DIGITAL TWINS FOR COOPERATION:

Living Labs Empowering Euro - Mediterranean Integration

Research notes **2**

DIGITAL TWINS FOR COOPERATION AND TRANSFORMATION:

Living Labs Empowering Euro - Mediterranean Integration

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Executive Summary

This Research Note explores the emerging role of Digital Twins (DTs) not only as tools for modelling and monitoring physical systems, but as strategic enablers of cooperation, experimentation and sustainable development across the Euro-Mediterranean space.

Far beyond their technical origin in engineering and control systems, Digital Twins are increasingly becoming living interfaces—bridging the physical and digital worlds to support dialogue between actors, integration of knowledge, and collective decision-making. When deployed within Living Labs, they allow stakeholders—researchers, citizens, institutions, and enterprises—to co-design, simulate, and iterate complex systems in real conditions.

By embedding Digital Twins into place-based innovation environments, we unlock their full potential as instruments for:

- territorial development and resilience,
- data-driven policymaking,
- transdisciplinary learning,
- and cross-border cooperation.

In the fragmented and uneven context of the Euro-Mediterranean region, Living Labs powered by Digital Twins offer a neutral and open ground where shared challenges (such as climate adaptation, food security, energy transition) can be explored collectively—combining local knowledge with system-level intelligence.

While the challenge of interoperability—semantic, technical, and institutional—remains a critical barrier to scaling these solutions, this Note argues that the answer lies not only in universal standards, but in adaptive, relational architectures that reflect the diversity of territories and actors involved.

By reframing Digital Twins as tools of mediation, experimentation, and cooperation, we suggest a new path toward a digitally enabled, inclusive and dialogic Mediterranean integration.

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Beyond Ontology Standards: A LLM-Based Approach to Dynamic Semantic Interoperability in Federated Digital Twin Systems

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

Semantic interoperability remains one of the principal challenges in federated Digital Twin (DT) environments. While reference ontologies such as SAREF, QUDT, and SSN/SOSA provide structured vocabularies for data exchange, their top-down design and static nature render them insufficient for handling the heterogeneity and dynamism of real-world distributed systems. This paper analyzes the limitations of current ontology-based approaches, reviews recent research on Large Language Models (LLMs) for ontology extraction, alignment, and transformation, and proposes a novel framework. In this framework, each node in a DT federation operates with its own local ontology—structured as a hierarchical object graph—while semantic interoperability is achieved via LLM-mediated dynamic mapping. This bottom-up, adaptive strategy avoids centralized standardization and enables scalable, evolutive, and decentralized digital infrastructures.

Introduction

Digital Twins (DTs) have emerged as a transformative paradigm for monitoring, simulating, and optimizing physical systems in real time. Initially developed for isolated assets in manufacturing, DTs are now increasingly envisioned as part of federated networks representing distributed infrastructures—such as energy grids, water networks, logistics corridors, or agro-industrial systems. In such federated architectures, DTs interact as autonomous nodes while collectively modeling interdependent processes across multiple domains and territories.

This evolution, however, introduces a fundamental requirement: semantic interoperability. As nodes are independently developed and reflect divergent modeling conventions, system architectures, and vocabularies, the ability to share not only data but also meaning becomes critical. Traditional approaches to this problem rely on pre-defined ontologies and semantic standards, assuming that interoperability can be enforced by design. In practice, however, the real-world deployment of DTs rarely conforms to such top-down prescriptions.

This paper argues for an alternative strategy: allowing each node to maintain its own localized semantic structure and leveraging LLMs as mediators capable of dynamically translating and aligning ontologies at runtime. This opens the possibility of achieving interoperability by construction—through adaptive translation—rather than by standardization.

The Limits of Current Ontology-Based Approaches

Ontologies are widely used to define shared vocabularies and formalize knowledge structures in semantic systems. Initiatives such as SAREF (ETSI), QUDT (Quantities, Units, Dimensions and Types), and SSN/SOSA (W3C) offer well-structured frameworks for describing concepts, relationships, and units of measurement in domains ranging from smart homes to industrial automation.

These ontologies are typically expressed in RDF, OWL, or JSON-LD and rely on hierarchical class structures, inheritance, and logical constraints to support machine reasoning. They enable the semantic annotation of data streams, facilitate resource discovery, and underpin linked data architectures.

However, when applied to federated DT systems—composed of heterogeneous, evolving, and loosely coupled components—these ontologies face four critical limitations:

1. Top-down rigidity: Centralized, expert-driven design makes it difficult to adapt ontologies to local innovations, emergent behaviors, or domain-specific constraints.

2. Limited structural expressiveness: While most ontologies capture naming conventions and type hierarchies, they often lack mechanisms for modeling the internal structure and dynamic behavior of complex objects (e.g., actuators, process units, composite devices).

3. Semantic mismatch between nodes: Nodes may represent the same physical object with different naming conventions, nesting logics, or aggregation levels. For instance, one node might express humidity data under irrigationModule.sensorData.humidity, while another uses climate.h_rel.

4. Manual integration burden: Aligning ontologies across systems currently requires human experts, extensive schema mapping, and context-specific rule definition. This process is not scalable for large, dynamic networks of DTs.

These challenges highlight the need for new strategies that support semantic integration in flexible, distributed, and evolving environments.

LLMs and the Shift Toward Dynamic Ontology Mediation

Recent advances in natural language processing, particularly the development of Large Language Models (LLMs), offer a compelling alternative to static, rule-based semantic integration. Unlike traditional tools that depend on hardcoded mappings or predefined ontological rules, LLMs can interpret contextual meaning, identify semantic similarities, and generate structured outputs from natural language inputs.

Research from Google Cloud (2023) demonstrates that LLMs can be used to extract domain-specific concepts, relations, and properties from textual documentation and convert them into OWL or RDF-compatible class hierarchies. This approach enables the semi-automatic construction of ontologies from unstructured sources, significantly reducing the reliance on manual taxonomy engineering.

In another study, Xu et al. (2023) explore the use of LLMs in multi-agent DT systems for collaborative logistics. They show that inconsistencies between heterogeneous agents—each modeled independently—can be resolved through semantic translation mediated by LLMs, enabling inter-agent cooperation without centralized schema enforcement.

