



Institute for
Sustainable
Infrastructure



WHITE PAPER

Advancing Infrastructure Sustainability Through Digital Twins



Market Context



The concept of the digital twin has moved rapidly from theory to practice across sectors. Once the domain of aerospace and manufacturing, digital twins are now finding their way into infrastructure planning, design, construction, and operations. The global conversation around digital twins has expanded significantly in recent years, driven by advances in IoT sensors, cloud computing, artificial intelligence, and the urgent need to optimize resource use in a time of constrained budgets and climate uncertainty.

For infrastructure owners and operators, the stakes are particularly high. Communities are asking for infrastructure that is not only reliable and cost-effective, but also resilient, sustainable, and adaptable to changing conditions. Digital twins offer options to help bridge that gap—enabling a way to anticipate performance, extend asset lifecycles, reduce risk, and make decisions with greater confidence. Yet the technology is still emerging, and adoption faces challenges: from high upfront costs and data integration hurdles, to questions of governance, cybersecurity, and long-term value creation.

This white paper is written to help infrastructure stakeholders make sense of this evolving landscape. By examining current market trends, opportunities, and challenges, it aims to clarify where digital twins can provide the most value, and how they might accelerate the shift toward more sustainable and resilient infrastructure systems. At a time when infrastructure investment is both urgently needed and under heightened public scrutiny, understanding the potential of digital twins is more than a technical issue—it is a matter of societal importance.

The American Society of Civil Engineers (ASCE) defines civil infrastructure as the constructed facilities and systems that support social and economic activities, encompassing 18 categories like aviation, bridges, dams, drinking water, energy, and transit (as outlined in the 2025 Report Card for America's Infrastructure). This includes both traditional built structures and modern systems, with a focus on their full life-cycle management, sustainability, and resilience.

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Executive Summary

Digital twins are rapidly shifting from being exploratory to driving practical innovation in the infrastructure sector. They could be considered as infrastructure's "smart sidekicks," keeping watch, running simulations, and preventing costly surprises. Enabled by advances in IoT, AI, cloud computing, and geospatial technologies, digital twins can help professionals developing infrastructure to make more informed decisions throughout the asset lifecycle, from planning and design through operations—and eventually, dignified retirement (or recycling) for aging infrastructure.

THE VALUE PROPOSITION

Communities expect infrastructure to be reliable, resilient, sustainable, and fiscally responsible. Digital twins respond to those demands by:

- Forecasting and modeling performance for stressors such as climate change
- Integrating siloed data to improve collaboration and decision making
- Monitoring real-time conditions to reduce failures and optimize operations
- Enhancing transparency and stakeholder engagement through visualization
- Reducing emissions, resource waste, and lifecycle costs

These capabilities align strongly with sustainability outcomes—making digital twins catalysts for better infrastructure governance and long-term value creation.

A CLEAR SUSTAINABILITY CONNECTION

The Envision Sustainable Infrastructure Framework provides the structure to quantify and validate the sustainability benefits that digital twins enable — including environmental stewardship, social equity, economic resilience, and strong governance. Mapping digital twin use cases to Envision categories demonstrates significant, proven value in climate resilience, resource efficiency, water management, safety, and public engagement — and emerging potential in equity and ecological metrics.

CURRENT STATE OF ADOPTION

Digital twins are most mature in design and operations, where real-time monitoring and simulation drive performance gains. Adoption in planning and construction is increasing, while end-of-life applications—like material recovery and circularity—remain underdeveloped. Currently, the three leading sectors in adoption are transportation, energy, and water.

BARRIERS STILL HOLDING THE INDUSTRY BACK

To scale digital twins, the industry must address:

- Data interoperability challenges across systems and standards
- Upfront costs and unclear ROI in early phases
- A workforce skills gap in digital technologies
- Governance needs around cybersecurity, data ownership, and trust

FUTURE DIRECTIONS—THE OPPORTUNITY

Digital twins can unlock more holistic sustainability outcomes when:

- Integrated from the earliest planning stages
- Extended across full asset lifecycles, including decommissioning
- Used for multidisciplinary coordination and transparency with communities
- Supported by shared platforms and supportive public policies

WHAT'S A DIGITAL TWIN?

Think of a **digital twin platform** as the **movie director**:

- The DT decides how all the pieces (actors, sets, camera feeds) come together to tell a coherent story in real time.
- The **supporting software** are the **cast and crew**—they contribute their data and expertise, but without the director (the twin), it's just a collection of disconnected performances.

THE BOTTOM LINE

Digital twins are becoming essential infrastructure intelligence—enabling proactive, accountable, sustainability-aligned decision making. By embedding digital twins into Envision-aligned processes, agencies can deliver infrastructure that performs better, lasts longer, wastes less, and earns public trust. That's not just innovation—that's proven progress.

1. Digital Twins and Sustainability: Key Benefits



Lifecycle Approach to Sustainability

Digital twins enable a holistic view of infrastructure, linking planning, design, construction, operations, and maintenance. By providing a single, evolving model, they help project teams test sustainability strategies early and validate them over time. They also expose inefficiencies in materials, energy, and operations—allowing owners to reduce waste, optimize resource use, and extend asset life.



Embodied Carbon and Energy Efficiency

One of the strongest emerging applications is in carbon accounting and energy optimization. Digital twins can simulate material choices and construction methods, supporting embodied carbon analysis and scenario testing to select lower-impact alternatives. Over time, real-time operational data can be fed back into the model to identify energy efficiency opportunities. These functions align directly with Envision's Climate & Resilience credits, supporting strategies for emissions reduction and climate mitigation.



Water Resilience & Resource Management

Digital twins play a critical role in managing hydrological risks and water resources. Predictive models allow agencies to prepare for floods, droughts, and changing precipitation patterns, while continuous monitoring supports water quality management and pollution prevention. This aligns with Envision's Quality of Life (QL) and Natural World (NW) credits by promoting both community wellbeing and ecosystem health.



Stakeholder Engagement and Transparency

Beyond technical benefits, digital twins provide a platform for transparent decision making. By combining geospatial visualization with real-time data, they help non-technical stakeholders understand complex trade-offs. Cities and agencies are already using digital twins in public engagement forums to demonstrate project impacts and alternatives, building trust, and fostering collaboration. These practices support Envision's Leadership (LD) and Quality of Life (QL) credits by encouraging meaningful stakeholder involvement.

Making the Invisible Visible

Geospatial visualization and real-time data help translate complexity into clarity—turning stakeholders into informed partners.



2. Introduction to Digital Twins in Civil Infrastructure

What are digital twins?

A digital twin is a dynamic, virtual representation of an asset, process, or system that interacts between the digital and physical environments through synchronization with data (real-time, continuous, recent, projected, or historical) to support improved decision making, optimization, and outcomes across its lifecycle.

Global standards and literature, such as Gemini, ISO, IEEE converge on *integration, synchronization, and decision support* as core features characterizing digital twins.

Digital twins capabilities make them particularly relevant to infrastructure challenges where complexity, systems interdependencies, and long operational timelines require flexible, adaptive solutions. These capabilities offer potential benefits across the full infrastructure lifecycle, from planning and design to operations and maintenance, and end of life.

Digital Twins

Updates in real-time, reflecting current state and behavior of physical object.

Combines bidirectional data exchange with predictive and diagnostic capabilities.

Enables cross-lifecycle tracking.

Enhances long-term performance, resilience, and sustainability.

VS

Traditional Modeling & Simulation

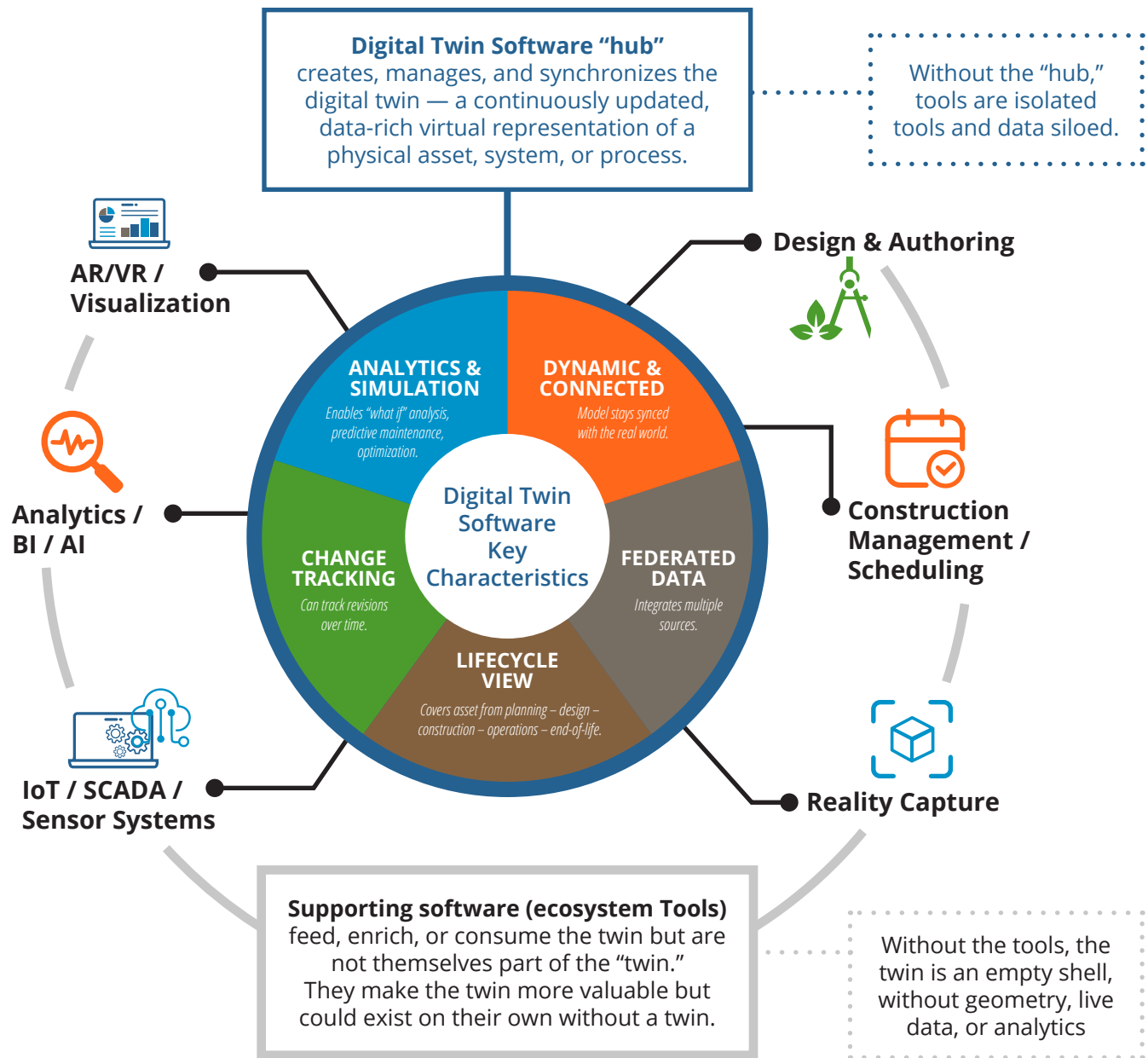
Incorporates static data, often lacking real time updates.

Allows one-way data flow

Primarily focuses on early planning and design phases.

Supports initial design accuracy and compliance.

Differentiating Digital Twins & Supporting Software



Supporting Software’s Role in the Twin Ecosystem and Examples

AR/VR / Visualization

Role: Help stakeholders interact with and visualize the twin in immersive ways.

Examples: NVIDIA Omniverse, Unity, Unreal Engine

Analytics / BI / AI

Role: Consume twin data to generate insights, dashboards, predictive models.

Examples: Power BI, Tableau, custom ML models

IoT / SCADA / Sensor Systems

Role: Stream live data to keep the twin current (asset condition, performance).

Examples: SCADA systems, IoT platforms (AWS IoT, Azure Digital Twins, Ignition SCADA)

Reality Capture

Role: Provide ground-truth context and updates for brownfield or as-built twins.

Examples: Drone photogrammetry (DroneDeploy), LiDAR, point cloud software (Leica Cyclone, Bentley iTwin Capture)

Construction Management / Scheduling

Role: Provide timelines, progress data, sequencing — can be linked into 4D/5D twins.

Examples: Primavera P6, MS Project, Procore, Trimble ProjectSight, Bentley SYNCHRO

Design & Authoring

Role: Provide geometry, asset definitions, and metadata that form the basis of the twin.

Examples: CAD, BIM, Civil Design Tools (Autodesk Revit, Bentley OpenRoads, Tekla, CATIA)

The Growing Role of Digital Twins in Infrastructure

When examining digital twins, seven use cases consistently emerge. These digital twin use cases, which are not sector-specific, capture the **main functions through which digital twins support sustainability and infrastructure outcomes** and describe cross-cutting capabilities that can be applied across systems and lifecycle phases.

We defined an infrastructure DT use case as a **structured and purposeful application of digital twin functionalities to support a specific goal, decision, or process across the infrastructure lifecycle**. A use case connects actors (e.g., project teams, technology providers, asset owners), functions or mechanisms (e.g., forecasting, monitoring, integration, simulation), and intended outcomes (e.g., improved performance, resilience, and decision making). This framing helps to highlight how technical capabilities are operationalized in practice.

