

Climate-Resilient Civil Infrastructure Through a Lifecycle Digital Thread: Data Fusion, Risk Intelligence and Predictive Maintenance

Ayesha Fatima¹, Mohammed Abbu Bakar²

^{1,2}(Civil Engineering Department, Muffakham Jah College of Engineering and Technology/Osmania University, Hyderabad 500034, India)

Abstract:

Background: Civil infrastructure faces pressures, such as mechanical stress, environmental changes and climate-related challenges. Civil infrastructure maintenance decisions are often made without using data from design, construction, inspection or operation.

Materials and Methods: We create a lifecycle view that brings together twins, embedded sensing, artificial intelligence, edge computing and predictive maintenance for climate-resilient civil infrastructure. Then seeing these tools as separate we examine how data can stay linked from planning to renewal for civil infrastructure.

Results: We find a lifecycle thread that turns observations into condition indicators risk estimates, possible interventions and confirmed results for infrastructure. Digital twins keep asset information continuous. Artificial intelligence helps find patterns and predict the future. Edge computing speeds up responses. Risk models link the state of the asset with its consequences.

Conclusion: The main research opportunity is not automation. Keeping evidence continuous. A lifecycle digital thread can cut information loss between project stages help prioritize maintenance and give a foundation, for resilience decisions. This will only work if we address uncertainty, interoperability, cybersecurity and long-term validation.

Key Word: Climate Resilience; Lifecycle Management; Digital Thread; Digital Twin; Predictive Maintenance; Structural Health Monitoring; Edge Computing; Infrastructure Risk.

Date of Submission: 06-10-2026

Date of Acceptance: 16-10-2026

I. INTRODUCTION

Infrastructure resilience is often talked about in terms of whether a structure can handle a hazard and get back to normal. In reality resilience is also a problem when it comes to information. Engineers need to know what was planned what was actually built, how the asset has changed over time what conditions it has been through and what actions have already been taken. When these details are scattered across drawings, inspection reports, sensor systems and maintenance records making decisions ends up depending on stories. Recent research on twins suggests that having continuously updated representations of assets can help with monitoring and decisions throughout their life [1], [2].

At the time structural health monitoring has gone beyond regular point measurements. MEMS, wireless sensors, fiber-optic systems and other technologies can now capture responses with more detail in space and time [3], [4], [5]. AI can process these observations to find issues. Estimate the condition of the asset while edge intelligence can cut down on communication delays and help with local processing [6], [7]. These changes give the tools needed for a system that tracks the life of an asset.

The main point of this paper is different from the idea that machines should act on their own. The important goal is to keep a clear and reliable chain of evidence that connects an infrastructure decision to the measurements and models that support it. This paper looks at the idea of a lifecycle thread for climate resilience and predictive maintenance.

1.1 Research Objectives

- Explain the role of a lifecycle thread in linking design, building, operation, checking and renewal.
- Look at how sensing, digital twins and AI provide kinds of evidence instead of doing the same jobs.

- Connect the condition of infrastructure to hazard, exposure, vulnerability and impact for maintenance planning.
- Find the challenges in keeping a continuous lifecycle of information including data quality, compatibility and security.
- Create a plan for research on evidence-based maintenance and planning for resilience.

1.2 Difference in this Review

The paper focuses on keeping information connected throughout the lifecycle and on maintenance based on risk. Self-healing materials are mentioned as one technology for fixing problems, not as the main idea. Also AI is seen as support for decisions, in a process not as a system that works by itself.