Furthermore, Zhou et al. (2024) propose embedding LLMs into federated learning architectures to enable dynamic semantic adaptation in edge computing contexts. Their work suggests that LLMs can continuously adjust semantic representations in response to context shifts, such as changes in mobility patterns, data availability, or operational constraints.

These developments collectively suggest that LLMs are not only capable of interpreting and generating ontologies, but can also act as runtime semantic mediators in distributed systems—mapping concepts, restructuring data objects, and aligning knowledge graphs dynamically.

Proposed Architecture: Local Ontologies and LLM-Based Semantic Mapping

This paper proposes an architecture in which each DT node maintains its own local ontology, developed autonomously in coherence with its specific physical configuration and control logic. These ontologies are represented as object-oriented graphs, where classes, attributes, and nested structures reflect the physical and operational reality of the system.

Rather than enforcing global standardization, interoperability is achieved through the mediation of an LLM that performs the following tasks:

- Conceptual alignment: Identifies semantic equivalences across node-specific terminologies, e.g., mapping umid1 to relativeHumidity or flowrate to volumetricFlow.
- Structural transformation: Translates nested or composite objects between different formats, enabling interoperability even when data schemas differ substantially.
- Context generation: Dynamically produces JSON-LD contexts or RDF graphs that map local terms to shared URIs based on public ontologies or inferred equivalence.
- Adaptive learning: Continuously refines mappings based on usage patterns, error signals, or user corrections, enabling ontological structures to evolve in practice.

This architecture allows nodes to remain semantically autonomous while enabling them to interoperate as part of a larger federated infrastructure. Interoperability becomes an emergent property of the system—constructed through interaction and mediated by intelligent translation—rather than imposed a priori.

Research Agenda and Open Challenges

The integration of LLMs into semantic interoperability frameworks introduces several open questions and defines a new research agenda for federated DT systems:

- Ontology graph interpretation: What is the optimal way to represent hierarchical object models such that LLMs can reason over their semantics?
- Robustness and verification: How can we ensure the accuracy, stability, and safety of LLM-generated mappings in critical infrastructure applications?
- Cross-domain generalization: To what extent can mappings be transferred or adapted across application domains (e.g., from agriculture to logistics)?
- Negotiation protocols: Can LLMs be embedded in multi-agent systems as active participants in semantic negotiation, contributing to the formation of emergent shared vocabularies?
- Human-in-the-loop design: How can expert knowledge and LLM inference be combined effectively to guide and validate semantic translations?

Addressing these challenges will require interdisciplinary collaboration across AI, knowledge representation, systems engineering, and domain-specific modeling.

Conclusion

Semantic interoperability is a foundational enabler for federated Digital Twin ecosystems. As these systems evolve from isolated platforms to distributed infrastructures, traditional ontology-based approaches prove increasingly inadequate. *This paper has proposed a paradigm shift: enabling each node to operate with its own local ontology and leveraging LLMs as dynamic, context-aware mediators.*

By doing so, we move from rigid standardization to adaptive construction—where meaning is not prescribed but negotiated through interaction. This opens the way for scalable, resilient, and intelligent infrastructures capable of collective modeling, simulation, and decision-making in complex socio-technical environments.

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Toward a Strategic Research Agenda for Adaptive and Federated Digital Twins

Strategic directions for scalable, adaptive, and interoperable infrastructures

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Next-Generation Digital Twin Systems

Digital Twin (DT) systems are increasingly expected to operate not merely as digital representations of physical entities, but as intelligent infrastructures capable of supporting real-time coordination, learning, and adaptation in complex, distributed environments. Whether applied to energy systems, logistics networks, or territorial resilience, future DT infrastructures must satisfy a set of cross-cutting functional requirements:

- Adaptability to changing environmental, operational, or systemic conditions.
- Interoperability across platforms, domains, and knowledge representations.
- Scalability across both spatial extent (nodes, regions) and temporal complexity (lifecycles, disruptions).
- Autonomy and Self-Configuration, including the ability to incorporate new actors, resources, or logic without global reprogramming.
- Semantic Legibility, allowing systems to interact meaningfully even in the absence of prior standardization.

To meet these conditions, two complementary lines of research are emerging as foundational: (1) the development of hybrid digital twin nodes, and (2) the design of digital twin federations as multi-agent systems.

These lines are not isolated—they intersect at multiple levels, and together form the basis of an integrated approach to real-world, real-scale, and real-time digital infrastructures.

Hybrid Digital Twin Nodes: Modeling Complexity in Operational Contexts

The first strategic line of research concerns the internal architecture of the Digital Twin node: how a single physical system (e.g., a greenhouse, water pump station, PV farm) is modeled, virtualized, and simulated in relation to its own behavior and context.

The key challenge is that real systems are neither purely physical nor purely statistical. They evolve, they fail, they reconfigure—and thus their models must go beyond static equations or black-box regressors. The emerging direction is the development of hybrid models, combining structural physical laws with adaptive, data-driven components.

This line of research addresses:

- The multi-state nature of real systems: operational modes vary based on thresholds, failures, or transitions.
- The evolving boundary between system and environment: requiring models to adapt or restructure over time.

- The integration of real-time data with simulation and prediction: not merely for control, but for strategic foresight.

From a systems perspective, the hybrid DT node becomes a dynamic modeling kernel, whose internal logic can accommodate multiple behavioral regimes, absorb new knowledge, and maintain continuity through reconfiguration. Research must therefore focus on how such kernels are architected, trained, validated, and embedded in operational environments without disrupting continuity.

Federated Digital Twins as Multi-Agent Systems: Coordination Without Centralization

The second line of research shifts from the node to the network: how multiple DT nodes—each autonomous, situated, and self-modeling—can participate in federated infrastructures, where collaboration is possible without structural unification.

This problem is ontologically and operationally distinct from classical distributed systems: in federated DTs, nodes are heterogeneous, unevenly capable, and semantically diverse, yet must engage in mutual understanding and collective behavior.

The most promising conceptual framework is that of the Multi-Agent System (MAS): each DT acts as an agent, possessing local goals, internal logic, and the capacity to perceive and react to external stimuli.