01 Simulation & forecasting



Enable scenario testing and predictive modeling for climate stressors (e.g., heat, flooding, storm surge), energy performance, and carbon emissions. Support diagnostics, prognostics, and the development of preventive maintenance regimes by forecasting asset behavior under varying conditions.

02 Optimization



Used to improve resource efficiency, minimize embodied carbon, and enhance system-level performance (e.g., water distribution, energy grids). Digital twins support safety, operational efficiency, and continuous asset monitoring by identifying anomalies and recommending real-time adjustments.

03 Visualization & prototyping



Facilitate immersive, data-rich representations of infrastructure systems, their components and processes. They enable the visualization of phenomena like urban heat islands and the prototyping and simulation of design alternatives before implementation.

04 Integration & interoperability



Serve as connective infrastructure across disciplines and platforms. Digital twins enhance interoperability between software tools, teams, and data layers, supporting collaborative planning and systems integration.

05 Monitoring & tracking



Provide real-time, continuous data on asset conditions, environmental performance, and operational metrics. They improve responsiveness to failures, optimize maintenance schedules, and ensure compliance through automated tracking systems.

06 Management & record-keeping



Act as live, digital repositories for infrastructure systems, which help in managing operational data, inventory, maintenance histories, and scheduling. They support smarter decision making through unified access to historical and real-time data (e.g., for smart grids or equipment inventories).

07 Virtualization of experiences & services



Enable the digital transformation of traditional functions through virtual alternatives, such as remote site inspections, VR simulations, digital stakeholder engagement tools, and e-services. These reduce the need for physical presence and expand accessibility.

Industry Adoption and Emerging Trends

Key Sectors Using Digital Twins

Adoption has been led by transportation, water, and energy sectors. In the transportation and energy sectors digital twins are primarily used to enhance operational performance and reduce emissions, including optimizing traffic flow to reduce fuel use and fine-tuning power grid operations to lower carbon emissions. Utilities and energy providers are using digital twins for grid management, performance monitoring, predictive maintenance, and managing renewable generation assets. Water infrastructure emphasizes resilience and risk management, including flood control and infrastructure durability under extreme events. Water systems also use digital twins for leak detection, network monitoring, treatment plant optimization, and regulation compliance. In addition, more comprehensive, city-level digital twins are becoming more common for planning, considering infrastructure interdependencies, environmental modeling, etc. Digital twins are being proposed as value-based tools for infrastructure asset management and as integrators of remote sensing data in large-scale projects.

Emerging Trends and Future Potential

To date, digital twins are most commonly used in the design and operations phases. In early stages, they support simulation, visualization, and scenario testing, while in operations they enable real-time monitoring, performance optimization, and asset management. Planning and construction see moderate use, and end-of-life applications are nearly absent, exposing a lifecycle gap. Without better integration at decommissioning, the potential for digital twins to support long-term sustainability tracking and post-use outcomes remains underdeveloped.

Sustainable Infrastructure

Sustainable infrastructure is defined by the United Nations Environment Programme (UNEP) as infrastructure that is “planned, designed, constructed, operated and decommissioned in a manner that ensures economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire infrastructure life cycle.” This life-cycle approach aligns infrastructure performance with long-term public and environmental goals, beyond short-term technical functionality alone.

To measure and promote these outcomes, numerous sustainability rating systems have been developed for buildings and communities, including LEED, BREEAM, WELL, Green Star, Living Building Challenge; and infrastructure, including FAST-Infra, IS Rating Scheme, and Envision.

3. Sustainability and Digital Twins

Aligning Best Practices to the Envision Sustainable Infrastructure Framework.

Digital twins have rapidly gained attention in engineering and planning for their ability to optimize performance, predict issues, and inform decision making. Advocates note that digital twins can significantly advance sustainability goals by improving energy efficiency, reducing waste, enabling predictive maintenance, and extending asset life through real-time data analysis and improved collaboration.

Why Envision?

The Envision Sustainable Infrastructure Framework provides a holistic and widely recognized structure for defining sustainability excellence across the full lifecycle of civil infrastructure. Because it evaluates not only environmental performance but also social equity, economic resilience, and governance quality, Envision creates an ideal benchmark for assessing the sustainability value of digital twins.

Digital twins are often promoted for their technical strengths—efficient operations, predictive maintenance, energy monitoring—but their broader sustainability impact can be overlooked without a structured assessment. Envision addresses this need by:

Providing a Comprehensive Sustainability Scope – Envision evaluates sustainability across numerous categories, subcategories, and credits, so digital twin use cases can be mapped to specific sustainability outcomes.

Supporting Lifecycle-Based Evaluation – Digital twins generate value at multiple stages—planning, design, construction, operations, and even decommissioning. Envision’s lifecycle approach aligns directly with how digital twins evolve and deliver continuous performance improvements over time.

Translating Technical Innovation into Verified Results – Envision’s verification process provides auditable evidence of sustainability performance. Digital twins can supply data, analytics, and documentation that help teams prove sustainability claims rather than just assume them.

Enabling Better Decisions Through Transparency – Digital twins enhance stakeholder communication and shared decision making—central pillars of Envision’s Leadership and Quality of Life credits. By making impacts visible, DTs strengthen trust and buy-in.



Digital twins support sustainability by helping to reduce inefficiencies, enable predictive analysis, and integrate distinct data, such as environmental and social data.



By connecting advanced technology with accountable outcomes, Envision offers a credible and practical framework for validating the role of digital twins in driving better, smarter, and more sustainable infrastructure.

Envision Sustainable Infrastructure Framework



What is Envision?

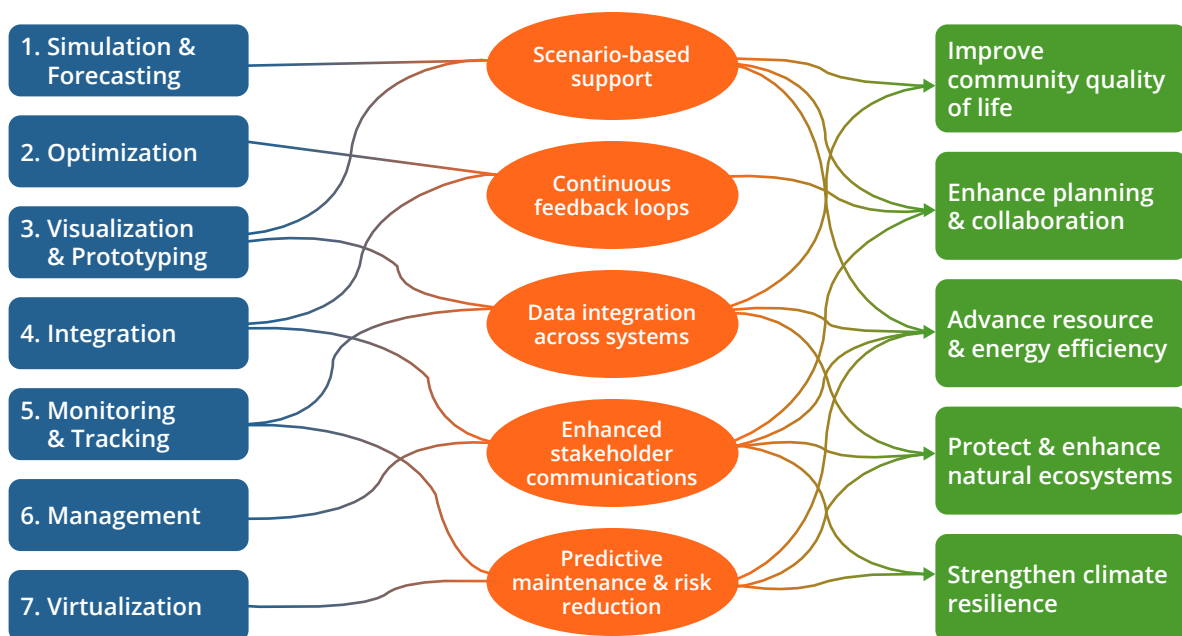
Envision is a holistic sustainability framework and rating system that guides and assesses the sustainability and resilience of all types of infrastructure. It is a comprehensive tool created to assist agencies, municipalities, consultants, contractors, and operators, in planning, designing, and delivering more sustainable infrastructure projects. The Envision framework is a decision-making tool that allows project teams to evaluate projects across a broad range of sustainability indicators, or “credits,” that address environmental, social, and economic dimensions of sustainability to encourage systemic change. At its core, Envision is about supporting higher performance through better choices in infrastructure development.

Mapping Digital Twin Use Cases to Envision Credits

Each digital twin use case was assessed for its potential to support the intent and requirements of Envision credits, mapping capabilities to credits based on functionality and real-world applications. The results offer insight into which digital twin functions are most mature and ready to support sustainability goals, and where there is under explored or emerging potential.

- **Quality of Life (QL):** Community engagement and real-time impact assessment.
- **Leadership (LD):** Data-driven decision making & collaboration.
- **Resource Allocation (RA):** Optimization of materials and waste reduction.
- **Natural World (NW):** Environmental monitoring and biodiversity protection.
- **Climate & Resilience (CR):** Climate impact modeling and adaptation strategies.

Digital Twin Use Cases as Pathways Toward Infrastructure Sustainability



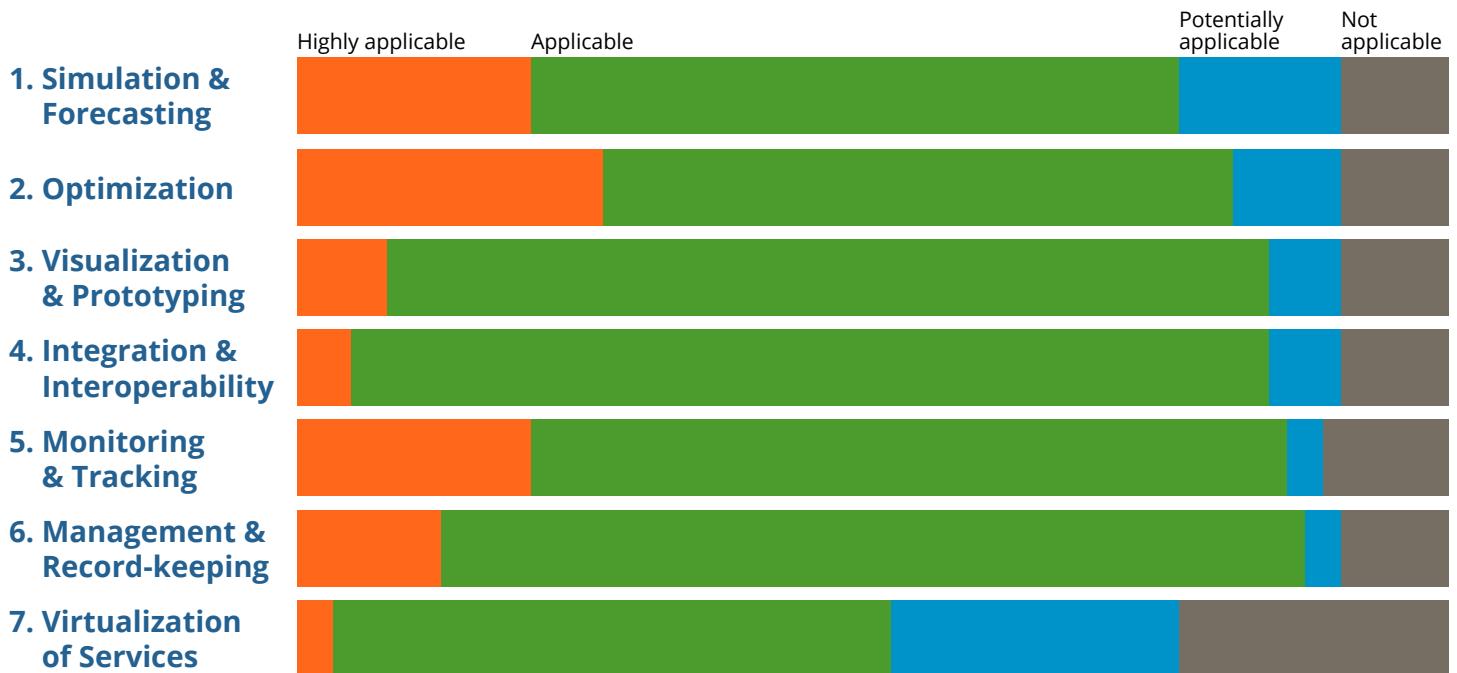
Mapping Digital Twin Use Cases to Envision Credits

The mapping assessed the applicability for each Envision credit across four levels, informed by both the credit intent and the performance metrics, with applicability rated across four levels:

- Highly applicable: Capabilities directly support the intent and metrics of the credit.
- Applicable: Capabilities align conceptually and have demonstrated use, though less systematically.
- Potentially applicable: Capabilities show promise but remain underdeveloped in current practice.
- Not applicable: Capabilities are not currently supporting the credit's intent and metric.

This mapping process revealed which of the capabilities are more mature and widely used in advancing sustainability, and which are still largely conceptual.

Number of Envision credits by applicability level for each digital twin use case



This illustrates where digital twin tools and capabilities could be leveraged to assist in meeting sustainability goals, where they provide moderate support, and where there is only speculative or emerging potential.

Digital Twin Use Cases Across the Infrastructure Lifecycle

Digital twins can serve as adaptive systems that evolve with infrastructure—not one-time models, but living companions across every phase.

