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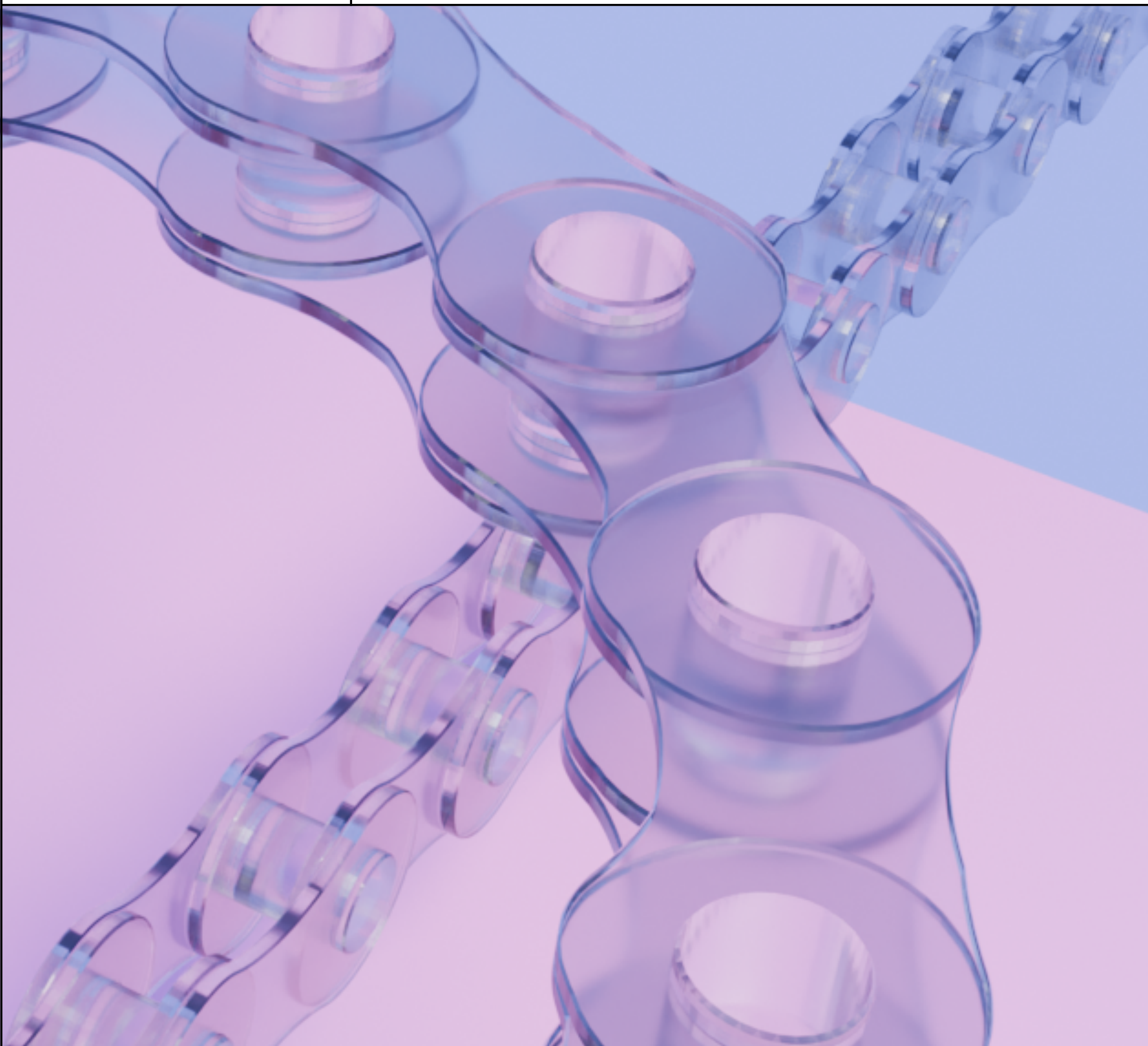
Research Report

Transnational Digital Twins

A Research Report on their Potentials, Challenges and Enabling Factors



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Executive Summary

This research report examines the concept of Transnational Digital Twins (TDTs), their potential, added value, and state of empirical implementation as well as key challenges and conditions for their development and possible successful implementation.

Digital Twins are increasingly relevant as digital representations of physical objects, systems, and processes such as transport infrastructure to enable new ways of integrating and utilising data, particularly in mobility, infrastructure and urban development. They offer innovative approaches to improve process efficiency, reduce resource consumption, and promote cross-sectoral collaboration, thereby supporting data-based planning, simulation, and decision making. However, current Digital Twin applications are often limited to specific domains, organisational contexts, and geographic areas, while the physical systems, processes, and objects they represent extend across countries, organisations, and sectors. This is particularly relevant for interconnected infrastructures such as rail networks, roads, public transport, and energy supply, which are inherently intertwined across borders, regions, and stakeholders. This report addresses this gap by taking a practice-oriented perspective on TDTs while paying particular attention to their benefits and added value, current implementation status, data bases, role of open data, challenges, enabling factors, and good practices. This report is primarily aimed at practitioners and project responsibles planning and implementing TDTs, such as infrastructure operators, decision makers in public authorities at national and European levels, and researchers in this field. This report aims to make the concept of TDTs more tangible, contribute to a shared understanding of their potential and prospects of use, and identify relevant challenges, enabling factors, existing use cases, and future pathways.