Research in this domain must address:

- How do agents discover one another, share capabilities, and negotiate shared scenarios?
- How is emergent coordination achieved in the absence of a centralized orchestrator?
- How are semantic ambiguities managed across agents that model the world differently?
- What forms of governance, resilience, and accountability are possible in such ecosystems?

Critically, these federations must not only scale technically, but adapt structurally: allowing new nodes to join, fail, recover, or evolve without triggering systemic collapse or global reconfiguration.

Converging the Two Lines: Toward Federated Adaptive Intelligence

Although distinct in focus—internal modeling vs. external coordination—these two lines of research are deeply interdependent. A federated DT system can only function if:

- Each node possesses sufficient modeling fidelity and adaptability to act coherently within a broader simulation;
- The federation possesses sufficient semantic and procedural flexibility to accommodate node-level heterogeneity without flattening diversity.

What emerges is a new paradigm: federated adaptive intelligence. Not a system designed once and implemented globally, but an infrastructure that grows, learns, and coordinates through interaction. Such a system does not rely on standardization as a prerequisite, but allows interoperability to emerge through composition.

The research agenda, therefore, must be as systemic as the problem itself. It must build architectures that are not only modular, but epistemologically open: capable of integrating partial models, diverse ontologies, and situated forms of reasoning into a shared operational grammar.

Conclusion: Digital Twins as a New Episteme for Systems Design

To realize the promise of Digital Twin infrastructures—whether for climate resilience, circular economy, or industrial optimization—research must move beyond tool development toward architectural, epistemological, and institutional innovation.

This means recognizing DTs not just as interfaces, but as agents of coordination; not just as digital tools, but as autonomous structures of knowledge.

Only by advancing the two strategic lines outlined—hybrid node intelligence and federated agent cooperation—can we approach the kind of infrastructure that adapts, scales, and evolves with the complexity of the world it aims to support.

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Digital Twins as Technical Infrastructure for Euro-Mediterranean Cooperation

From declarations to operational alignment

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

The Euro-Mediterranean region is facing a critical juncture. Climate volatility, resource pressures, and infrastructure asymmetries are accelerating, while cooperation frameworks remain largely fragmented or symbolic. Despite decades of dialogue and investment, many joint initiatives have failed to produce lasting technical alignment, especially in areas where concrete coordination is most needed: energy, water, logistics, and circular economy systems.

Digital Twins offer a unique opportunity to reshape cooperation, moving beyond abstract policy frameworks into real, functioning systems. They allow distributed actors across the Mediterranean—municipalities, industrial clusters, research hubs—to simulate, optimize, and exchange models of reality, without requiring centralization or standardization of everything. In this sense, the Digital Twin is not just a digital replica of a system. It is a shared technical grammar through which diverse systems can speak, learn, and adapt together.

From fragmented projects to a cooperative infrastructure

Most cooperation programs operate through time-limited projects, with fixed deliverables and rigid structures. These often struggle to produce systemic change or continuity. Once the funding ends, so does the collaboration. Digital Twins enable a shift in paradigm: <u>from isolated efforts to a living infrastructure</u>, where systems are continuously modeled, scenarios shared, and mutual understanding built over time.

This approach is particularly relevant in the Mediterranean, where technical capacities are uneven, and operational conditions vary dramatically. Instead of enforcing uniformity, the Digital Twin enables <u>diverse systems to cooperate on their own terms</u>, using a shared logic to align where it matters—on flows, feedbacks, and outcomes.

A federated system of real-world cooperation

This initiative does not propose to harmonize policies or replicate technologies. It proposes to <u>connect existing systems</u>, each embedded in its own reality, into a wider federation. Greenhouses in North Africa, water systems in Southern Europe, waste recovery hubs in port cities—each can become a node in a distributed structure that mirrors how the Mediterranean already works: through movement, exchange, and negotiated interdependence.

Each node contributes what it can: a model of a process, a dataset, a policy simulation, a risk scenario. Together, these elements form a collective intelligence that can support decisions, test interventions, and coordinate actions in a way that no single actor could achieve alone.

The Digital Twin as a tool for resilience

In an age of cascading crises—climate events, supply chain disruptions, infrastructure failures—the ability to simulate, adapt, and coordinate across regions is vital. Yet traditional systems are siloed, slow, and reactive. A shared digital infrastructure enables real-time awareness and foresight, grounded in the actual systems that sustain life and economy across the region.

By anchoring cooperation in the logic of mutual modeling—rather than mutual reporting—the Digital Twin provides a space where decisions can be tested, aligned, and improved collaboratively. Not because everyone shares the same structure, but because everyone participates in the same process of understanding and response.

The Mediterranean, Federated by Infrastructure

To transform Euro-Mediterranean cooperation into a tangible and enduring reality, we must approach it as an engineering and operational challenge. A federated network of Digital Twins provides exactly this: not a centralized system imposed from above, but a shared infrastructure—built from the ground up, aligned through practical needs, and capable of evolving through continuous interaction.

It is through this form of technically grounded cooperation that the Mediterranean can become not just a geographic space, but a space of collective operational intelligence.

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Digital Twins and Living Labs: a new paradigm for advanced education and capacity building

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

As the Euro-Mediterranean region navigates the dual challenges of ecological transition and technological transformation, the question of how territories build knowledge, skills, and resilience becomes central. While infrastructure and data are essential, they are not sufficient: capacity building—the ability of regions to learn, adapt, and innovate—is what ultimately defines long-term sustainability.

In this context, the convergence between Living Labs and Digital Twin systems offers a unique and powerful response. It combines the material presence of operational systems with the modeling, simulation, and interoperability capacities of digital infrastructures. But beyond optimization and monitoring, it enables something deeper: a new paradigm for advanced education, technical training, and institutional learning.

From passive users to active producers of knowledge

Traditional models of technical assistance or training often treat territories as recipients of pre-defined knowledge: content is developed elsewhere, standardized, and transferred. This approach underestimates the diversity of local conditions—and misses the opportunity to activate the full potential of territorial systems as learning environments.

A network of Living Labs, each embedding a real and operational Digital Twin, changes this dynamic. These are not abstract simulations detached from reality. They are working systems—agro-industrial plants, water-energy loops, solar fields, circular economy platforms—instrumented and virtualized to support modeling, scenario design, and decision-making in real time.