- In **planning and design**, they bring foresight through simulation and visualization, allowing teams to test scenarios and design for resilience from the outset.
- During **construction**, digital twins improve oversight, transparency, and efficiency through real-time tracking and virtual collaboration.
- In **operations**, they become the backbone of asset management—supporting predictive maintenance, performance optimization, and data-driven sustainability reporting.
- Finally, as assets reach **renewal or decommissioning**, digital twins help capture institutional knowledge, inform material recovery, and ensure responsible transitions.

By mapping these capabilities to lifecycle stages, owners and practitioners can see where digital twins provide the strongest sustainability leverage—and how integrating them with frameworks like Envision can yield measurable improvements over time.



PRIMARY DIGITAL TWIN USE CASES

4. Key Technologies and Tools Supporting Digital Twins in Infrastructure

The evolution of digital twins in infrastructure is driven by an interconnected ecosystem of technologies that enable real-time monitoring, predictive analytics, and data-driven decision making. At the core, **Internet of Things (IoT)** sensor networks capture continuous streams of data from physical assets, feeding accurate and timely information into digital models. Complementing this, **artificial intelligence (AI)** and machine learning algorithms analyze complex datasets to detect patterns, forecast performance, and support proactive maintenance. Together, these technologies empower infrastructure owners and operators to optimize asset management, improve resilience, and enhance sustainability.

Supporting this technological backbone are a range of software platforms that facilitate data integration, visualization, and simulation. By leveraging these tools, organizations can not only replicate the physical world digitally but also explore “what-if” scenarios, assess risk, and make informed strategic decisions, unlocking the full potential of digital twins in modern infrastructure.

Category	Function / Role	Examples / Notes
IoT Sensor Networks	Collect real-time data from assets and environments to feed digital twins	Structural sensors, environmental monitors, flow meters, smart meters
Artificial Intelligence (AI) & Machine Learning (ML)	Analyze data, detect patterns, predict failures, optimize maintenance and operations	Predictive algorithms, anomaly detection, AI-driven decision support
Predictive Analytics Platforms	Forecast asset performance, identify risks, prioritize interventions	Integrated analytics dashboards, risk assessment tools
Digital Twin Software Platforms	Visualize, simulate, and integrate data to replicate physical infrastructure digitally	ESRI, Bentley Systems, open-source frameworks (e.g., OpenDT)
Open-Source vs. Proprietary Solutions	Provide flexibility and customization vs. robust support and specialized features	Open-source: modular, customizable; proprietary: scalable, enterprise-grade



Geospatial Data & GIS Integration

In today's data-driven infrastructure landscape, geospatial data and GIS are foundational. Across planning, design, construction, and operations, GIS integration enables teams to visualize complexity, understand interdependencies, and make decisions informed by spatial, social, and environmental context. As infrastructure challenges grow, the ability to integrate and communicate spatial data is central to achieving sustainability goals. Geospatial intelligence provides critical context for how infrastructure interacts with communities, ecosystems, and climate systems. When embedded in workflows, it enhances risk modeling, adaptive design, and transparent stakeholder engagement—all key principles within the Envision Sustainable Infrastructure Framework.

While GIS adoption is widespread, integration with digital twins remains limited. Many organizations use GIS for mapping, but fewer leverage it as a real-time, interoperable platform that connects data, models, and lifecycle management. The next step is turning spatial data into living digital environments—a goal advanced through emerging partnerships like Bentley, Cesium, and Google, which are shaping the next generation of geospatially intelligent digital twins.

From maps to real-time intelligence, geospatial tools empower smarter, more resilient infrastructure decisions.

Bentley, Cesium & Google: Strengthening Geospatial Foundations for Digital Twins

Bentley's acquisition of Cesium in September 2024 represents a milestone in the geospatial digital twin landscape. Cesium is widely recognized for its open 3D geospatial platform—including CesiumJS, Cesium ion, and the 3D Tiles open standard—which enables streaming massive 3D datasets for realistic, large-scale visualizations. Combining Cesium's capabilities with Bentley's iTwin digital twin platform, has created a more cohesive toolkit for infrastructure practitioners; one that aligns engineering, reality capture, subsurface, IoT, and enterprise data—all within rich 3D geospatial context. This fusion helps scale digital twins from the macro (networks, terrain, context) down to millimeter-level detail of individual assets, improving fidelity and enabling deeper insight into infrastructure performance.

The Bentley-Google partnership builds on this foundation by offering high-quality geospatial content and cloud-powered capabilities that enhance what engineers and operators can see and analyze. As of October 2024, Bentley users (via iTwin and related applications) are able to integrate Google's photorealistic 3D Tiles and other Maps Platform content to provide immersive, context-rich visualizations throughout the infrastructure lifecycle—from planning and design through construction and operations.

This means that instead of working in abstraction, teams can view assets in their actual terrain, with realistic surroundings and geospatial context, which supports better decision making around siting, climate risk, aesthetics, and environmental interaction.

The partnership also pairs with Google Cloud's AI and analytics tools, enabling analyses such as predictive simulations, performance assessments, and risk modeling that are grounded in accurate geospatial data.

These changes are helping to improve what digital twins can deliver. The resulting platforms are more interoperable, more visually compelling, and better able to support real-world, sustainability-aligned applications.

They strengthen alignment with frameworks like Envision:

 <p>Climate and Resilience—through modeling and risk visualization</p>	 <p>Natural World—by placing infrastructure in ecological/spatial context</p>	 <p>Leadership—related to governance and stakeholder engagement, working toward making geospatial information accessible and transparent.</p>
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Geospatial Data & GIS Integration

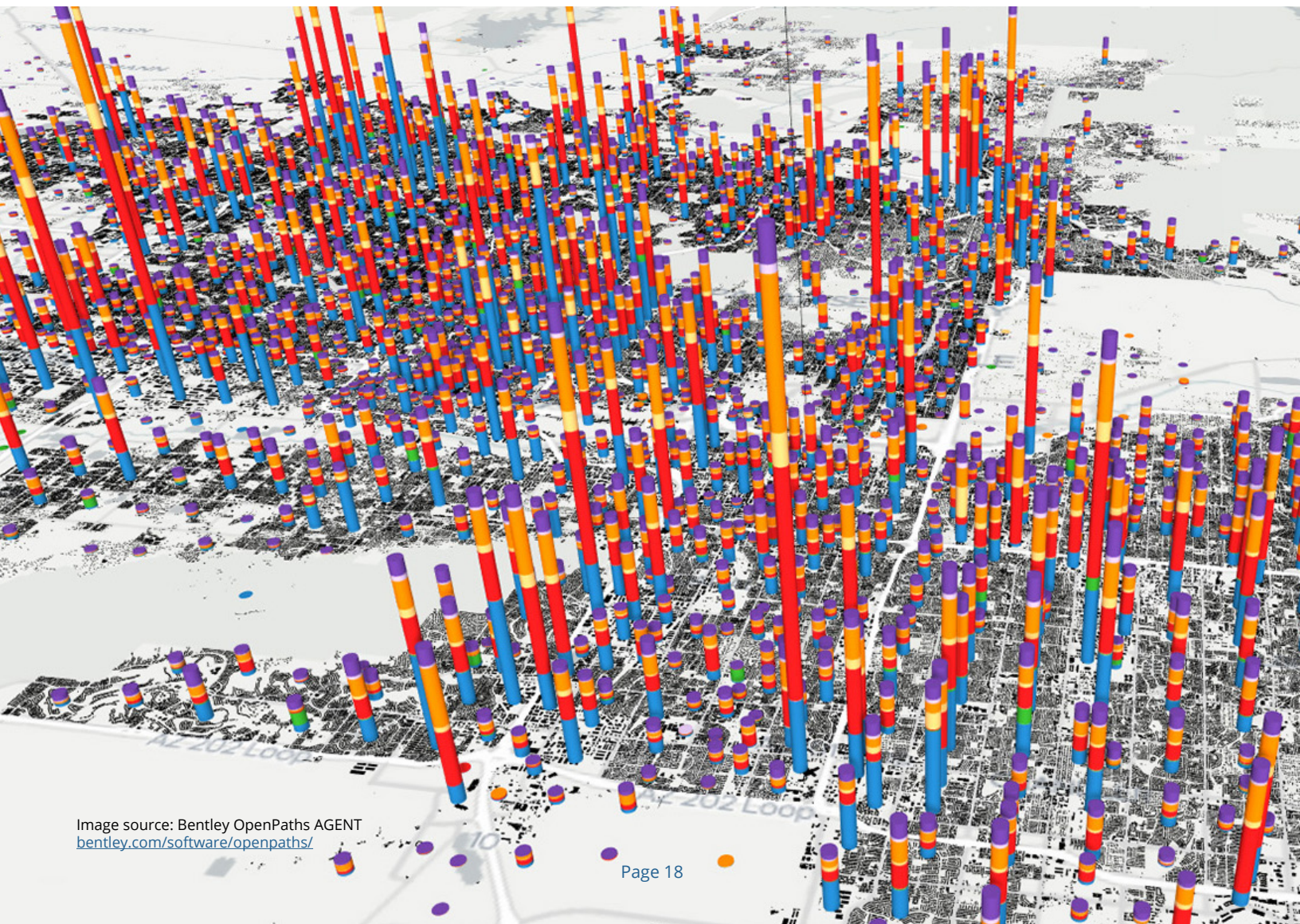
3D Visualization and Mapping for Planning and Impact Assessment

Digital twins are increasingly used for 3D visualization and mapping to support planning, design, and impact assessment in infrastructure projects. By integrating GIS, BIM, and real-world data—such as terrain models, sensor inputs, and aerial imagery—digital twins create a living 3D model of assets and their surroundings.

This spatially accurate environment allows planners and stakeholders to visualize proposed designs in context, assess environmental and social impacts, and model scenarios such as flooding, traffic, or energy performance. Because digital twins update in real time as new data becomes available, they enable dynamic impact assessment over time—helping agencies make better-informed, transparent decisions while reducing uncertainty in project approvals and long-term sustainability outcomes.

Seeing the Whole Picture

Digital twins bring projects to life in 3D—helping planners, designers, and communities visualize impacts before decisions are made.



IoT & AI in Digital Twins

The convergence of the Internet of Things (IoT) and Artificial Intelligence (AI) is transforming digital twins from static models into intelligent, self-learning systems. IoT sensors continuously feed real-time data—on temperature, vibration, energy use, or environmental conditions—into digital twins, ensuring they reflect the current state of infrastructure assets. AI then analyzes these data streams to detect anomalies, forecast failures, and optimize performance automatically.

Together, IoT and AI enable digital twins to move beyond visualization toward predictive and adaptive management, helping infrastructure owners improve efficiency, resilience, and sustainability across the asset lifecycle.

Sensor Networks for Real-Time Infrastructure Monitoring

Sensor networks form the backbone of modern digital twins, enabling the continuous collection of real-time data across infrastructure systems. These networks integrate IoT-enabled devices—such as strain gauges on bridges, flow meters in water systems, or air quality sensors in urban environments—to monitor asset conditions and environmental factors. The data they generate feeds directly into digital twin platforms, keeping the virtual model synchronized with the physical asset. This real-time feedback loop allows for early detection of issues, such as material fatigue, leaks, or inefficiencies, before they escalate into costly failures.

When combined with AI-driven analytics, sensor networks unlock predictive capabilities that go far beyond traditional monitoring. Machine learning algorithms can analyze vast, time-series datasets to identify subtle patterns, forecast asset degradation, and recommend optimal maintenance interventions. This fusion of IoT and AI supports data-informed decision making and enhances infrastructure resilience, helping owners optimize operations, extend asset life, and achieve sustainability goals. In essence, sensor networks transform digital twins from passive data repositories into proactive management tools, driving smarter, safer, and more sustainable infrastructure systems.