Lifecycle Digital Thread for Climate-Resilient Infrastructure

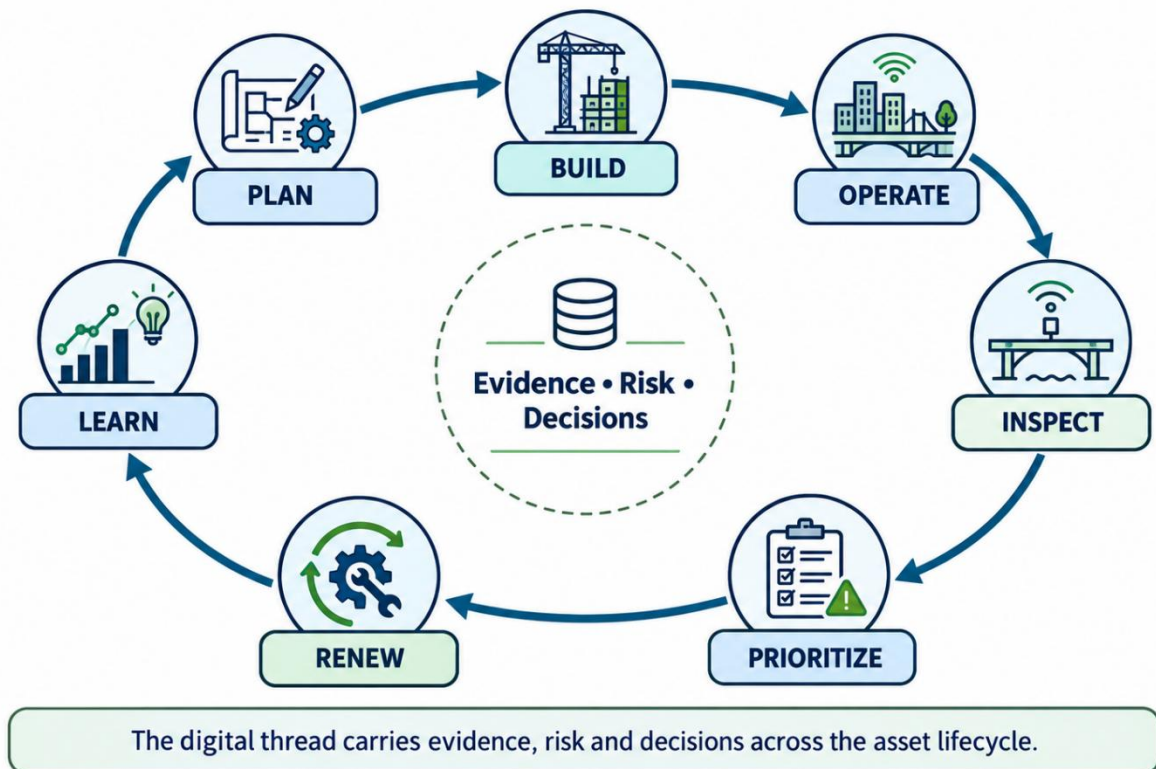


Fig. 1. Lifecycle digital thread connecting planning, construction, operation, inspection, prioritization, renewal and organizational learning.

II. LIFECYCLE DIGITAL THREAD: CONCEPT AND REQUIREMENTS

A digital thread is a flow of information that connects data across all stages of an asset's life. It allows knowledge to be built, updated and reused from design to operation and maintenance. In engineering the digital thread goes beyond just a 3D model. It includes identifiers, records of where data came from version tracking and clear links between real-world observations and engineering decisions. A digital twin can be a part of this thread but the thread also includes inspection logs, repair history, environmental data and design assumptions [1], [2], [8].

The real value lies in continuity. When sensors collect data during operation that data can be understood in context—compared with the design, materials and assumptions. An inspection report can be linked to repairs. Maintenance choices can be checked against how the asset performed. Without this continuity every new analysis must start again from scratch rebuilding history. That wastes time and raises costs. Opens the door for different people to make decisions based on different possibly conflicting assumptions.

2.1 Data Provenance

In infrastructure knowing where data came from is just as important as the data itself. A sensor measurement may look the same but if the calibration was different the date of inspection changed or the environmental conditions were not the same the meaning can shift. The processing method or the model version used may also affect results. A lifecycle digital thread must keep track of this provenance—where the data came from how it was collected and what tools were used. That way decisions can be. Audited even if the software or model has changed later.

2.2 Interoperability

Interoperability is more than sharing files between systems. It means systems can work together because they use the asset IDs, consistent units, shared meanings for data and clear links between geometry, condition and maintenance actions. Research, on twins shows that keeping different data sources in sync remains a challenge [2],[8]. Systems often use formats, definitions or ways of organizing data. A true digital thread must solve these issues so that all information fits together no matter where it came from.