Training within such a system is no longer about absorbing concepts. It becomes situated learning: engineers, technicians, planners, and administrators interact with live data, test responses to simulated shocks, explore policy scenarios, and engage in cross-border comparisons. In doing so, they become co-creators of models, not just users of tools.

Advanced learning for a distributed technical culture

Digital Twins embedded in Living Labs enable a new generation of training programs that go beyond classic disciplines. Participants learn how to:

- Integrate physical processes with computational models
- Work with semantic metadata and interoperable structures
- Simulate system behavior under variable and uncertain conditions
- Adapt interfaces and control strategies to local constraints
- Collaborate across nodes with shared frameworks but autonomous logic

This opens the door to modular and scalable curricula, adapted to the specific configuration of each node, but also part of a larger ecosystem. A greenhouse in Tunisia, a battery reuse hub in Italy, and a logistics platform in Morocco may all run different systems—but they can participate in a common learning architecture, exchanging experiences, methods, and improvements in real time.

Moreover, this infrastructure supports non-technical learning as well: governance actors can visualize the implications of planning decisions; SMEs can test business models in safe environments; communities can engage with resource flows through transparent, interactive interfaces.

Capacity building as territorial intelligence

The ultimate goal is not just to train individuals, but to build territorial intelligence: the collective ability of a region to sense, learn, respond, and evolve in the face of dynamic challenges. This involves:

- Localizing innovation, so that new technologies are not just imported but appropriated, transformed, and re-applied;
- Retaining knowledge within institutional and educational ecosystems;
- Supporting decision-makers with real-time feedback and modeling capacity;
- Fostering cross-institutional cooperation across public, private, and academic domains.

In this sense, Digital Twin–based Living Labs become permanent infrastructures for capacity building, not just technical demonstrators. They are always on, always learning, and always open to integration with new actors, questions, and programs.

Implications for Euro-Mediterranean development

For the Euro-Mediterranean region, this model holds particular strategic value. It provides a mechanism to balance asymmetries, enabling each territory to build competence on its own terms, while participating in a federated network. It strengthens regional cooperation through shared operational languages, rather than political harmonization. And it creates a platform for continuity, where capacity building is not an add-on, but a built-in function of the system.

In this perspective, Living Labs with Digital Twins are more than a pedagogical innovation. They are a structural response to fragmentation, dependency, and disconnection. They turn cooperation into co-production, training into transformation, and learning into resilience.

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Digital Twins and the Strategic Resilience of Critical Infrastructure in the Euro-Mediterranean Region

Anticipation, simulation, and preparedness in complex and interdependent systems

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

In an age of interconnected risks and cascading failures, the resilience of critical infrastructure has become a defining challenge for modern societies. From energy blackouts and cyber-attacks to climate-induced floods and supply chain disruptions, the continuity of essential services increasingly depends not only on the robustness of individual systems, but on the ability to anticipate, coordinate, and adapt across interdependent sectors and territorial boundaries.

In this context*, Digital Twin systems offer a strategic layer for preparedness,* transforming how we model, monitor, and govern critical infrastructures—particularly in complex geopolitical spaces like the Euro-Mediterranean region.

What are Critical Infrastructures—and why do they matter?

Critical infrastructures (CIs) are the backbone of modern life. They include energy supply chains, water distribution, health systems, communication networks, transportation corridors, and digital platforms. A failure in any one of these can have severe consequences, especially when it propagates through others—what systems thinkers call cascading effects.

Recognizing this, the European Union has significantly reinforced its legal framework for the protection and resilience of CIs. The Directive (EU) 2022/2557 on the resilience of critical entities (replacing the older 2008 directive) introduces a preventive, risk-based and systemic approach. It mandates:

- A national strategy on CI resilience;
- Risk assessments across sectors and cross-border networks;
- Minimum resilience measures for operators;
- Crisis communication and coordinated incident response mechanisms;

But legal frameworks alone are not sufficient. What is missing in most Member States—and even more in the EU–MENA interface—is a live infrastructure for anticipation, coordination, and simulation. This is where Digital Twins come in.

Digital Twins as Dynamic Risk Environments

Digital Twins are not simply virtual replicas of physical assets. At their most advanced, they are interactive, adaptive systems that fuse real-time data, predictive modeling, and simulation logic, creating a living environment for operational decision-making. In the context of CIs, this means:

- Continuous monitoring of systems across variables, thresholds, and domains;
- Scenario simulation: from routine variations to high-impact low-probability events;

- Impact forecasting, including second- and third-order effects (e.g., how a substation failure impacts urban mobility, hospital services, or cold chains);
- Distributed mitigation planning, with dynamic resource allocation and stakeholder coordination;
- Learning environments for preparedness training, including real-world test cases and cross-sectoral drills;

Unlike static risk assessments, Digital Twins are never finished. They evolve with the system they represent, incorporating new data, re-calibrating assumptions, and enabling institutions to learn over time.

Preparedness, not just response

A key innovation of Digital Twins lies in shifting the focus from response to preparedness.

Emergency management has traditionally relied on:

- predefined protocols;
- static contingency plans;
- and reactive decision-making;

But the nature of modern risk—non-linear, distributed, and cross-sectoral—demands systems that can anticipate, adapt, and simulate before the shock occurs. Preparedness is not just about having a plan; it's about knowing how systems behave under stress, how actors will interact, and where the tipping points lie.

Digital Twins provide this capacity by enabling:

- virtual stress tests of infrastructure networks under various hazard scenarios;
- cooperative planning between sectors (e.g., energy and mobility, health and transport);
- real-time dashboards for local authorities and emergency responders;
- advanced early warning systems based on pattern recognition and scenario modeling;
- the training of operators through live interaction with evolving models and simulation loops;

By embedding Digital Twins into Living Labs, the project environment becomes a safe but realistic test space, where preparedness can be trained—not just administratively, but operationally.