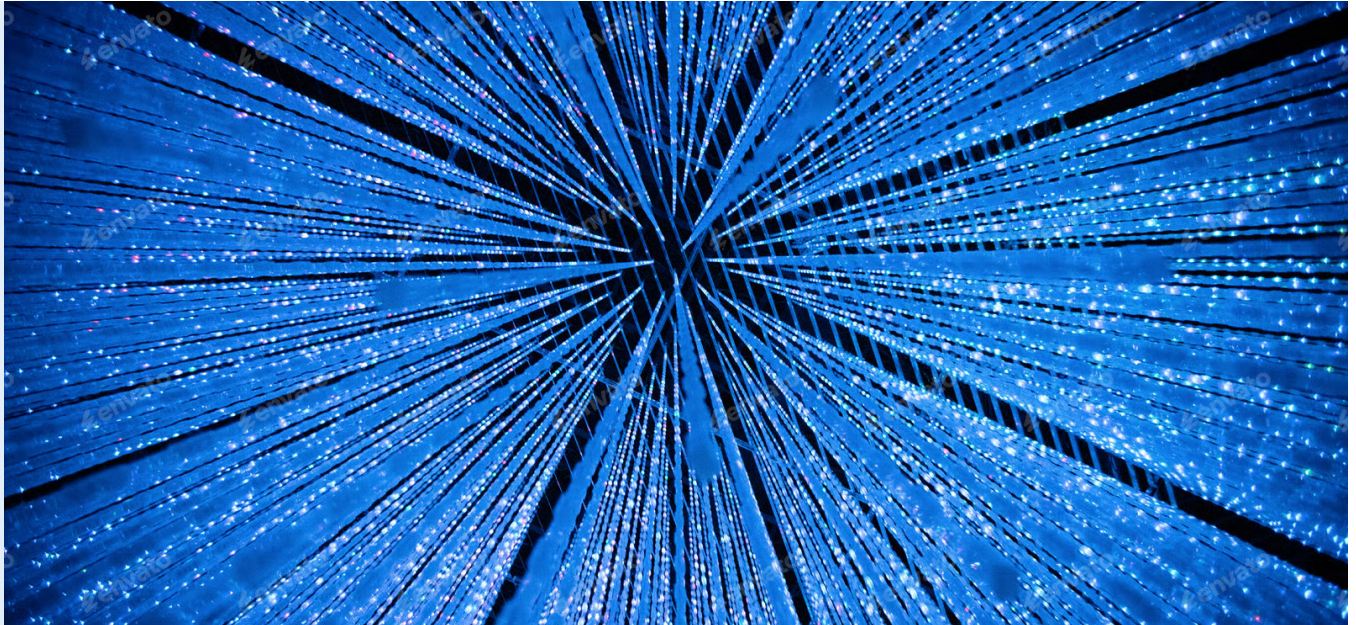


AI-Driven Predictive Analytics In Asset Management

AI-driven predictive analytics represents one of the most transformative capabilities within digital twin ecosystems, particularly when paired with IoT-enabled data collection. By analyzing continuous sensor inputs—from vibration monitors, temperature probes, or structural health sensors—AI models can detect patterns that precede equipment degradation or system failures. These predictive insights allow infrastructure owners to shift from reactive to proactive maintenance, scheduling interventions only when and where they are needed. The result is reduced downtime, optimized resource allocation, and lower lifecycle costs, all while maintaining or improving performance reliability.

In asset management, predictive analytics extends beyond failure prevention. AI algorithms can model future performance scenarios under varying environmental or operational conditions, helping planners and operators test resilience strategies before implementing them. This capability supports long-term sustainability by enabling infrastructure systems to adapt to climate impacts, population growth, or shifting energy demands. When integrated into digital twins, AI-powered predictive analytics becomes not just a diagnostic tool, but a strategic decision-support system—one that empowers infrastructure owners to make data-informed investments that enhance resilience, extend asset longevity, and deliver greater value to communities.

Software Ecosystem for Digital Twins



Open-Source Vs. Proprietary Solutions in Digital Twin Adoption.

The digital twin landscape is increasingly shaped by the balance between open-source and proprietary solutions, each offering distinct advantages and trade-offs. Open-source platforms—such as FIWARE, Eclipse Ditto, and OpenGIS-based frameworks—promote interoperability, transparency, and innovation by allowing users to customize code and integrate data from multiple systems. These solutions are especially valuable for research institutions, public agencies, and infrastructure owners that prefer to not be locked-into one solution and don't want to develop a custom-tailored approach to digital twin implementation. They also align well with sustainability goals, as open standards support lifecycle data sharing, system transparency, and long-term resilience planning.

Proprietary platforms, on the other hand, typically provide robust, turnkey functionality with higher levels of technical support, data security, and integration between modeling, simulation, and asset management tools. Vendors like Bentley, Autodesk, and Siemens offer deeply specialized capabilities that streamline workflows for complex infrastructure projects.

However, these advantages often come at the cost of limited interoperability and higher licensing expenses, which can constrain flexibility and cross-sector data exchange. As digital twins evolve toward greater integration of IoT, AI, and GIS data, the most effective strategies may combine both models—leveraging open-source frameworks for interoperability and proprietary systems for performance and scalability—to ensure digital twins remain adaptable, transparent, and future-ready.

Looking for Balance

The future of digital twins isn't open or proprietary—it's hybrid. Combining open standards with high-performance tools delivers the best of both worlds.

Software Ecosystem for Digital Twins

Overview of Industry Tools

Platform	Type	Core Strengths	Key Features	Relevance to Sustainable Infrastructure
Bentley iTwin Platform	Hybrid <i>Uses open-source technology so others can build on it, but platform itself runs as a licensed Bentley service in the cloud</i>	Infrastructure-focused digital twin ecosystem	Integrates BIM, GIS, and IoT data; supports asset lifecycle management and engineering workflows	Widely used in transportation, water, and energy sectors. Enables lifecycle tracking, predictive maintenance, and carbon performance measurement.
Autodesk Tandem	Proprietary	Design-to-operations continuity	Focused on BIM-based twins for design, construction, and handover phases; strong integration with Autodesk ecosystem	Streamlines design coordination and handover documentation, supporting Envision categories related to efficiency and resource optimization.
Esri ArcGIS / ArcGIS Urban / GeoBIM	Proprietary	Geospatial intelligence and mapping	Integrates GIS with BIM, IoT, and 3D visualization; strong in planning, mapping, and impact assessment	Excels in environmental modeling, scenario visualization, and spatial sustainability metrics—key for Envision’s Natural World and Quality of Life categories.
Siemens Xcelerator / NX / MindSphere	Proprietary	Industrial and manufacturing integration	Strong IoT and AI-driven analytics for asset performance and predictive maintenance	Applicable to energy and utilities; emphasizes decarbonization and operational optimization of industrial infrastructure.
Dassault Systèmes 3DEXPERIENCE	Proprietary	High-fidelity modeling and simulation	Combines physics-based modeling, materials simulation, and product lifecycle management (PLM)	Effective for complex system design and circular economy analysis in infrastructure and mobility projects.
Hexagon Smart Digital Reality (SDR)	Proprietary	Geospatial precision and industrial data integration	Merges reality capture, GIS, and operational data; strong in monitoring and control systems	Useful for large-scale asset monitoring, safety, and operational optimization in smart city and industrial contexts.
Cityzenith SmartWorldOS	Proprietary	Urban-scale sustainability modeling	Designed for smart cities and carbon reduction analytics	Supports city-scale planning, emissions tracking, and stakeholder engagement in alignment with Envision’s Climate & Resilience goals.
FIWARE Foundation Platform	Open Source	Interoperability and data standardization	Open-source architecture for IoT, AI, and smart city data integration	Promotes transparency, open data sharing, and cross-sector collaboration for sustainable infrastructure planning.
Eclipse Ditto	Open Source	Digital twin framework for IoT ecosystems	Provides real-time synchronization between physical and digital entities	Ideal for scalable, flexible twin development; supports adaptive and transparent sustainability monitoring.

5. Future Directions: Digital Twins and Sustainable Infrastructure

Challenges in Adopting Digital Twins

DATA INTEROPERABILITY AND INTEGRATION ISSUES

One of the largest barriers to scaling digital twins is the lack of data standards and interoperability. Infrastructure systems draw from disparate sources—IoT sensors, BIM models, GIS platforms, SCADA systems—that often operate in silos. Without standardized formats, integrating real-time data into a single twin is costly and technically complex, limiting scalability.

COST BARRIERS AND RETURN ON INVESTMENT CONCERNS

Costs for initial investment in sensors, data infrastructure, and modeling platforms could cause hesitation for agencies considering using digital twins, especially those with limited budgets. While long-term savings through predictive maintenance and performance optimization are well-documented, the ROI case is not always immediately visible, making it harder to justify in traditional capital planning cycles.

WORKFORCE SKILLS GAP IN DIGITAL TWIN ADOPTION

Deploying and managing digital twins requires specialized expertise in data science, AI, and digital modeling, skills not yet widespread among infrastructure professionals. The result is a workforce skills gap that slows adoption, emphasizing the need for training, reskilling, and interdisciplinary collaboration between engineers, IT specialists, and sustainability experts.

Policy and Regulatory Considerations

STANDARDS AND GUIDELINES FOR DIGITAL TWIN IMPLEMENTATION

Global adoption will depend heavily on developing standards and best practices for digital twin use. Frameworks like the UK's Centre for Digital Built Britain's Gemini Principles are early steps, but consistent approaches to data quality, ownership, and cybersecurity are needed to ensure trust and comparability across projects.

GOVERNMENT AND PRIVATE SECTOR ROLES IN ACCELERATING ADOPTION

Policy changes will play a critical role in accelerating adoption of digital twins. Governments can incentivize adoption through funding programs, procurement requirements, and performance-based regulations, while the private sector drives innovation through platform development and industry partnerships. Aligning these efforts ensures digital twins don't remain niche tools, but instead become part of mainstream infrastructure practice.

Opportunities for Scaling Digital Twin Use in Envision Projects

EMERGING RESEARCH AND FUNDING OPPORTUNITIES

Research and funding opportunities are emerging for digital twin applications for infrastructure. Federal, state and private organizations are exploring how digital twins can enhance resilience, decarbonization, and smart city development. Leveraging these opportunities allows agencies to experiment with lower risk and cost.

OPPORTUNITIES FOR CROSS-SECTOR COORDINATION ON SHARED DIGITAL TWIN PLATFORMS

Infrastructure systems are interconnected. Energy, water, transport, and communications depend on one another. As digital twins evolve, they likely will begin to focus on shared platforms that enable cross-sector modeling of cascading risks and co-benefits. For Envision users, this opens new avenues to demonstrate system-wide sustainability and resilience outcomes, moving from isolated projects to integrated, resilient infrastructure networks.

STRATEGIES FOR INFRASTRUCTURE OWNERS TO INTEGRATE DIGITAL TWINS INTO ENVISION PROJECTS

Digital twins can serve as a practical bridge between Envision's sustainability framework and day-to-day project decision making. In the planning and design phases, twins allow teams to test multiple scenarios—such as siting options, material choices, and design strategies—against Envision's categories, providing real-time insights into trade-offs and long-term implications. This early integration ensures that sustainability objectives are embedded from the start rather than retrofitted later.

As projects move into construction and operations, digital twins provide auditable, data-rich evidence to demonstrate performance across Envision categories like Climate & Resilience, Natural World, and Quality of Life. By continuously documenting impacts—energy use, water efficiency, ecological outcomes, stakeholder engagement—digital twins not only help with verification but also make the case for sustainability investments by showing how choices translate into measurable results over time.

In this way, digital twins extend the value of Envision beyond a scoring framework: they transform it into a living management tool, guiding projects through the full lifecycle while ensuring accountability and transparency at every stage.

6. Conclusion and Call to Action

The opportunity ahead is clear: digital twins can evolve from project-specific tools into shared infrastructure for sustainability innovation. By aligning efforts across sectors, agencies, and technology providers—and grounding adoption in frameworks like Envision—the industry can accelerate progress toward infrastructure that is smarter and more resilient. Collaboration is the key to unlocking the full value of digital twins as models for systemic change.

Summary of Key Takeaways

Digital twins are **already delivering measurable sustainability benefits** by enhancing performance, efficiency, and resilience, particularly in areas such as energy use, carbon reduction, water management, and risk preparedness.

Digital twins enable **adaptive, flexible solutions** that help infrastructure owners and operators respond to evolving challenges and extend asset lifespans.

Adoption is **uneven**: the strongest applications are in performance-driven areas, while equity, ecology, and governance dimensions remain underdeveloped.

The Envision framework provides a **roadmap for more comprehensive application** of digital twins, ensuring technical innovation aligns with broader sustainability goals.

Real-world projects are **demonstrating value**, from transportation and water systems to city-scale models, but broader use across lifecycle stages—especially planning, decommissioning, and community engagement—is still limited.

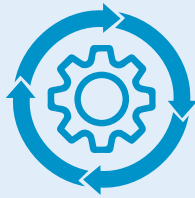
The **future lies in integration**: advancing from efficiency-focused capabilities toward equity-centered, ecological, and governance applications will unlock the full potential of digital twins as enablers of systemic sustainability and resilience.

Recommendations for Industry Practitioners

Digital twins are rapidly moving from concept to practice, but their true potential for sustainability will only be realized through collective action. Practitioners, policymakers, and technology providers must work together to embed digital twins across the full infrastructure lifecycle and align their use with sustainability frameworks like Envision.

Start Early

Integrate digital twins at the planning and design stages to evaluate sustainability strategies before construction.

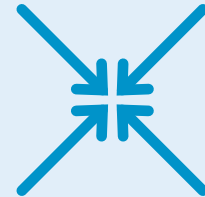


Think Lifecycle

Extend digital twin use across construction, operations, and eventual decommissioning to capture long-term performance and outcomes.

Align with Frameworks

Use Envision as a guide for structuring and evaluating digital twins, ensuring they address not just efficiency but also equity, ecology, and governance.

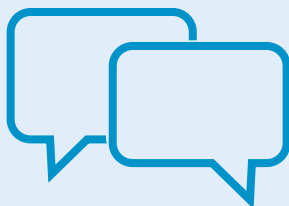


Build Capacity

Invest in training and cross-disciplinary teams that combine engineering, digital expertise, and stakeholder engagement.

Collaborate Across Sectors

Develop shared platforms and data standards that enable coordination between transportation, water, energy, and ecological systems.



Engage Stakeholders

Leverage digital twins as a transparency tool to foster trust, communicate trade-offs, and improve decision making.