Lifecycle stage	Information generated	Useful digital function	Typical loss of information
Planning	Hazards, demand, service targets	Risk baseline and asset identity	Changing assumptions
Design	Geometry, materials, calculations	Reference model and traceability	Model fragmentation
Construction	As-built condition, changes	Configuration record	Unrecorded deviations
Operation	Loads, environment, sensor data	Continuous condition update	Data silos
Inspection	Observed defects and ratings	Evidence-linked diagnosis	Subjective/incomplete records
Maintenance	Interventions, costs, downtime	Performance comparison	Weak feedback to design
Renewal	Residual capacity and lessons	Next-cycle planning	History discarded

III. SENSING AND EDGE INTELLIGENCE FOR CONTINUOUS CONDITION EVIDENCE

3.1 From Sensor Data to Condition Indicators

Raw measurements usually do not directly match engineering decisions. Acceleration, strain, temperature, humidity or images must be changed into indicators that explain how a structure is behaving or breaking down. MEMS-based systems can offer small vibration monitoring while fiber-optic methods can allow measurements over areas [3] [5]. The best type of system depends on the kind of failure that is expected and on how easy it is to reach the asset.

Environmental compensation is very important. Temperature, humidity and how the system is being used can change the readings without meaning there is damage. A good monitoring system should collect these details at the same time as the structural measurements. This helps avoid thinking that normal changes in the environment are actually signs of damage.

3.2 Edge Computing

Edge intelligence puts some processing work near where the sensors are. It is most useful when there is a lot of data when there are not good communication links or when fast checking is needed. Recent studies about monitoring structures show that small models can help with finding problems on IoT devices [6]. Edge processing does not stop the use of the cloud or servers; instead it divides the work so that quick checking happens locally and older data and model building stay in one place.

Processing location	Best suited task	Advantage	Constraint
Sensor node	Filtering, event trigger	Very low latency	Limited compute and energy
Edge gateway	Feature extraction, anomaly screening	Reduced bandwidth and rapid response	Hardware maintenance
Cloud/server	Model training, fleet analysis	Large compute and storage	Connectivity dependence
Digital twin platform	State integration and scenario analysis	Lifecycle context	Synchronization complexity

3.3 Data Quality as an Engineering Variable

Long- term sensing systems can experience drift, missing observations, communication failures and changes in operating conditions. Consequently, monitoring quality should be reported using metrics such as data availability, calibration stability, false-alarm rate and uncertainty, not only AI classification accuracy. This is particularly important when a monitoring output is later used to prioritize expensive or safety-critical work.

IV. DIGITAL TWINS FOR CONDITION AND RISK CONTEXT

4.1 The Twin as a State Estimator

A twin is most helpful when it links measurements with a changing view of the physical thing being watched. Recent studies describe twins for checking the health of structures as tools for mixing real-time data with models and past information [2], [8]. The twin can help tell if a change seen is something expected or not by looking at temperature, traffic, how the system has been used before and past changes made.

This job is not the same as keeping sensor data. A place to store data answers what was recorded; a twin that focuses on the state tries to answer what the condition of the thing really means. This difference matters when there is no data or when the data is not clear because engineering models and past behavior can add more understanding.

4.2 Scenario Analysis

Once a twin is kept as a view of the state it can be used to look at possible future situations. Examples are traffic, very hot weather being underwater getting worse because of rust or different ways to do maintenance. The goal is not to say exactly what will happen but to look at possible situations and what could happen because of them.

V. CLIMATE RISK INTELLIGENCE AND PREDICTIVE MAINTENANCE

5.1 A Risk-Based View

Infrastructure When a structure gets worse it becomes a problem when the condition meets a danger, where it's what could happen. A small problem in a part that does not matter much may not get much attention as the same problem in a part that is very important for support or in a place that is very busy, with movement. Predictive maintenance should then go beyond just looking at the condition. Think about risk when deciding what to do.



Fig. 2. Risk-to-decision chain linking hazard, exposure, vulnerability and observed condition to consequence and intervention.

$$\text{Risk} \approx \text{Probability of adverse state} \times \text{Consequence of that state}$$

This statement is intentionally general. In a system probability would be based on models that show how things wear down and the environment they are in while consequences would include things like service being stopped, safety issues, money loss and how important the area is.

5.2 AI for Forecasting

AI can help with predicting when something might break by learning how different signs relate to how things get worse.. Data about infrastructure often has few times when things actually broke and the information from the same place is very connected. This makes splitting the data into training and testing parts possibly

wrong. Using data from places checking over time and looking at uncertainty are better ways to see if a model can help with future maintenance [7].