Territorial integration and Euro-Mediterranean coordination

Nowhere is this approach more needed than in the Euro-Mediterranean area. The region is:

- exposed: to droughts, sea level rise, heatwaves, seismic risk;
- interconnected: through energy corridors, port infrastructure, logistic chains;
- institutionally asymmetric: with uneven technical capacity and fragmented regulatory frameworks;

Here, a federated Digital Twin infrastructure allows each node—port, water facility, energy grid control center—to simulate and manage its own risks while also contributing to a shared regional preparedness environment. This means:

- sharing scenario templates and system behaviors across borders;
- practicing decentralized coordination in simulated crisis situations;
- aligning civil protection agencies, operators, and municipal authorities on joint action plans;
- supporting cross-border investments in redundancy and mutual aid;

Such an approach aligns with the EU Civil Protection Mechanism, the Resilience Goals 2030, and the Interreg NEXT MED strategic priorities.

From resilience as policy to resilience as infrastructure

What this shift reveals is that resilience is no longer only a policy goal—it must become an operational infrastructure. Laws and standards set the direction, but Digital Twins build the capacity to execute, adapt, and evolve.

They allow infrastructure to:

- sense disruptions early;
- simulate systemic responses;
- coordinate decentralized actors;
- and adapt governance to real-time complexity;

In this sense, *resilience becomes a continuous function of the system*, not a one-time plan. It becomes intelligent, situated, and collaborative.

A Preparedness Infrastructure for a Connected Region

As risks grow more complex and interconnected, so must our tools for managing them. Digital Twins are not a silver bullet—but they are an enabling layer for a more adaptive, anticipatory, and cooperative approach to critical infrastructure.

In the Euro-Mediterranean region, where technical asymmetries meet physical interdependence, they can serve as:

- bridges between systems;
- platforms for learning;
- and anchors for joint preparedness;

This is not simply about knowing more. It is about *governing complexity through shared simulation and collective foresight.*

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From Nodes to Federation: Building Collective Intelligence through Real-Scale Digital Twins

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Interoperability not by design, but by construction

Infrastructures speak many languages. They are built across different timelines, technologies, and institutional logics. Nowhere is this more evident than in the Euro-Mediterranean region—a space where agricultural systems, water networks, logistics corridors and energy platforms coexist in geographic proximity but operational disconnection. In this fractured landscape, digitalization is often promised as a unifying solution. Yet when implemented from the top down, it tends to replicate the very fragmentation it seeks to overcome.

What if interoperability were not a prerequisite, but an outcome?

What if, instead of designing abstract standards, we could construct real infrastructures that learn to speak to each other—not by imposition, but through participation?

This is the proposition behind a federated system of Digital Twins, built from the ground up, rooted in physical processes, and scaled through cooperation, not centralization. It is a shift from digital strategy to digital architecture, and from technical alignment to collective operational intelligence.

From isolated twins to federated systems

A Digital Twin—when grounded in a real system—offers more than a simulation. It becomes a way to observe, test, and govern a complex process: a greenhouse optimizing irrigation based on humidity patterns; a port terminal simulating cargo flows under new regulations; a regional water loop modeling resource stress under climate volatility.

But the power of Digital Twins multiplies when they are federated. Not linked through a central server or forced integration, but connected as autonomous agents in a wider ecosystem.

Each node—whether in Sfax, Catania, or Alexandria—can model its own reality while remaining legible to others.

Together, they form a distributed intelligence: not one system, but many systems in relation.

In this federation:

- A PV plant in Tunisia can inform regional energy balancing;
- A port in Sicily can coordinate waste tracking with North African terminals;
- An agro-industrial cluster in Southern Italy can align production planning with water availability from upstream basins.

The infrastructure is the language

Unlike traditional digitalization, which begins with a blueprint and seeks to implement it, the bottom-up approach begins with what exists—and builds interoperability through practice.

Each node constructs its own twin: shaped by its constraints, goals, and capacities. As these twins interact—sharing variables, aligning scenarios, exchanging outputs—a common grammar of cooperation begins to form.

This means:

- interoperability is not enforced but emerges;
- convergence happens through use, not through standardization;
- the system grows by connection, not by expansion.

The infrastructure itself becomes the language of mutual intelligibility—and that language is shaped by operations, not by declarations.

Working at real scale: the only scale that matters

Laboratory simulations and pilot projects have their place. But they often fail to capture the volatility, asymmetry, and coupling of real-world systems. A Digital Twin built on a spreadsheet model is not a twin—it's a metaphor.

This federation is different: it works on real infrastructures.

It begins with systems that are already in operation, already producing, already under pressure.

And it doesn't simulate an ideal—it simulates what is happening, or what could happen next.

By embedding Digital Twins in active infrastructures—waste sorting plants, desalination units, smart greenhouses—each node becomes a living site of experimentation, not a showcase. And each federation becomes a distributed testbed for region-wide innovation, training, and emergency preparedness.

Interoperability as a Constructed Commons

In complex and fragmented territories, interoperability cannot be legislated. It must be built.

Not through abstraction, but through interaction.

Not through control, but through cooperation.

A bottom-up federation of Digital Twins shows how this can be done.

By grounding digital systems in real processes, connecting them through shared logic, and allowing intelligence to emerge from the flow of operations, we can move from disconnection to coordination, and from coordination to shared capacity.

This is not simply about making systems work better.

It is about making systems work together—as a new form of territorial commons, where each node is sovereign, and every connection adds intelligence.

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Federated Digital Twins in Real-World Systems: State of the Art, Emerging Challenges, and Systemic Architecture

Towards a scalable and adaptive infrastructure for modeling complex territorial systems

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

Digital Twins (DTs) are rapidly gaining recognition as a transformative digital paradigm—not merely as tools for visualization or simulation, but as dynamic systems capable of evolving with the physical entities they represent. Unlike traditional simulators, which operate within well-defined parameters and use static or predefined models, Digital Twins aim to accompany the physical system throughout its entire lifecycle, adapting to its changing states, behaviors, and environmental interactions. This paper explores what makes a Digital Twin distinct, how its capabilities differ from conventional simulators, and why its full realization requires strategic research investment—particularly in the direction of adaptive and evolutive modeling.