7. Case Studies

The following case studies are organized according to their primary digital twin use case, with additional supporting and emerging applications identified for each project. Together, these demonstrate how digital twins are being applied across infrastructure sectors to enhance sustainability, resilience, and operational efficiency. Each project is analyzed through its digital twin use cases, highlighting the mechanisms through which data-driven capabilities translate into measurable outcomes. The cases highlight key benefits, such as improved decision making, optimized performance, and reduced environmental impact; and connect these outcomes to relevant Envision sustainability subcategories. Collectively, the case studies illustrate a growing ecosystem of practice where digital twins enable measurable sustainability outcomes through integrated data, informed design, and adaptive management.

East Side Coastal Resiliency (ESCR) Project.	27
Ithaca NY Urban-Scale DT for Decarbonization	29
Bank Monument Station Upgrade/London Underground	31
Virtual Singapore, National-Scale Digital Twin	33
Fujian Yongfu Offshore Wind Farm Foundation	35
SABESP Integra 4.0 São Paulo	37
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Georgia DOT Statewide Roadway Data Extraction	43
Robert Street Bridge Rehabilitation	45

CASE EXAMPLE

East Side Coastal Resiliency (ESCR) Project

Envision Gold
2022

The East Side Coastal Resiliency (ESCR) Project in New York, NY, is one of the largest urban climate adaptation initiatives in the US, protecting approximately 110,000 residents, including 28,000 residents in NYC Housing Authority managed housing, along 2.4 miles of Manhattan's East River shoreline from storm surge and sea level rise. The project integrates flood protection into public open spaces, such as raised parks, floodwalls, berms, and a series of movable flood gates, while preserving community access to the waterfront. Digital twin tools are used to simulate storm surge and inundation scenarios, evaluate design alternatives, and forecast performance under future climate conditions.

Primary DT Use Case



Simulation & Forecasting is the primary use case for replicating storm surge, sea level rise, and flood inundation dynamics in the ESCR corridor.

The workflow enabled testing of multiple flood protection scenarios (adjusting elevation levels, flood barrier configurations, and park redesign) to forecast how different interventions perform under future storm events and rising water levels. The modeling results support decision making on which infrastructure options deliver the highest resilience and value under various climate risk pathways. The simulation framework supports iterative scenario testing to optimize gate size, elevation thresholds, and deployment timing. It allows planners to visualize inundation extents, test performance across future climate pathways, and quantify cost-benefit and risk-reduction metrics.

One key outcome was the design of 18 movable flood gates, including the first installed in 2022, measuring 42 feet long, 10 feet high, and weighing 32,000 pounds. These gates can be deployed in under three minutes, sealing vulnerable access points while remaining integrated with raised parkland and public walkways. The system's adaptive elevation design allows for future height adjustments as sea level projections evolve.





















Beneficial Sustainability Outcomes



- Enables evaluation of multiple resilience scenarios to determine the most effective protective configuration
- Supports design optimization of movable flood gates, berms, and raised parkland for adaptive performance
- Improves decision making through evidence-based forecasting of flood hazards
- Enhances community engagement by integrating protection with accessible public spaces
- Maintains rapid response capability with deployable flood gates designed for three minute activation
- Provides support for long-term adaptation planning by modeling sea level rise, storm surge, and asset life-cycle impacts

CASE EXAMPLE: EAST SIDE COASTAL RESILIENCY (ESCR) PROJECT

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Simulation & Forecasting <i>(Primary)</i> 	<ul style="list-style-type: none"> Storm surge and inundation modeling under sea level rise scenarios 	<ul style="list-style-type: none"> Improved predictive hazard forecasting Better climate adaptive design for resilient infrastructure 	<ul style="list-style-type: none">  Wellbeing  Planning  Resilience
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> 3D visualization of inundation scenarios and infrastructure responses 	<ul style="list-style-type: none"> Improved stakeholder engagement Enhanced transparency and public trust of resilience options 	<ul style="list-style-type: none">  Wellbeing  Community  Collaboration  Planning
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Integration of hydrodynamic, climatic, and infrastructure datasets Unified flood data, climate projections, asset models 	<ul style="list-style-type: none"> Enhanced governance Streamlined interagency coordination Data coherence across planning teams Shared data ecosystem for resilience planning 	<ul style="list-style-type: none">  Collaboration  Planning
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Data archives of simulations, performance tracking 	<ul style="list-style-type: none"> Informed lifecycle asset management Knowledge base for future iterations 	<ul style="list-style-type: none">  Collaboration  Planning  Resilience
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> Testing design configurations for resilience, cost, and community value 	<ul style="list-style-type: none"> Cost-effective climate adaptation Prioritized resilience investments 	<ul style="list-style-type: none">  Planning  Economy  Resilience



Sources:
 Bentley, <https://youtu.be/KpRfV5koEU8?si=X5TSk5oxNNDfSXXo>
 NYC, <https://www.nyc.gov/site/ddc/about/press-releases/2022/pr-080122-ESCR-ISI.page>
 NYC, <https://www.nyc.gov/site/escr/about/sustainable-design.page>
 ISI, <https://sustainableinfrastructure.org/nycddc-east-side-coastal-resiliency-project-receives-envision-gold/>

CASE EXAMPLE

Ithaca NY Urban-Scale DT for Decarbonization



Image source: Bentley Systems; Ithaca Green New Deal project shows the city's buildings color-coded from red to green, indicating different heights or heat levels. Image courtesy of ESLab, CRLab Cornell.

The City of Ithaca, New York, developed a citywide digital twin to identify where building retrofits and electrification could most effectively reduce carbon emissions while improving energy efficiency and equity. The model analyzed 5,468 buildings to evaluate the potential impacts of upgrades such as insulation, windows, solar PV, and heat pumps. The twin integrates LIDAR, photogrammetry, land-use data, tax records and utility data to model building energy performance, occupant and envelope characteristics, rooftop solar potential, and embodied carbon. The goal is to reach carbon neutrality by 2030 for the city under its Green New Deal resolution.

Primary DT Use Cases



Simulation & Forecasting and **Optimization** are the primary use cases driving the initiative to run scenario analyses for retrofits such as insulation, window upgrades, solar PV, and heat pump adoption. The system ran scenario analyses to assess cost-benefit, carbon savings, and equity implications, revealing that multi-family buildings in low income neighborhoods offered the highest carbon savings per dollar invested. Based on simulation outputs, retrofit sequencing and solar placement are spatially optimized to identify best-value interventions and target neighborhoods for investment. Together, these use cases enable the city to prioritize retrofit projects based on carbon savings per dollar and rooftop suitability, supporting a more strategic and equitable decarbonization pathway.






































Beneficial Sustainability Outcomes



- Targeted retrofits and rooftop solar siting reduce emissions and energy use
- Envelope-first strategies minimize load increases and improve efficiency
- Improves cost-efficiency and prioritization of investments
- Centralized data enhances decision making and planning
- 3D visualization improves stakeholder engagement and transparency
- Enables virtual inspections and planning
- Provides a foundation for long-term adaptation and resilience

CASE EXAMPLE: ITHACA NY URBAN-SCALE DT FOR DECARBONIZATION

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Simulation & Forecasting <i>(Primary)</i> 	<ul style="list-style-type: none"> Scenario modeling of building retrofits (envelope, PV, heat pumps), load forecasting 	<ul style="list-style-type: none"> Emissions reduction Resource efficiency Equitable benefit distribution Lower peak loads through envelope-first strategies 	<ul style="list-style-type: none">  Planning  Economy  Emissions  Resilience
Optimization <i>(Primary)</i> 	<ul style="list-style-type: none"> Prioritized interventions based on emissions saved per dollar and rooftop suitability 	<ul style="list-style-type: none"> Cost-efficient decarbonization Improved ROI Strengthened infrastructure investment planning Targeted interventions in priority neighborhoods 	<ul style="list-style-type: none">  Wellbeing  Community  Economy  Energy  Emissions
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> 3D building models Building envelope performance visualization and analysis 	<ul style="list-style-type: none"> Improved stakeholder engagement Transparency Community trust 	<ul style="list-style-type: none">  Wellbeing  Community  Collaboration  Planning  Energy
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Unified datasets (LIDAR, utility, land use, emissions) 	<ul style="list-style-type: none"> Enhanced decision making, governance Data coherence Support for evidence-based policy design 	<ul style="list-style-type: none">  Collaboration  Planning  Economy  Siting
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Central data repository for retrofit tracking 	<ul style="list-style-type: none"> Better lifecycle asset management Improved tracking of sustainability performance Programmatic reporting and accountability 	<ul style="list-style-type: none">  Planning  Economy  Energy  Emissions
Virtualization of Services <i>(Supporting)</i> 	<ul style="list-style-type: none"> Remote inspections, scenario sharing, digital engagement 	<ul style="list-style-type: none"> Reduced field burdens Improved access Broader stakeholder participation 	<ul style="list-style-type: none">  Wellbeing  Community  Collaboration  Planning
Monitoring & Tracking <i>(Emerging)</i> 	<ul style="list-style-type: none"> Future continuous performance data integration (e.g., smart meters, IoT) 	<ul style="list-style-type: none"> Ongoing performance verification Adaptive management Living digital twin 	<ul style="list-style-type: none">  Planning  Energy  Emissions  Resilience

Sources:

Bentley, Ithaca's Digital Beating Heart, <https://blog.bentley.com/insights/smart-heat-digital-twin-and-cornell-researchers-help-ithaca-stay-warm-while-moving-toward-carbon-neutrality/>

Jingyi Tang, Hung Ming Tseng (Cornell Environmental Systems Lab), Timur Dogan (Cornell Environmental Systems Lab), Stephen Abbott (2024). How "Digital Twins" Are Enabling City-Wide Electrification, RMI, <https://rmi.org/how-digital-twins-are-enabling-city-wide-electrification/>

CASE EXAMPLE

Bank Monument Station Upgrade/London Underground



Image source: <https://www.railexpress.com.au/3d-modelling-used-to-simulate-re/design-of-bank-monument-station/>

The Bank Monument Station complex, located in the City of London and served by five Underground lines plus the DLR, handles more than 52 million passenger entries each year, making it one of the busiest subterranean interchange hubs in the world. The upgrade project aims to improve passenger access, circulation, interchange capacity, reduce congestion, enable step-free access, and future proof the station until 2081.

Primary DT Use Case



The project's primary use case is **Visualization & Prototyping**, applying advanced modeling and pedestrian simulation tools to test and validate design improvements under realistic operational conditions. The simulations visualized passenger movement throughout the expanded station, allowing designers to assess how proposed changes to platforms, tunnels, escalators, and entrances would affect crowding, circulation, and accessibility. By virtually modeling both construction phase impacts and long-term commuter patterns, the team was able to refine layouts and construction phasing before implementation. This approach provided evidence-based insights that informed design adjustments and stakeholder engagement. The upgrade is expected to increase passenger capacity by 45% during peak hours and reduce average journey time delays by over three minutes in the morning rush.


























Beneficial Sustainability Outcomes



- Improved crowd management and commuter safety by validating design virtually
- Reduced journey times and improved station capacity via data-driven modeling
- Enhanced accessibility (e.g., new elevators, step-free access) and improved interchange flows
- Early design validation minimized risk of undercapacity and construction rework
- Operational CO2 emissions estimated to be cut by 23% through more energy-efficient measures
- Helps future-proof infrastructure by simulating long-term demand and capacity until 2081

CASE EXAMPLE: BANK MONUMENT STATION UPGRADE

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Visualization & Prototyping <i>(Primary)</i> 	<ul style="list-style-type: none"> Simulation of pedestrian flows, 3D visualization of circulation and design alternatives 	<ul style="list-style-type: none"> Better circulation design quality Reduced congestion risk Improved crowd management and commuter safety Enhanced accessibility (step-free access, elevators) Improved user experience and comfort 	<ul style="list-style-type: none">  Wellbeing  Mobility  Planning  Resilience
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Integration of simulation outputs with BIM and CAD design tools and station asset data 	<ul style="list-style-type: none"> Improved design coordination Reduced errors and rework Faster decision making across teams Data-driven design decisions 	<ul style="list-style-type: none">  Collaboration  Planning  Economy
Simulation & Forecasting <i>(Primary)</i> 	<ul style="list-style-type: none"> Scenario modelling of passenger demand, peak loads, and congestion under different design options 	<ul style="list-style-type: none"> Anticipated and validated future capacity needs Data-driven investment planning Improved operational resilience Risk mitigation for future operations 	<ul style="list-style-type: none">  Planning  Economy  Energy  Resilience
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Documentation of simulation results, design versions and performance metrics 	<ul style="list-style-type: none"> Improved documentation Traceability of design decisions Better quality assurance 	<ul style="list-style-type: none">  Wellbeing  Planning  Economy
Optimization <i>(Supporting)</i> 	<ul style="list-style-type: none"> Use of simulation results to optimize layout, way-finding, and passenger routing 	<ul style="list-style-type: none"> Cost efficient station improvement and design solutions Enhanced commuter experience Reduced lifecycle impacts 	<ul style="list-style-type: none">  Wellbeing  Planning  Economy  Materials  Energy  Emissions

Source:

Bentley, <https://www.bentley.com/wp-content/uploads/CS-LEGION-Bank-Station-Capacity-Upgrade-LTR-EN-LR.pdf>