5.3 Maintenance Prioritization

A system for maintenance should not always pick the cheapest option. When to fix something affects safety, keeping service going, the environment and future work. So, decisions should look at things like reducing risk, time without service, what resources are available and the total cost over time.

Decision factor	Example indicator	Why it matters
Condition	Crack growth, modal change, corrosion indicator	Describes current deterioration
Hazard	Flood, heat, seismic or traffic demand	Defines external stress
Exposure	Location, usage, network role	Determines likelihood of being affected
Consequence	Safety, downtime, economic importance	Defines priority
Intervention	Cost, duration, effectiveness	Defines feasible response
Uncertainty	Prediction interval / confidence	Controls decision conservatism

VI. EVIDENCE-BASED DECISION ARCHITECTURE

6.1 Five Evidence Tiers

To make sure every result from a computer is not seen as true this review suggests a way to rank evidence. This ranking separates observations from results that are made from those observations, predictions, choices for fixing and proof that the fix worked. It can act as a list to check if a decision about infrastructure is supported enough.

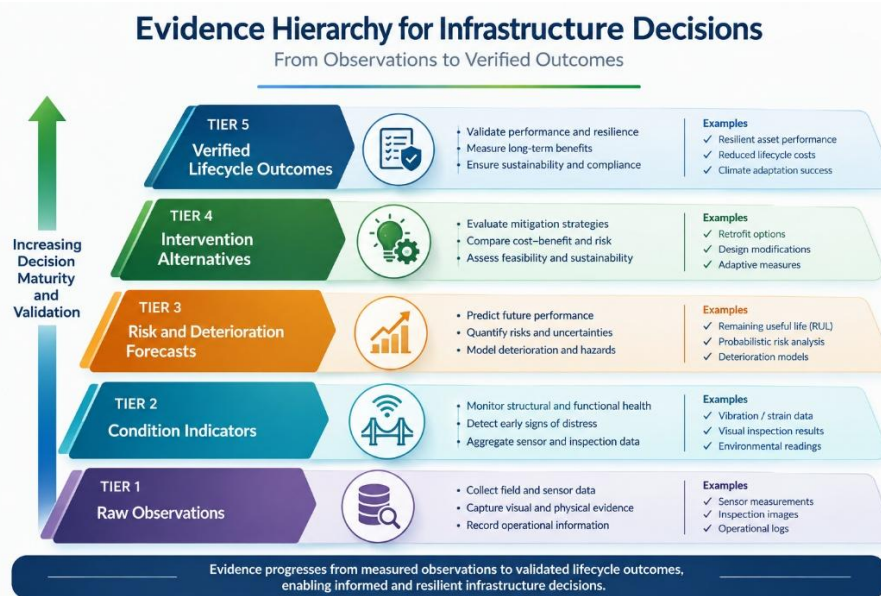


Fig. 3. Evidence hierarchy proposed for traceable infrastructure decisions.

Tier	Meaning	Minimum question
1. Observation	Measured or inspected evidence	Is the source trustworthy?
2. Condition	Interpreted asset state	What physical condition does the evidence indicate?
3. Forecast	Expected future behavior or risk	How might the condition change?
4. Decision	Selected intervention or maintenance option	Why is this action preferable?
5. Outcome	Observed post-intervention performance	Did the action achieve its intended result?

6.2 Human Oversight

The way evidence is ranked naturally supports levels of automation. Collecting data and checking it can often be done by machines. Deciding what the condition is can be helped by AI. Big changes should still have engineers in charge. After a fix independent proof should be used to see if the expected benefit happened. This setup stops computer confidence from being the same as an engineer's approval.

VII. SELF-HEALING AND ADVANCED MATERIALS WITHIN THE LIFECYCLE THREAD

Self-healing materials are still important for the lifecycle thread because they add a way to respond that can be watched using the same monitoring system. Reviews talk about ways that concrete can heal itself like using bacteria, tiny capsules and other ways [9]–[12]. The digital thread can note where the self-healing material was used what conditions make it work any cracks that show up and proof that it works again.