Introduction

In recent years, the concept of the Digital Twin (DT) has evolved from static digital replicas of individual assets into dynamic, data-driven systems capable of modeling, monitoring, and simulating real-world infrastructure. While the adoption of DTs in manufacturing and industry is now relatively mature, the application of Digital Twin architectures to distributed, open, and multi-domain environments—such as territorial systems, circular economy networks, or cross-border infrastructures—remains at an early and exploratory stage.

A growing number of initiatives now propose to build federated networks of Digital Twins, where each node corresponds to a real-world system (e.g., greenhouse, water plant, PV field, port terminal) and contributes to a broader mesh of collaborative modeling and simulation. This shift—from centralized platforms to distributed federations—raises new opportunities but also profound challenges.

This article outlines the current state of the art, identifies the critical bottlenecks in federated DT systems, and introduces a systemic architectural framework grounded in hybrid modeling, semantic interoperability, and multi-agent coordination.

The Promise of Federated Digital Twins

Federated Digital Twins offer a compelling alternative to monolithic or platform-based digitalization. Instead of creating a single, integrated system that attempts to manage all variables, the federated approach builds distributed digital models, each reflecting a real-world system embedded in a specific operational context.

Each node in such a federation:

- captures its own data streams from local sensors and controllers,
- runs simulations based on localized models,
- exposes interfaces or outputs to other nodes in the network.

Federation allows these DTs to interact, exchange, and synchronize, enabling collective simulation of complex phenomena—e.g., resource flows across industrial symbiosis, cascading failures across infrastructure layers, or coordinated scenarios for circular economy transitions.

However, implementing this vision at scale and in real-world conditions exposes four core challenges, examined below.

Hybrid Modeling: The Core of Real-World Digital Twins

One of the primary limitations of current DT implementations lies in the fragility and rigidity of the models themselves. While traditional Digital Twins often rely on first-principles models (e.g., thermodynamics, fluid dynamics, structural mechanics), these become difficult to maintain and scale in dynamic, data-rich, and uncertain environments.

Purely data-driven models, on the other hand—such as neural networks or black-box regressors—lack explainability, robustness, and generalizability outside of narrow contexts.

Hybrid models, which combine the structure of physical models with the flexibility of data-driven components, offer a middle ground.

These models:

- preserve causal structures and conservation laws,
- incorporate machine learning components to capture unmodeled dynamics,
- adapt over time as new data becomes available.

In a federated DT system, hybrid modeling is essential because:

- each node must operate autonomously, using models that reflect its unique configuration;
- yet it must also participate in shared simulations, requiring models that are comparable and composable.

Challenge: Despite recent research progress (e.g., physics-informed machine learning, symbolic regression, surrogate modeling), there is still no unified methodology for constructing, validating, and exchanging hybrid models in federated environments.

Interoperability and the Problem of Semantics

The second critical barrier lies in semantic interoperability. Unlike closed systems, a federation of Digital Twins must allow:

- different systems to share data and models in ways that are understandable and meaningful,
- variable names, units, structures, and assumptions to be interpreted and translated dynamically.

While syntactic interoperability (e.g., APIs, data formats) is relatively well managed, semantic interoperability remains fragile and largely manual.

Existing efforts (e.g., SAREF, QUDT, AGROVOC) provide useful ontological frameworks, but:

- are often domain-specific, incomplete, and non-extensible,
- lack contextual adaptability, especially in real-time environments,
- do not support automated mapping between divergent local schemas.

Challenge: Federated DTs require a new class of semantic infrastructures, capable of:

- expressing variable-level metadata,
- adapting to evolving vocabularies and use cases,
- enabling on-the-fly negotiation of meaning across heterogeneous nodes.

Federation as a Scalable Multi-Agent System

A federation of DTs can be conceptualized as a multi-agent system (MAS), in which:

- each DT acts as an autonomous agent,
- agents interact via shared scenarios, messages, and feedback loops,
- the system exhibits emergent coordination without centralized control.

However, building MAS on top of real-world infrastructure is non-trivial. Key research issues include:

- Scalability: how to maintain performance and responsiveness as nodes are added or removed?
- Adaptivity: how to allow nodes to learn, adjust, or negotiate behavior over time?
- Conflict management: how to resolve conflicting objectives or inconsistent assumptions between agents?

To address these issues, we propose a taxonomy of MAS properties relevant to federated DT networks:

Property	Description
Autonomy	Each DT maintains local control, data ownership, and modeling strategy.
Legibility	Each DT exposes a minimal semantic contract for external comprehension.
Negotiability	Nodes can engage in scenario-based exchanges and mutual adaptation.
Scalability	The network can grow or shrink without re-architecting the system.
Resilience	The system tolerates local failure and supports substitution of nodes.
Emergence	New capabilities arise from interaction, not pre-programming.

Challenge: Implementing this taxonomy requires new mechanisms for discovery, coordination, and governance in digital ecosystems where no single authority controls the whole.

Toward an Operational Research Infrastructure

The transition to a real-world federated DT network implies a rethinking of research itself. Rather than developing models in silico and testing them on static datasets, researchers can:

- deploy new modeling approaches directly in live nodes,
- run comparative experiments across domains and regions,
- observe learning dynamics in real-time,
- use the network as a testbed for resilience, interoperability, and governance**.**

Such a system can host:

- live challenges (e.g., drought scenario simulation, port congestion optimization),
- collaborative experiments between academic, public, and private actors,
- open competitions for model improvement or semantic translation.

In this vision, the federated DT network becomes not just a tool for managing reality, but a platform for advancing scientific understanding of how complex systems adapt and cooperate.

Conclusion

Federated Digital Twins represent a major shift in how we model, understand, and govern complex systems. But their realization requires:

- new hybrid modeling paradigms,
- new semantic infrastructures,
- and new approaches to distributed intelligence.

These are not solved problems—they are research frontiers. And only by grounding them in real, interconnected, operational nodes can we move from theory to transformation.

The next phase is not simply to deploy more DTs, but to construct the conditions for their federation—and to let intelligence emerge, not from design, but from interaction.

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Digital Twins: Definitions, Lifecycle Intelligence, and Research Outlook

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

Digital Twins (DTs) are rapidly gaining recognition as a transformative digital paradigm—not merely as tools for visualization or simulation, but as dynamic systems capable of evolving with the physical entities they represent. Unlike traditional simulators, which operate within well-defined parameters and use static or predefined models, Digital Twins aim to accompany the physical system throughout its entire lifecycle, adapting to its changing states, behaviors, and environmental interactions.

