers

Untrained workers hesitate to work with Digital Twins technology, which causes delays in the project like happened in the One Penn 1 Building and the Gordie Howe Bridge project. Chances of mistakes increase, until the workers and engineers are well trained, to use technology properly.
Solution: Short guides and videos help to fix the training gaps. This also helps to train the teams fast.

Weather Problems

Weather conditions, like rain, cold, and wind, are a barrier in the Digital Twins. These barriers do not let the sensors transfer the errors effectively. Like in the Site C Dam project, rain did not let all the errors be detected. And the cold weather caused issues in the Gordie Howe Bridge project.

- *Solution:* To keep the data accurately maintained, use special sensors that work effectively even in rain and cold weather like used at the Site C and Gordie Howe project.

Resistance to New Technology

People new to this technology, and who are familiar with old inspection methods, sometimes resist using the Digital Twins technology. It happens more in smaller projects and places which are new to Digital Twin technology.

- *Solution:* To reduce resistance levels, holding events help, where people learn how Digital Twins work. Along with it, teaching this technology in schools and colleges helps to educate new engineers.

So, challenges are solved by using these solutions, which make Digital Twin enabled Structural Health Monitoring more practical to use, and safer, for a strong infrastructure.

RESEARCH METHODOLOGY

This section explains how the data are collected, and then studied, to know about the Digital Twin-enabled Structural Health Monitoring (SHM) system. A simple approach is used to gather true information and to understand it clearly.

Data Collection

To collect data, we studied real projects, company reports, articles, and had talks with industry experts. We studied four projects, in which we have a bridge in New York, a bridge between the USA and Canada, a dam in Canada, and a building in New York City. These helped us to know the real life uses, benefits, challenges, and solutions while implementing Digital Twins. Next, we learnt about Structural Health Monitoring by reading reports from companies who built these structures. Reading articles from engineering journals helped us to know about technology better. Finally, talking with engineers who have worked on these projects helped them to know about their firsthand experience and about the projects. This mixture of reports, articles, and talks helped us to gain clear knowledge about how Digital Twin enabled Structural Health Monitoring helps infrastructure projects.

Analytical Frameworks

To know better, how Digital Twins are a great fit, we compared it with old methods and learnt how the structures are built more safer and easier to maintain, using this technology. We selected projects from busy and far away areas, and which are built differently like bridges, dams, and buildings.

This helped me to know deeply how Digital Twins perform, in different structures. We looked at comparisons like repair needs, and safety between Digital Twins projects and projects using old methods of monitoring.

By studying Digital Twin implementation challenges, like setup issues and rules, we understood how to implement the technology effectively, by fixing the problems, and found why Digital Twins is a great option, when compared with old methods.

CONCLUSIONS

Digital Twin-enabled Structural Health Monitoring is updating the infrastructure industry and is changing the way we take care of bridges, dams, and buildings, in a better way. Studying projects, like a bridge in New York, a cross-border bridge, a dam in Canada, and a city building, helped us know that Digital Twins find the damage quickly, save money spent on repairs, and help to keep the structures strong for longer durations.

Examples studied prove that technology works effectively for all kinds of infrastructure. However, Digital Twin problems, like setup costs, data sharing, and strict rules, slow down the implementation process.

On the other hand, solutions, like worker training, better cloud data sharing technology, special sensors, and updated rules, help in the technology implementation process. In the future, Digital Twin enabled Structural Health Monitoring will be made stronger, using AI and IOT tools, which enable stronger, safer, and greener infrastructure for everyone.

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Disclosure of Interests

I declare that this research has no competing interests, and our findings on the Digital Twins vs. old methods are done fairly.

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