CASE EXAMPLE

Virtual Singapore, National-Scale Digital Twin

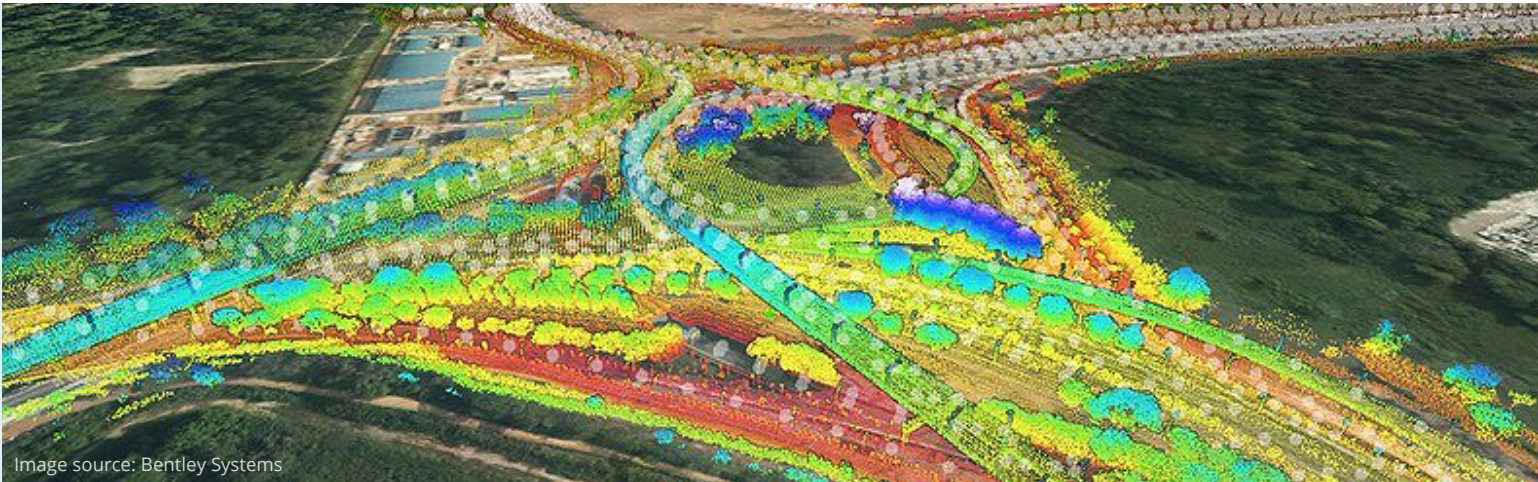


Image source: Bentley Systems

Singapore has developed a national-scale digital twin that supports multiple government sectors including transport (road and rail), water, land use and telecommunication infrastructure. The system brings together high-resolution geospatial mapping, aerial LiDAR, street mounted scanning and sensor networks to create a detailed 3D and real-time model of the city-state. Multiple agencies share data on a unified platform, enabling cross-domain collaboration, scenario modelling and operational decision making across infrastructure types.

Primary DT Use Case



Virtual Singapore is a model example of **Integration & Interoperability**, demonstrating how a national-scale digital twin can unify data, models, and analytics across sectors. Built on a federated geospatial platform, the system integrates datasets from transportation networks, water infrastructure, land use planning, telecommunications, and utilities, linking over 100 government and research institutions. The platform connects real-time sensor feeds, 3D mapping data, and simulation models into a common digital environment that serves as a single source of truth for the city-state's physical assets.

This integrated architecture enables government agencies to analyze interdependencies across sectors, such as how road construction affects underground utilities, or how coastal flooding could disrupt transport and energy systems. The digital twin facilitates live data exchanges between agencies, breaking down silos and improving collaborative decision making. It supports diverse applications, from urban heat analysis and traffic optimization to disaster preparedness, through interoperable APIs and standardized 3D data models.

The digital twin promotes data coherence, efficiency, and coordinated governance, making Singapore's infrastructure management both anticipatory and adaptive.






Beneficial Sustainability Outcomes



- Enables cross-agency collaboration by unifying data from transport, water, land use and utilities systems
- Accelerates decision making by providing a single source of truth for infrastructure assets and scenarios
- Supports multi-domain scenario modelling (e.g., flood simulation + telecommunications resilience + traffic flows) in one environment
- Reduces data duplication and administrative overhead through interoperable architecture
- Enhances resilience and sustainability planning via integrated modelling of climate, infrastructure and land use risks

CASE EXAMPLE: VIRTUAL SINGAPORE

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Integration & Interoperability <i>(Primary)</i> 	<ul style="list-style-type: none"> Integration of multi-sectoral datasets (transport, land use, water, telecommunications, utilities) into a unified digital twin environment Interoperability between 3D GIS, IoT sensor data, and simulation models across agencies 	<ul style="list-style-type: none"> Improved cross-agency collaboration and data sharing Reduced duplication of datasets Faster and more coordinated policy and infrastructure decisions 	<ul style="list-style-type: none"> Wellbeing Mobility Community Collaboration Planning Economy
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> 3D city model, scenario visualization for transport/land use, interactive tools for public consultation and planning review 	<ul style="list-style-type: none"> Greater transparency and stakeholder engagement Better visualization of complex planning tradeoffs Enhanced accessibility of information for citizens and policymakers 	<ul style="list-style-type: none"> Mobility Community Collaboration Planning
Simulation & Forecasting <i>(Supporting)</i> 	<ul style="list-style-type: none"> Scenario modeling of urban systems including transport congestion, flood resilience, and energy demand Integration of predictive analytics to assess policy and infrastructure options 	<ul style="list-style-type: none"> Data-driven planning for future growth and climate adaptation Early identification of infrastructure vulnerabilities Stronger resilience and sustainability planning 	<ul style="list-style-type: none"> Wellbeing Planning Economy Materials Energy Water Emissions Resilience
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Centralized storage of infrastructure records, models, and geospatial assets within a shared digital platform Version control for asset updates 	<ul style="list-style-type: none"> Streamlined lifecycle asset management Improved traceability of planning and design decisions Consistent baseline for interagency coordination 	<ul style="list-style-type: none"> Community Collaboration Planning Economy
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> Use of integrated datasets to optimize infrastructure investment, public service delivery, and maintenance scheduling across multiple sectors 	<ul style="list-style-type: none"> Increased efficiency of infrastructure spending Reduced resource and energy use through optimized operations Long-term cost savings and performance improvements 	<ul style="list-style-type: none"> Collaboration Planning Economy Materials Energy Siting Emissions

Sources:

Infrastructure Global, <https://infra.global/singapores-digital-twin-from-science-fiction-to-hi-tech-reality/>

WGI Council, <https://wgicouncil.org/digital-twinning-a-country-singapore>

www.bentley.com/wp-content/uploads/cs-singapore-land-authority-ltr-en-lr.pdf

CASE EXAMPLE

Fujian Yongfu Offshore Wind Farm Foundation



Image source: Bentley Systems; Fujian Yongfu Power Engineering needed to build a large wind farm in an area prone to typhoons, earthquakes, and shifting soil.

Fujian Yongfu Power Engineering developed a large offshore wind farm in China's Fujian Province using advanced geotechnical and structural modelling tools. Through synchronized soil analysis and digital modelling, the engineering team evaluated multiple foundation configurations under real-world ocean and soil conditions. The digital twin allowed designers to test structural stability, installation feasibility, and environmental implications before construction. The optimal solution is a three-pile suction conduit frame foundation, which reduced costs by approximately 30 percent and helped preserve water quality, limit erosion, and protect marine and bird habitats.

Primary DT Use Case



Visualization & Prototyping is the main use case in this project. Engineers developed a detailed 3D digital twin of seabed and structural interactions using soil-structure modelling and hydrodynamic analysis. The twin synchronized geotechnical and structural parameters to simulate pile behavior, load transfer, and stability across different foundation types. These visual simulations enabled engineers to compare alternatives, refine installation methods, and anticipate potential failure modes before deployment. This virtual prototyping process significantly reduced the number of physical tests required and allowed environmentally sensitive planning in alignment with coastal protection standards.
















Beneficial Sustainability Outcomes



- About 30% cost reduction compared with conventional wind turbine foundations
- Improved soil-structure understanding reduced design uncertainty
- Lower embodied materials and reduced seabed disturbance during installation
- Minimized erosion and turbidity, protecting marine and avian ecosystems
- Strengthened lifecycle reliability through digital design validation
- Supported China's renewable-energy and decarbonization targets

CASE EXAMPLE: OFFSHORE WIND FARM

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Visualization & Prototyping <i>(Primary)</i> 	<ul style="list-style-type: none"> • 3D digital twin of seabed and structure • Synchronized soil-structure modelling • Virtual testing of alternative foundation geometries under realistic hydrodynamic loads 	<ul style="list-style-type: none"> • Optimized foundation type and configuration • Reduced need for physical modelling • Lower environmental footprint • Improved long-term structural performance • Enabled stakeholder visualization of design rationale 	<ul style="list-style-type: none">  Collaboration  Planning  Materials  Siting  Conservation  Emissions
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> • Integration of soil data, hydrodynamic simulations, and structural modelling through interoperable file formats and data exchange between design platforms 	<ul style="list-style-type: none"> • Streamlined multidisciplinary collaboration • Faster iteration between geotechnical and structural teams • Reduced modelling errors • Ensured consistency between analysis domains 	<ul style="list-style-type: none">  Collaboration  Planning  Materials
Simulation & Forecasting <i>(Supporting)</i> 	<ul style="list-style-type: none"> • Dynamic simulations of wave, current, and load impacts over time • Stress-strain forecasting for foundation behavior under extreme events 	<ul style="list-style-type: none"> • Improved predictive capacity for performance • Validated resilience under future storm conditions • Enhanced design safety factors • Informed adaptive maintenance planning 	<ul style="list-style-type: none">  Wellbeing  Planning  Energy  Conservation  Ecology  Resilience
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> • Centralized digital record of geotechnical investigations, model iterations, and testing results integrated into lifecycle documentation 	<ul style="list-style-type: none"> • Strengthened design traceability • Improved data reuse for future offshore projects • Reduced documentation redundancy • Enabled regulatory compliance reporting 	<ul style="list-style-type: none">  Collaboration  Planning  Economy  Resilience
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> • Use of simulation insights to optimize pile spacing, geometry, and installation methods for material and energy efficiency 	<ul style="list-style-type: none"> • Further material savings • Lower embodied carbon • Reduced construction risk and downtime • Faster installation in challenging marine environments 	<ul style="list-style-type: none">  Wellbeing  Planning  Economy  Materials  Siting  Conservation  Ecology  Emissions  Resilience

CASE EXAMPLE

SABESP Integra 4.0 São Paulo, Brazil



Image source: Bentley Systems

The Companhia de Saneamento Básico do Estado de São Paulo (SABESP), serving 375 municipalities across the state of São Paulo, a population of 28 million people for drinking water and 25 million for wastewater treatment. SABESP launched the Integra 4.0 initiative to modernize its water and wastewater operations using digital twin technology in order to meet growing service demands, environmental pressures, and regulatory expectations. Integra 4.0 brings together multiple operational layers into a cohesive platform.

Primary DT Use Case



Monitoring & Tracking is the primary use case of Integra 4.0 supporting the continuous real-time monitoring and governance of water and sewage operations housed in the Collection Operation Center (COC), which supports rapid detection of anomalies, early diagnosis of failures, proactive maintenance planning, and operational decision making. The system uses 90 maintenance-hole-level sensors that transmit signals every five minutes, allowing SABESP to monitor flow and overflow conditions across 110 kilometers of sewer network. This monitoring framework directly reduced sewer overflows and improved system reliability, while also enabling targeted maintenance actions that cut operational emissions.

In addition, simulation, visualization, optimization, and integration act as reinforcing pathways. The use of the DT use cases enabled operational excellence, sustainability gains, and measurable improvements across service delivery, environmental outcomes, and resilience.


