This article explores what makes a Digital Twin distinct, how its capabilities differ from conventional simulators, and why its full realization requires strategic research investment—particularly in the direction of adaptive and evolutive modeling.

What Is a Digital Twin? A Dynamic Concept Beyond Simulation

A Digital Twin is a digital counterpart of a physical object or system, continuously updated with real-world data and capable of simulating, predicting, and interacting with that object's behavior in real time. The twin is not a static model; it is a living digital structure, intended to reflect the object across time, context, and operational conditions.

Whereas a simulator might model an idealized version of a pump, a solar plant, or a reactor under controlled scenarios, a Digital Twin is designed to represent the physical object as it actually evolves, including wear, degradation, reconfiguration, and usage-specific variations.

The Lifecycle Perspective: Multiple States, Changing Models

One of the foundational principles of Digital Twin architecture is the ability to follow the physical system through its full lifecycle. This lifecycle is not linear, and the object does not maintain the same structure, behavior, or operational constraints at all times.

A Digital Twin must therefore be capable of representing:

- Multiple operational states (startup, steady-state, shutdown, maintenance, failure modes)
- Transitions between states, triggered by planned processes or emergent events
- Variations in system behavior, due to environmental interaction or system evolution
- Adaptation to new conditions, including unforeseen usage patterns or environmental contexts

For instance, a wastewater treatment plant may operate under normal flow rates using one process configuration. However, in flood conditions, or when industrial effluents change composition, the plant may enter a new operational state, requiring a different internal logic and process model.

This is especially evident in batch processes, where the same infrastructure undergoes fundamentally different behaviors across stages (e.g., filling, reaction, draining). But in large infrastructures—such as energy networks, transport systems, or multi-unit industrial platforms—these states may be unforeseen, and may emerge from interactions with the environment or system-wide reconfigurations.

From Static Models to Adaptive and Evolutive Digital Twins

In such scenarios, the limitations of a fixed internal model become apparent. A simulator built for normal operating conditions cannot anticipate nor respond to emergent modes of operation.

A Digital Twin must therefore include the capability to:

- Adapt its internal model based on new data and behavior
- Detect when a model no longer describes the system adequately
- Trigger the generation or integration of a new internal model able to respond to novel or extreme environmental scenarios

This leads to the concept of an *evolutive Digital Twin*: *one that not only adjusts parameters but can restructure its own internal representation, incorporating new forms of knowledge or reconfiguring its logic in response to unforeseen changes.*

Imagine a port logistics platform whose DT tracks standard cargo handling operations. A geopolitical disruption causes massive delays, shifting flows and operations. The existing twin must now reframe the logistical model to incorporate new storage behaviors, routing constraints, or bottlenecks never observed before. A static simulator would fail here; an evolutive DT would be capable of reconstructing its own logic, or at least signaling that a new model is required.

Strategic Implications: Research, Architecture, and Long-Term Investment

Realizing the full potential of Digital Twins is not just a matter of deploying sensors or building dashboards. It requires:

1. Multi-layered architectures capable of accommodating model transitions
2. Hybrid modeling frameworks combining physical knowledge with data-driven learning
3. Semantic and behavioral descriptors for identifying state transitions and mode shifts
4. Mechanisms for dynamic model substitution, extension, or co-existence

These elements are not fully developed in current industrial applications, and lie at the frontier of ongoing research.

Long-term development of Digital Twins must therefore be recognized as a strategic research challenge, akin to building intelligent systems capable of continuous learning, adaptation, and contextual awareness. This is particularly crucial in sectors where systems face evolving demands and unexpected perturbations—such as energy, water, mobility, and climate-sensitive infrastructure.

Is Digital Twin Just a Hype?

Some critics argue that Digital Twins are little more than a technological rebranding of simulation and monitoring tools. While the term is certainly subject to marketing inflation, the underlying ambition of a Digital Twin—lifelong, adaptive, and co-evolving with its physical counterpart—is a valid and disruptive one.

Market research supports this trend:

- MarketsandMarkets forecasts the global Digital Twin market will grow from USD 10.1 billion in 2023 to USD 110.1 billion by 2028 (CAGR 61.3%).

- Grand View Research estimates a CAGR of 35.7% between 2024 and 2030.
- Market.us predicts a jump to over USD 520 billion by 2033.

These figures suggest more than hype: they signal increasing demand for systems capable of dynamic intelligence, not just visualization.

Conclusion: Digital Twin as a Foundation for Adaptive Infrastructure

The conceptual power of the Digital Twin lies in its ability to evolve with the physical system it represents—across states, behaviors, and even crises. Unlike simulators, it is not designed for static experiments, but for permanent cognitive presence across the lifecycle of the system.

To fulfill this promise, a Digital Twin must:

- monitor reality,
- detect discontinuities,
- transition between states,
- and, ultimately, generate new models to survive and adapt.

Such capabilities do not yet come out-of-the-box. They require a sustained research ecosystem—one that combines systems engineering, machine learning, semantics, and control theory.

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Digital Twin: A Unified Framework for Education, Research, and Critical Infrastructure Development