The main need is checking. Just because a crack is closed does not mean the structure is fully fixed. The property that is fixed must be clear: things like how easy it's for water to get through how stiff it is, how strong it is, how long it lasts or another service rule. Testing over a time is also needed because what works in a lab might not work in real life or after repeated damage [9]–[12].

This view puts self-healing materials in their lifecycle. They are options within a system, not a replacement for checking looking at risk or checking after a fix.

VIII. IMPLEMENTATION CHALLENGES

8.1 Model and Sensor Drift

Infrastructure changes slowly. Sensors and models can get worse all the time. Losing calibration, different traffic, fixing work and weather can change how data matches the state of the system. So continuous checking should include finding if the model is changing and steps to retrain or have experts look at it.

8.2 Cybersecurity and Trust

A lifecycle digital thread creates a way to share information and so a bigger area for security risks. Research on twins for important infrastructure focuses on keeping the lifecycle secure, controlling access and protecting connected systems [8]. Security needs to cover devices sending data, storing it, updating models and user rights. Tracking where data comes from is also important because a fake measurement can lead to an unsafe conclusion.

8.3 Cost and Organizational Barriers

The money for infrastructure is not just about how much sensors cost. Installing, setting up sending data, managing it, connecting software and having experts can be more expensive over time. Companies also need ways to turn analysis into work orders and engineering choices. Without this way to connect, smart analysis can stay separate from management of assets.

IX. RESEARCH ROADMAP

- 2026–2027: establish common asset identifiers, data-provenance rules and benchmark monitoring datasets.
- 2028–2029: integrate digital twins with condition indicators, inspection histories and climate-exposure data.
- 2030–2031: develop uncertainty-aware deterioration and risk forecasting validated across multiple assets.
- 2032–2033: evaluate decision-support systems against real maintenance constraints, cost and service disruption.
- 2034 onward: demonstrate long-term lifecycle benefits through field-scale digital-thread deployments and independently verified outcomes.

The plan is a research path of a guess about when things will be used. Its main goal is to move from data sources to clear proof that stays useful all through the life of an asset.

X. DISCUSSION

The main point from this review is that resilience should be managed as a flow of information. Digital twins are useful not because they make a model but because they can keep track of how a real thing is, what has happened before and what might happen next. AI is useful not because it takes the place of engineers but because it can find patterns and handle data in a way that people can't easily do. Edge computing is useful when it makes things faster and moves data. Sensing is useful when what it sees stays true for the needed time.

A lifecycle digital thread also changes what it means to have infrastructure intelligence. Success is not a score on a test. It is the ability to have a maintained asset with proof that shows what happened, less problems that could be avoided and a better way to understand uncertainty. This changes how we measure things to look at things like when to delay maintenance, when to avoid emergency work, how much data is available, how good predictions are and if things work after they are fixed.

The framework has limits. It is a way to think about things, not a test and the research uses different ways to describe things, data and levels of development. So, the suggested steps should be seen as a way to do research that needs to be checked with projects.

XI. CONCLUSION

Strong infrastructure for the climate needs more than materials or better AI models. It needs information that stays connected from when it's planned, used and renewed. This paper showed the lifecycle thread as a way to link sensing, digital twins, AI predictions looking at risk and maintenance choices.

The review says the best way is to manage infrastructure around evidence. Raw observations should become things that show the condition; condition should help with risk; risk should guide when to fix something; and every fix should give new proof about the asset. Self-healing materials can be part of this process as one way to respond. Their performance must be checked at the right level. Future research should then focus on being able to work dealing with uncertainty, keeping things safe, checking across different assets and looking at long-term results, over the whole life of an asset.