Beneficial Sustainability Outcomes

- 30% reduction in sewer overflows and backflows
- BRL 3.1 million saved in corrective maintenance in seven months
- 2,800 hours saved in fieldwork
- Improved pressure stability and service reliability
- More effective targeting of infrastructure investments

CASE EXAMPLE: SABESP INTEGRA 4.0 SÃO PAULO, BRAZIL

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Monitoring & Tracking <i>(Primary)</i> 	<ul style="list-style-type: none"> Sensor network Collection Operation Center Real-time alerts 	<ul style="list-style-type: none"> 30% overflow reduction Improved reliability, CO₂ reduction, governance structure 	<ul style="list-style-type: none">  Water  Emissions  Resilience
Simulation & Forecasting <i>(Supporting)</i> 	<ul style="list-style-type: none"> Hydraulic modeling Scenario testing for future development 	<ul style="list-style-type: none"> Reduced errors Targeted investments Adaptive capacity 	<ul style="list-style-type: none">  Planning  Economy  Resilience
Optimization <i>(Supporting)</i> 	<ul style="list-style-type: none"> Pressure optimization Loss reduction 	<ul style="list-style-type: none"> 29% reduction in apparent losses Water savings CO₂ reduction 	<ul style="list-style-type: none">  Economy  Water  Emissions
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Power BI dashboards Bentley interfaces 	<ul style="list-style-type: none"> Better communication Internal team collaboration Faster situational awareness 	<ul style="list-style-type: none">  Collaboration  Planning
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Big data platform, GIS + commercial + operational integration 	<ul style="list-style-type: none"> Unified data environment Helped overcome software limitations Faster decision cycles 	<ul style="list-style-type: none">  Collaboration  Planning  Water
Virtualization of Services <i>(Supporting)</i> 	<ul style="list-style-type: none"> Remote monitoring Digital coordination and governance 	<ul style="list-style-type: none"> Less fieldwork Faster response More efficient operations 	<ul style="list-style-type: none">  Wellbeing  Planning  Water

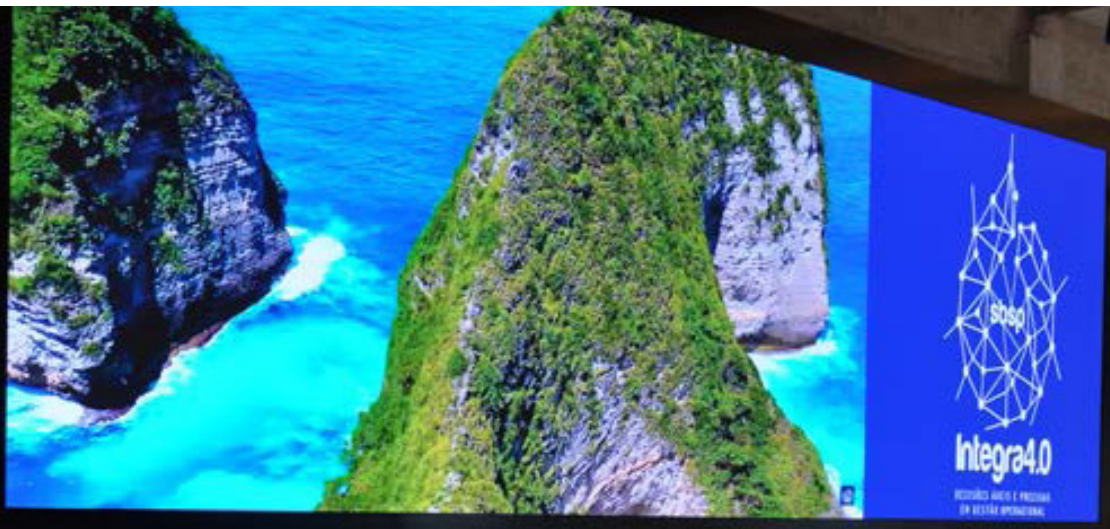


Image source: Bentley Systems

CASE EXAMPLE

Hawaii DOT Automated Highway Inspection

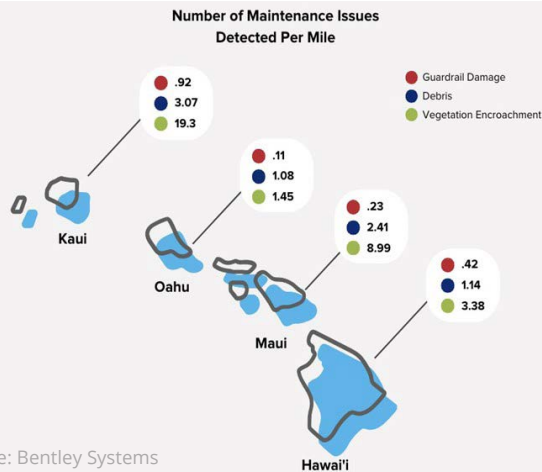


Image source: Bentley Systems

The Hawaii Department of Transportation (HDOT) manages over 1,000 miles of roadways across diverse geographic and climatic conditions. Historically, road maintenance relied on labor-intensive, manual surveys. In 2022, HDOT deployed Blynscy by Bentley, a digital platform that integrates crowdsourced dashcam imagery and machine learning to automate roadway inspection, detect maintenance issues, and store condition data in centralized digital repositories.

This deployment represents a major shift from manual reporting and dispersed data to a digital twin-enabled system that enables faster, more accurate, and more cost-effective infrastructure management.



Primary DT Use Cases

Monitoring & Tracking and **Management & Record-Keeping** are primary use cases that function together for the HDOT Automated Highway Inspection. The core of the system is a centralized, digital inspection and record keeping process. Imagery from dashcams is automatically collected and analyzed with machine learning models to detect striping, guardrail damage, debris, and cracking, and integrated into HDOT's Web Map Service and Web Feature Service platforms.

This allows inspection records to be stored, shared, and acted upon across departments, replacing fragmented spreadsheets, duplicate worker reports, and manual logs.








Beneficial Sustainability Outcomes



- USD \$940,000 per year in operational savings
- 95% reduction in manual survey requirements
- 23,286 lbs of CO₂ saved annually per work vehicle
- Elimination of duplicate reporting and improved data reliability
- 930 issues detected weekly on average
- Verification of work completed in correct locations

CASE EXAMPLE: HAWAII DOT AUTOMATED HIGHWAY INSPECTION

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Management & Record-Keeping <i>(Primary)</i> 	<ul style="list-style-type: none"> Centralized digital inspections, Web Map Service (WMS) and Web Feature Service (WFS) integration eliminates duplicate worker and driver reports 	<ul style="list-style-type: none"> Lower operational costs Reduced paperwork and administrative burden Reduced emissions from fewer field trips Improved governance Efficient resource allocation Consistent reporting 	<ul style="list-style-type: none"> Mobility Planning Economy Emissions
Monitoring & Tracking <i>(Primary)</i> 	<ul style="list-style-type: none"> Continuous automated collection of roadway condition data from crowdsourced dashcam imagery, and machine vision detection of striping, cracking, guardrail damage, debris, vegetation encroachment PASER (Pavement Surface Evaluation and Rating System) integration 	<ul style="list-style-type: none"> Early hazard detection Safer roadways Real-time visibility of roadway conditions Reduction of manual survey requirements 	<ul style="list-style-type: none"> Wellbeing Mobility Resilience
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Geospatial visualization dashboards Spatial distribution of identified issues 	<ul style="list-style-type: none"> Faster resource allocation, Improved decision making, Better planning Improved transparency 	<ul style="list-style-type: none"> Collaboration Planning
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Linking imagery, machine learning (ML), PASER (Pavement Surface Evaluation and Rating System) scoring, GIS, WMS/WFS 	<ul style="list-style-type: none"> Enhanced governance and coordination, Reduced duplication, Faster decision cycles 	<ul style="list-style-type: none"> Collaboration Planning Economy
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> Prioritization algorithms based on monitoring insights, like issue detection frequency and location 	<ul style="list-style-type: none"> Reduction of operational costs Better asset management Improved efficiency 	<ul style="list-style-type: none"> Wellbeing Economy Energy Emissions
Virtualization of Services 	<ul style="list-style-type: none"> Remote inspections, digital access to roadway data 	<ul style="list-style-type: none"> Lower emissions, improved safety Efficient workflows 	<ul style="list-style-type: none"> Collaboration Planning Emissions
Simulation & Forecasting <i>(Potential)</i> 	<ul style="list-style-type: none"> Predictive modeling potential on accumulated imagery and PASER scoring 	<ul style="list-style-type: none"> Long-term planning Anticipatory proactive maintenance Lifecycle cost reduction 	<ul style="list-style-type: none"> Planning Economy Emissions Resilience

Source: Blyncsy, Hawaii DOT switched to Blyncsy to automate roadway condition assessment and damage detection, <https://blyncsy.com/active-projects/hawaii-department-of-transportation/>

CASE EXAMPLE

Perry Green & Grey Infrastructure Digital Twin

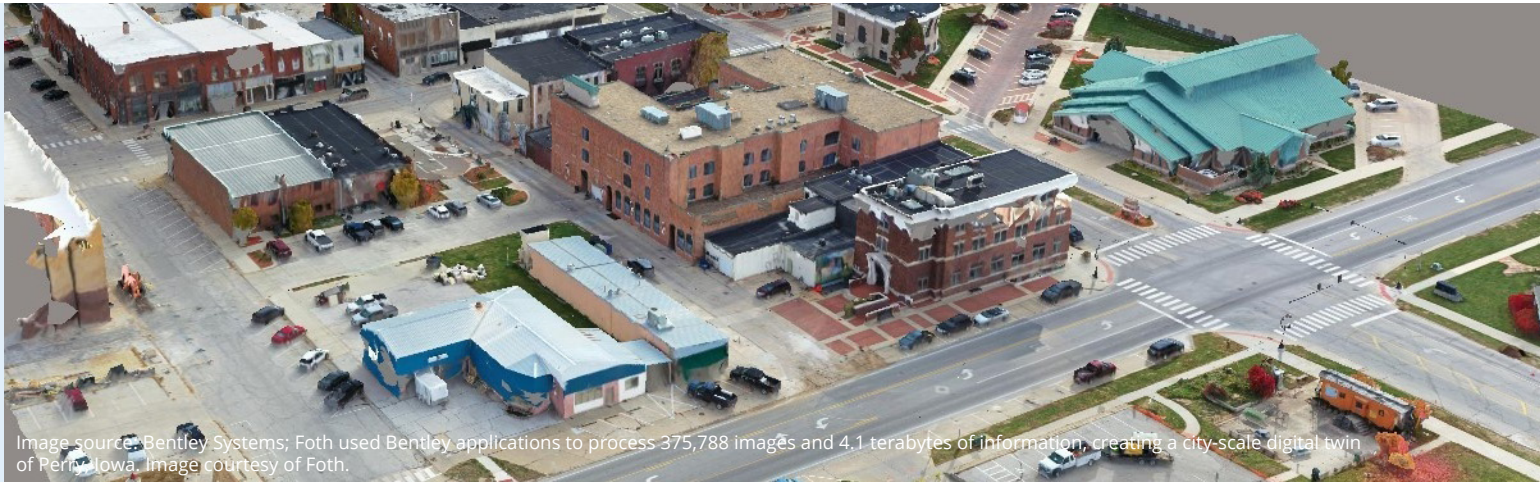


Image source: Bentley Systems; Foth used Bentley applications to process 375,788 images and 4.1 terabytes of information, creating a city-scale digital twin of Perry, Iowa. Image courtesy of Foth.

The city of Perry, Iowa, (population ~8,000) implemented a city-scale digital twin to better manage both its grey infrastructure (roads, sidewalks, curbs) and green infrastructure (trees, natural spaces, non-native species mitigation). This digital twin was built using mobile LiDAR and photogrammetry, producing over 4.1 terabytes of data and a detailed 3D reality mesh of the entire town. The project utilized tools to capture, process and store the city's asset and environmental infrastructure data. The twin now allows the city to integrate disparate asset datasets, inspect historic buildings, plan tree canopy and natural-space restoration, and respond more effectively to infrastructure and environmental challenges.

Primary DT Use Case



In this project the key use case is **Management & Record-Keeping**. Perry's digital twin functions as a centralized infrastructure and environment repository, consolidating data on sidewalks, ramps, curbs, street assets, buildings, trees, and natural spaces. The workflow begins with city-wide LiDAR capture of streets and landscapes, the processing of hundreds of thousands of images into a reality mesh, and the assimilation of these data into MicroStation/OpenRoads and ProjectWise environments. This digital foundation enables the city to query, monitor and manage both built and natural assets, from ADA compliance of sidewalks to mapping tree species for green space restoration. The twin supports auditability, lifecycle tracking, and the planning of future infrastructure and ecological initiatives. By housing all asset information in one place, Perry has enabled new projects (such as tree canopy expansion and invasive species mitigation) that are data informed and more efficient.








Beneficial Sustainability Outcomes

- Consolidates city-wide asset data into a single digital repository, increasing operational transparency and efficiency
- Enables environmental and green space initiatives (tree mapping, non-native species mitigation) using detailed asset and landscape data
- Supports ADA compliance efforts and historic building preservation by providing accurate baseline models of sidewalks, ramps and buildings
- Reduces future field survey efforts by providing a high-resolution digital baseline of built and natural infrastructure
- Enhances disaster response preparedness by enabling rapid assessment of damage (e.g., trees, buildings) using the digital twin as the reference model
- Strengthens the framework for "smart city" services, such as autonomous vehicle routing, emergency response planning and sustainable infrastructure investment

CASE EXAMPLE: PERRY GREEN & GREY INFRASTRUCTURE DIGITAL TWIN

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Management & Record-Keeping <i>(Primary)</i> 	<ul style="list-style-type: none"> City-wide digital twin repository of assets and environment Querying and lifecycle tracking of trees, sidewalks, ramps and buildings 	<ul style="list-style-type: none"> Reliable asset inventory Data-driven infrastructure/green space planning Reduced survey costs 	<ul style="list-style-type: none"> Collaboration Planning Materials Conservation Ecology Emissions
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Integration of LiDAR/ photogrammetry data, CAD/BIM assets, landscape features and infrastructure system 	<ul style="list-style-type: none"> Unified dataset across disciplines Streamlined data workflows and decision making 	<ul style="list-style-type: none"> Collaboration Planning Materials
Monitoring & Tracking <i>(Supporting)</i> 	<ul style="list-style-type: none"> Use of the digital twin to monitor condition of trees, natural spaces, sidewalks, curbs and ramps over time 	<ul style="list-style-type: none"> Early detection of natural asset degradation Improved maintenance planning 	<ul style="list-style-type: none"> Planning Conservation Ecology
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> 3D reality mesh and models used to visualize green space restoration, tree canopy planning and infrastructure design 	<ul style="list-style-type: none"> Better stakeholder engagement More intuitive planning for environment and infrastructure 	<ul style="list-style-type: none"> Collaboration Planning Conservation Ecology
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> Use of the twin's data to optimize tree species planting, infrastructure updates, and maintenance schedules 	<ul style="list-style-type: none"> More efficient use of resources Better alignment of environment/ infrastructure objectives 	<ul style="list-style-type: none"> Planning Economy Materials Conservation Ecology