Author: Sebastiano Martignano, research strategy advisor -CRF Italy

Abstract

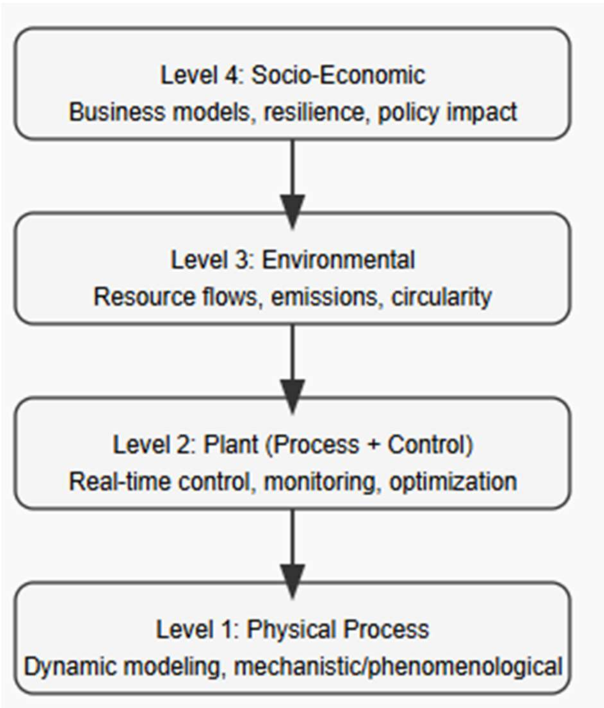
The integration of Digital Twins into education, scientific research, and industrial innovation is rapidly emerging as a key paradigm to address the challenges of ecological transition, systemic innovation, and infrastructure resilience. This paper proposes a unified, multi-layered framework that incorporates dynamic modeling, process control, environmental impacts, and socio-economic outcomes. The framework supports both advanced training (through virtual and phygital labs) and applications to complex territorial scenarios under exogenous stressors, offering decision-making tools for long-term planning.

Introduction

The evolution of Digital Twins from simple digital replicas to multi-domain predictive and decision-making tools marks a methodological turning point. Modern applications enable process simulation, real-time control, environmental analysis, and long-term sustainability and resilience assessment at the territorial scale. Circular Research Foundation proposes a unified approach that integrates education, modeling, and territorial governance through an open, modular digital infrastructure.

Framework Architecture

The conceptual architecture is structured across four hierarchical and interconnected layers:



Each layer inherits dynamics and states from the preceding one and enriches the system with new indicators and decision logics. The transition from process to plant model includes the integration of control systems (e.g., PID, MPC, discrete logic). The environmental model adds sustainability metrics, while the socio-economic level allows scenario evaluations, aggregated impacts, investment returns, and resilience strategies.

Integration with Digital Tools and Operational Prototyping

The effectiveness and scalability of the framework are enhanced by its ability to incorporate modeling environments, digital design tools, and computational modeling languages. The combination of parametric design platforms, interactive environments, and phygital systems enables the creation of working prototypes that can be deployed in physical-digital labs for training and applied research. These prototypes can then be seamlessly transferred to robust operational platforms through processes of architectural adaptation, ensuring consistency between ideation and implementation phases. This approach fosters alignment among models, digital infrastructures, and real-world applications.

Hybrid Models for Robustness and Strategic Decision-Making

A core component of the proposed framework is the use of hybrid models, combining physics-based components (first-principle models such as conservation equations of mass, energy, and momentum) with data-driven components derived from historical or real-time data. This integration ensures coherence in representing the underlying phenomena while benefiting from the adaptive and predictive power of statistical or machine learning models. Hybrid models are particularly valuable in complex scenarios where data-only models are insufficient due to semantic closure, lack of transparency, and limited generalizability. In critical decision-making contexts—such as environmental resource management, infrastructure security, or territorial planning—interpretability and traceability are essential. Hybrid models ensure robustness and explainability, providing a reliable foundation for decisions that impact public well-being and socio-ecological balance over the long term.

Digital twins for Training and education

Applications and Educational Integration Digital Twins are proving especially valuable in education due to their ability to support flexible, personalized, and experiential learning. As knowledge doubles over increasingly shorter timespans, educational models must adapt. Digital Twins address this challenge by enabling continuous content updates, simulating systems in varied conditions, and fostering peer learning and self-responsibility. The framework supports:

- <u>Virtual Labs</u>: Interactive simulations to introduce dynamic modeling and control systems;
- <u>Phygital Labs</u>: Integration of digital models with physical hardware to support testing and experimentation;
- <u>Upskilling/Reskilling Programs</u>: Modular and customizable training for professionals, technicians, and system designers;
- <u>Problem-Based Learning</u>: Real-case simulations that involve territorial dynamics and multi-domain interactions.

An advanced example is provided by the Copenhagen School of Marine Engineering and Technology Management, which has integrated Digital Twin-based modules in its curricula, especially in the fields of industrial and naval automation. Through dynamic virtual models, students can explore complex operational scenarios, program automated systems, and validate them virtually before deploying physical devices. This approach:

- Increases the number of machine and system configurations students can explore;
- Reduces the time and cost associated with traditional hands-on learning;
- Enhances collaboration with industry during internships and thesis projects;
- Strengthens students' skills in design, simulation, and commissioning.

Digital Twins for Regenerative Agriculture and Bioeconomy Districts

Digital Twin technologies are increasingly being explored as enablers of regenerative agriculture and circular bioeconomy districts. By creating virtual replicas of agro-ecological systems, including soil health dynamics, crop performance, biodiversity indicators, water flows, and nutrient cycles, Digital Twins support decision-making aligned with the principles of regeneration, resilience, and ecosystem restoration. These systems integrate sensor data, satellite imagery, and agronomic models to provide tools for adaptive management. At district scale, they simulate resource flows (biomass, energy, water), support logistics, and enhance coordination among stakeholders. The integration of ecological and socio-technical data supports regenerative planning aligned with SDGs and the EU Green Deal.

Digital Twins in Biotech and Bioprocessing 4.0

In biotechnology and bioprocessing, Digital Twins model, simulate, and optimize complex biological systems. A Digital Twin typically represents the full production chain—from fermentation to purification—and integrates real-time sensor data, control parameters, and historical data. Applications include:

- Process Optimization;
- Batch-to-Batch Consistency;
- Scale-Up Support;
- Continuous Bioprocessing. Digital Twins support Bioprocessing 4.0 by embedding IoT, AI/ML, and predictive analytics, enabling yield improvement, downtime reduction, and faster time-to-market.

Conclusions

This paper has outlined a unified Digital Twin framework capable of integrating education, research, and territorial system innovation through a multi-level architecture. The framework leverages hybrid modeling strategies, combining first-principles and data-driven methods, to provide robustness, traceability, and explanatory power in complex decision-making contexts. Digital Twins foster experiential learning and continuous professional development via Virtual and Phygital Labs, empowering learners and professionals to engage with complex systems and deliver high-quality solutions. Their application in regenerative agriculture and bioprocessing exemplifies their versatility as cognitive infrastructures for innovation and sustainable development.

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