References

- [1]. A. Afolabi, O. Ogunrinde, and A. Zabihollah, "Digital Twin and AI Models for Infrastructure Resilience: A Systematic Knowledge Mapping," *Applied Sciences*, vol. 15, no. 24, Art. no. 13135, 2025, doi: 10.3390/app152413135.program (NCEP) expert panel on detection, evaluation, and treatment of highblood cholesterol in adults (adult treatment panel III) finalreport. *Circulation*. 2002;106(25, article 3143).
- [2]. Q. Wang, B. Huang, Y. Gao, and C. Jiao, "Current Status and Prospects of Digital Twin Approaches in Structural Health Monitoring," *Buildings*, vol. 15, no. 7, Art. no. 1021, 2025, doi: 10.3390/buildings15071021.
- [3]. F. Di Nuzzo, D. Brunelli, T. Polonelli, and L. Benini, "Structural Health Monitoring System With Narrowband IoT and MEMS Sensors," *IEEE Sensors Journal*, vol. 21, no. 14, pp. 16371–16380, 2021, doi: 10.1109/JSEN.2021.3075093.
- [4]. J. Huang, A. Broekman, G. Markou, and H.-P. Chen, "Framework for a practical and cost-effective IoT-enhanced structural health monitoring and damage diagnostics system with digital twinning," *Journal of Civil Structural Health Monitoring*, vol. 15, pp. 2059–2084, 2025, doi: 10.1007/s13349-025-00927-9.
- [5]. N. V. Golovastikov, N. L. Kazanskiy, and S. N. Khonina, "Optical Fiber-Based Structural Health Monitoring: Advancements, Applications, and Integration with Artificial Intelligence for Civil and Urban Infrastructure," *Photonics*, vol. 12, no. 6, Art. no. 615, 2025, doi: 10.3390/photonics12060615.
- [6]. X. Yu, Y. Zhao, S. Cui, X. He, Y. Fu, and Q. Yang, "Efficient edge intelligence for onboard data anomaly classification in wireless structural health monitoring using knowledge distillation on low-cost IoT nodes," *Structural Health Monitoring*, 2025, doi: 10.1177/14759217251349533.
- [7]. B. F. Spencer Jr., S.-H. Sim, R. E. Kim, and H. Yoon, "Advances in artificial intelligence for structural health monitoring: A comprehensive review," *KSCE Journal of Civil Engineering*, vol. 29, no. 3, Art. no. 100203, 2025, doi: 10.1016/j.kscej.2025.100203.
- [8]. T. Itäpelto, M. Elhajj, and M. van Sinderen, "Digital twin application in lifecycle security of critical infrastructures: A systematic literature review," *International Journal of Critical Infrastructure Protection*, vol. 50, Art. no. 100783, 2025, doi: 10.1016/j.ijcip.2025.100783.
- [9]. L. Zhang, M. Zheng, D. Zhao, and Y. Feng, "A review of novel self-healing concrete technologies," *Journal of Building Engineering*, vol. 89, Art. no. 109331, 2024, doi: 10.1016/j.jobe.2024.109331.
- [10]. L. Jiang, M. Wu, F. Du, et al., "State-of-the-Art Review of Microcapsule Self-Repairing Concrete: Principles, Applications, Test Methods, Prospects," *Polymers*, vol. 16, no. 22, Art. no. 3165, 2024, doi: 10.3390/polym16223165.
- [11]. S. Rajadesingu, N. Palani, K. C. Mendonce, P. Vijayakumar, P. Monisha, and S. Ayyadurai, "State-of-the-art review on advancements of eco-friendly bacterial-infused self-healing concrete for sustainable constructions," *Journal of Building Engineering*, vol. 91, Art. no. 109669, 2024, doi: 10.1016/j.jobe.2024.109669.
- [12]. H. Tumwiine, T. Chala, H. Ssenyonjo, D. Kirigoola, and A. Al-Fakih, "On the use of self-healing materials in concrete technology: A comprehensive review of materials, mechanisms, and field applications," *Materials Today Chemistry*, vol. 48, Art. no. 103001, 2025, doi: 10.1016/j.mtchem.2025.103001.
- [13]. X. Li, F.-L. Zhang, W. Xiang, W.-X. Liu, and S.-J. Fu, "Structural health monitoring system based on digital twins and real-time data-driven methods," *Structures*, vol. 70, Art. no. 107739, 2024, doi: 10.1016/j.istruc.2024.107739.
- [14]. Y. Yang, H. Lin, G. Qian, Z. Hu, and M. D. Todd, "A Privacy-Preserving Framework Using Federated Learning for Structural Health Monitoring with Miter Gates Application," *Structural Health Monitoring*, 2025, doi: 10.12783/shm2025/37568.
- [15]. P. K. Pooja and N. Tarannum, "Self-healing concrete: a path towards advancement of sustainable infrastructure," *Discover Applied Sciences*, vol. 7, Art. no. 703, 2025, doi: 10.1007/s42452-025-06529-w.