Sources:

Bentley, <https://www.bentley.com/wp-content/uploads/esdg-yiii-showcase-city-of-perry.pdf>

<https://triplepundit.com/2024/digital-twins-tree-mapping/>

CASE EXAMPLE

Georgia DOT Statewide Roadway Data Extraction

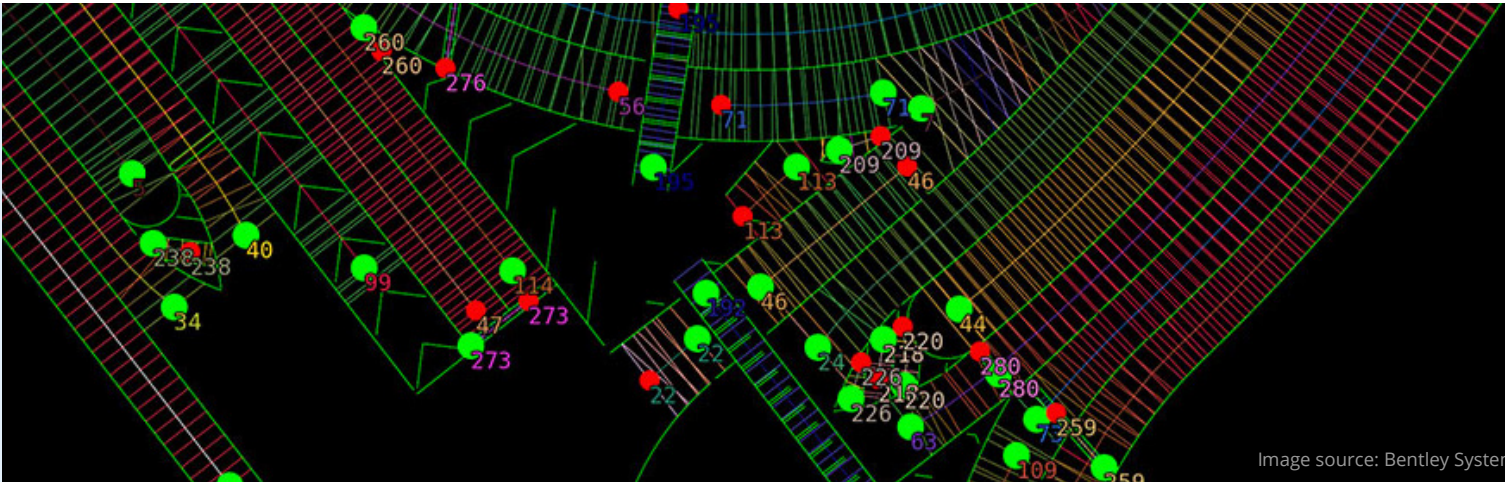


Image source: Bentley Systems

The Georgia DOT launched a large-scale digital twin initiative to analyze over 80,000 miles of roadway for latent ('dark') asset data such as lane widths, traffic signal locations and infrastructure geometry. The system ingested legacy CAD drawings, GIS layers and construction records, then applied AI-driven feature detection to extract structured asset attributes from unstructured sources.

Primary DT Use Case



This project exemplifies a **Management & Record-Keeping** use case. Georgia DOT created a digital twin of its roadway network that serves as a live repository of asset data, design history, and extracted geometry. Through generative-AI and feature-recognition workflows, the twin converts previously inaccessible "dark or hidden data" into usable structured information that supports planning, maintenance, and budgeting. The system allows engineers to query lanes, signals and pavement widths statewide, enabling data-driven decisions and operational oversight on a scale rarely achieved in highway infrastructure.

























Beneficial Sustainability Outcomes



- Structural and geometric data for more than 80,000 miles of roads converted from legacy drawings to live asset records
- Enhanced planning and maintenance prioritization through rich, "dark or hidden data"
- Reduced manual data collection burden and improved data accuracy
- Improved alignment of infrastructure investment with actual asset conditions
- Enabled scalable statewide oversight rather than piecemeal local analyses

CASE EXAMPLE: GEORGIA DOT STATEWIDE ROADWAY DATA EXTRACTION

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Management & Record-Keeping <i>(Primary)</i> 	<ul style="list-style-type: none"> Creation and consolidation of a structured, query-able database of statewide roadway assets through the application of generative AI to extract geometric and attribute data (e.g., lane width, signals, signage, pavement type) from legacy CAD, PDF, and GIS sources 	<ul style="list-style-type: none"> Comprehensive digital inventory of 80,000 miles of roadway assets and attributes Recovery of previously inaccessible “dark or hidden data” for statewide planning Reduced manual surveying and data entry costs Improved data governance and decision support for maintenance, design, and budgeting 	<ul style="list-style-type: none">  Mobility  Collaboration  Planning  Economy
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Linking CAD, GIS, and AI-derived data into a unified twin platform for continuous data ingestion and model updates 	<ul style="list-style-type: none"> Seamless data exchange between departments and contractors Streamlined workflows across asset management, planning, and operations Reduced redundancy and human error in multi-system data handling 	<ul style="list-style-type: none">  Collaboration  Planning  Economy
Monitoring & Tracking <i>(Supporting)</i> 	<ul style="list-style-type: none"> Continuous synchronization of updated roadway and asset geometry Near-real-time refresh of network datasets 	<ul style="list-style-type: none"> Improved data accuracy across the state Early detection of asset condition issues or geometric inconsistencies Stronger basis for performance tracking and compliance reporting 	<ul style="list-style-type: none">  Mobility  Planning  Economy
Visualization & Prototyping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Virtual dashboards summarizing network-wide asset attributes and AI detection confidence levels across Georgia’s 80,000-mile system 	<ul style="list-style-type: none"> Improved transparency and awareness for decision makers 	<ul style="list-style-type: none">  Mobility  Collaboration  Planning
Optimization <i>(Emerging)</i> 	<ul style="list-style-type: none"> Use of extracted data to optimize maintenance scheduling, investment prioritization, and asset lifecycle planning. 	<ul style="list-style-type: none"> Data-driven resource allocation and predictive maintenance Reduction in lifecycle cost through smarter planning Enhanced resilience through evidence-based infrastructure decisions 	<ul style="list-style-type: none">  Planning  Economy  Materials  Energy  Siting  Emissions

Sources:

Bentley, <https://www.bentley.com/events/going-digital-awards/2023-yearbook-articles/mining-data-to-build-digital-twins/>

CASE EXAMPLE

Robert Street Bridge Rehabilitation



Image source: Bentley Systems;
View of historic Robert Street Bridge

The Robert Street Bridge, a nearly 100-year-old landmark spanning the Mississippi River in St. Paul, Minnesota, is undergoing its first major rehabilitation since 1989. To modernize inspection and planning, the Minnesota Department of Transportation (MnDOT) and Collins Engineers adopted an AI-enabled digital twin workflow that used drone imagery, reality modeling, and cloud-based collaboration tools to virtualize the inspection process. The bridge's 57,000 drone captured images were processed with Bentley's reality modeling software to create a high resolution digital twin, allowing 80% of inspection tasks to be performed virtually before field deployment.

Primary DT Use Case



The Robert Street Bridge project demonstrates how **Virtualization of Services** transforms traditional engineering workflows. The 3D digital twin enabled senior engineers to inspect, annotate, and verify bridge conditions remotely, drastically reducing time on site and improving safety.

AI-assisted image recognition identified cracks and spalls automatically, while inspectors verified conditions through virtual models accessible via tablets and shared cloud platforms.

This virtual workflow supported remote collaboration, reduced roadway closures, and enabled experienced engineers to consult from off site locations, addressing workforce shortages in the bridge inspection field.






























Beneficial Sustainability Outcomes



- 80% of inspection completed virtually before site visits
- 70% of defects identified remotely through AI-assisted reality modeling
- USD \$90,000 in savings during the inspection phase
- USD \$15 million estimated savings for MnDOT through improved contractor bidding and accuracy
- 20% reduction in materials used during construction
- Fewer traffic disruptions and improved worker safety
- Faster verification and shared accountability via cloud-based inspection data
- Enables remote expert participation and workforce capacity expansion

CASE EXAMPLE: ROBERT STREET BRIDGE REHABILITATION

Table of DT Use Cases

DT Use Case	Functions	Outcomes /Benefits	Alignment with Envision Subcategories
Virtualization of Services <i>(Primary)</i> 	<ul style="list-style-type: none"> Drone-based inspections, digital collaboration, and cloud-based annotation 	<ul style="list-style-type: none"> Reduced on site work and emissions from travel Improved worker safety and accessibility Lower operational energy footprint Faster inspection cycles Workforce efficiency 	<ul style="list-style-type: none">  Wellbeing  Planning  Economy  Energy  Emissions  Resilience
Monitoring & Tracking <i>(Supporting)</i> 	<ul style="list-style-type: none"> Automated defect detection, progress tracking through AI and image analytics 	<ul style="list-style-type: none"> Early detection of deterioration reduces repair materials and waste Continuous structural data collection Supports proactive maintenance, minimizing carbon intensive interventions 	<ul style="list-style-type: none">  Wellbeing  Collaboration  Planning  Emissions  Resilience
Management & Record-Keeping <i>(Supporting)</i> 	<ul style="list-style-type: none"> Centralized digital repository for inspection and maintenance data 	<ul style="list-style-type: none"> Improved accountability and documentation Streamlined quality assurance and compliance Long-term lifecycle tracking for sustainability performance 	<ul style="list-style-type: none">  Wellbeing  Collaboration  Planning  Materials
Integration & Interoperability <i>(Supporting)</i> 	<ul style="list-style-type: none"> Shared access among MnDOT, design, and construction teams linking drone data, AI outputs, and design models for decision making 	<ul style="list-style-type: none"> Avoids redundant inspections and data duplication Seamless data handoff across teams Enhances governance and data-driven coordination 	<ul style="list-style-type: none">  Collaboration  Planning  Economy
Optimization <i>(Supporting)</i> 	<ul style="list-style-type: none"> Use of AI insights and modeling to plan rehabilitation sequencing and material use 	<ul style="list-style-type: none"> 20% reduction in materials used during construction Lower embodied carbon footprint Cost and resource efficiency 	<ul style="list-style-type: none">  Wellbeing  Planning  Economy  Materials  Energy  Emissions

Sources:

Bentley, <https://www.bentley.com/wp-content/uploads/2023-year-in-infrastructure-human-interest-collins-engineers-final.pdf>
<https://www.bentley.com/wp-content/uploads/CS-AEGEA-Manaus-LTR-EN-LR.pdf>



The Institute for Sustainable Infrastructure is an education and research nonprofit (a 501c3) based in Washington DC. It was established in 2010 by the American Public Works Association (APWA), the American Society of Civil Engineers (ASCE), and the American Council of Engineering Companies (ACEC). Responding to the need for a comprehensive sustainability framework and rating system suitable for use in civil infrastructure development, ISI collaborated with the then Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design to develop Envision.

Envision is a holistic sustainability framework and rating system that guides and assesses the sustainability and resilience of all types of infrastructure. It is a comprehensive tool created to assist agencies, municipalities, consultants, contractors, and operators, in planning, designing, and delivering more sustainable infrastructure projects. The Envision framework is a decision-making tool that allows project teams to evaluate projects across a broad range of sustainability indicators, or “credits,” that address environmental, social, and economic dimensions of sustainability to encourage systemic change. At its core, Envision is about supporting higher performance through better choices in infrastructure development.



The Zofnass Research Program conducts research that examines sustainable infrastructure topics and supports development and use of the Envision Sustainable Infrastructure Framework. The program was originally developed in 2007 at the Harvard University Graduate School of Design, where it was called the Zofnass Program for Sustainable Infrastructure, named after its benefactors Paul and Joan Zofnass.

After its founding in 2010, ISI worked closely with the Zofnass program to integrate the best of industry experience with cutting-edge academic research to develop and release Envision in 2012. This achievement responded directly to the need for a comprehensive sustainability framework and rating system suitable for use in civil infrastructure development. In 2022, the program moved from Harvard to ISI, where it is now called the Zofnass Research Program, so that it could more readily engage with the private sector and evolve to serve the diverse needs of the AEC industry.

SUSTAINABLE INFRASTRUCTURE ADVISORY BOARD

The Sustainable Infrastructure Advisory Board (SIAB) is a dedicated group of AEC firms that support the Zofnass Research Program. Their financial assistance, expert feedback, and guidance are integral to the development, promotion, and continued improvement of the Envision framework. Representatives from these firms, which are involved in the planning, designing, and engineering of infrastructure projects, engage with researchers to provide guidance and insight from the infrastructure industry. We are grateful for the SIAB’s commitment to sustainable infrastructure and ongoing advocacy of Envision.

The SIAB plays a vital role in shaping the future of sustainable infrastructure by providing strategic input, financial support, and thought leadership. In an era where public discourse centers on combatting climate change, meeting sustainability and resiliency goals is paramount for governments, corporations, and AEC firms alike. As a member, you will be at the forefront of innovative research and developments in sustainable infrastructure, enabling your organization to lead in this critical field.

For more information, visit sustainableinfrastructure.org/