Defining the concept of Transnational Digital Twins

Currently, there is no shared understanding of the concept of Transnational Digital Twins in practice or in the related literature. Hence, this report starts by establishing a conceptualisation and working definition of TDTs. This report draws on the institutional and strategic contexts of the European Union (EU) as the research framework and geographical scope of this empirical analysis and provides enabling conditions and possible definitional elements and analyses existing technical architectures that can already support TDT applications in practice. Based on these foundations, this report proposes the following working definition of a Transnational Digital Twin[1], which can be adapted to specific application contexts:

> *Transnational Digital Twins can be understood as decentralised, cross-border digital representations of physical objects, processes, and systems that extend across national and sectoral boundaries. Transnational Digital Twins are typically designed as decentralised, federated systems in which data remains within its original legal and organisational contexts while being exchanged in a sovereign, secure, and an interoperable manner.*

[1] The full definition is outlined in section 2.4.

Application areas and added value of Transnational Digital Twins

Based on our analysis of existing use cases, desk research, and expert interviews, this report identifies key application areas for TDTs in mobility, transport, infrastructure, and cities. Across the EU, 77 relevant projects and initiatives were identified across five categories covering different areas of application: *Mobility: Transport management and planning*, *Environmental and climate research*, *Cities and urban governance, Energy and crisis prevention*, and the overarching category of *Border regions*, which serve as implementation and testing spaces for TDTs. These findings show that mobility is a particularly suitable field of application that specifically benefits from coordinated, data-based planning, operation, and optimisation.

Overall, this analysis highlights the strong potential of TDTs to support integrated decision making across countries and sectors, for example, in areas such as cross-border traffic management, rail operations, and multimodal mobility management. Their further development can generate benefits for public authorities, infrastructure operators, private sector, and citizens alike. The following example illustrates how TDTs can create added value practically:

TDT use case: Cross-border planning of charging infrastructure for electric mobility
A Transnational Digital Twin can, for example, support the planning of cross-border charging infrastructure for electric mobility by combining transport data, traffic flows, charging-point availability, energy grid capacity, and spatial planning data from different countries within one shared analytical framework. This makes interdependencies among mobility demand, energy supply, and environmental objectives more visible and supports better coordinated investment decisions, more efficient infrastructure deployment, and a more reliable assessment of sustainability impacts across borders. In this way, it can improve planning for public authorities, infrastructure operators, and mobility providers while also contributing to a more coherent and user-oriented charging network for citizens.[2]

Main challenges and enabling factors

This analysis shows that the successful implementation of TDTs depends on addressing challenges in three closely connected dimensions: organisation and governance, technical and data infrastructure, and political and regulatory frameworks.

1. Organisation and governance: The main challenges for planning and implementing Transnational Digital Twins are primarily related to organisational and governance aspects. Their development typically involves complex multi-stakeholder consortia with public, private, and academic actors across countries and therefore requires coordination structures that can align different institutional logics, legal frameworks, technical systems, and organisational cultures. At the same time, successful implementation depends on a shared and conceptually clear vision that links local needs, concrete problems, and tangible benefits for participating actors. This vision must be translated into targeted, user-oriented use cases and credible success stories in order to demonstrate practical relevance, strengthen political and funding support, and sustain cooperation over time. In addition, unequal starting conditions across countries, cities, and institutions must be

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[2] Based on Begonia's Use Case 3. See overview of use case 3 at https://www.begonia-project.eu/wp-content/uploads/2024/08/Use-case-3.pdf

addressed, as differences in data infrastructures, resources, governance arrangements, and institutional capacities can significantly hinder collaboration, requiring targeted mechanisms for alignment and support.

2. Technical and data infrastructure: The success of Transnational Digital Twins depends on data that can be exchanged, interpreted, and used consistently across systems, organisations, and countries, which requires, above all, semantic interoperability based on common data models and shared standards. At the same time, while open data provides an important starting point, mature and operational TDTs often require a mixed data base that combines open data with partner-provided, operational, sensitive, proprietary, and other privately held datasets. In addition, cross-border implementation depends on layered and federated technical architectures that allow data to remain within its original legal and organisational contexts while still enabling a secure and controlled exchange. Building such architectures, for example, through data spaces as enabling infrastructures, is therefore essential to support interoperability, governance, and trustworthy access across actors and subsequently TDTs.

3. Political and regulatory frameworks: Planning and implementing Transnational Digital Twins require not only technical and organisational capacities but also supportive political and strategic conditions. As TDTs are still at an early stage of development, their progress requires both initial and sustained funding structures to move beyond short-term pilot projects and foster durable implementation structures. At the same time, coherent regulatory frameworks are needed to improve data access, support harmonisation across countries, and create stable conditions for long-term, cross-border deployment. This includes stronger alignment between national and European strategies, more consistent implementation across sectors and member states (e. g. in the implementation of National Access Points (NAPs)), and effective coordination across the multi-level European system. Furthermore, TDT applications related to critical infrastructure need to address heightened concerns around security, sovereignty, and regulatory control, which can further slow cross-border integration.

TDTs should be understood less as an established concept or finished technology, and more as an emerging strategic approach to cross-border, data-driven infrastructure governance, with the potential to enable more integrated, cross-sector, and evidence-based decision making across Europe. Their main challenges are currently less related to technical than they are to organisational, political, institutional, and legal dimensions of interoperability. Implementing them successfully depends on jointly developing interoperable data infrastructures, reusable governance models, long-term political and financial support, and stronger capacities for cross-border cooperation. TDTs are therefore unlikely to result from a single technological breakthrough, but rather from a gradual process of integrating existing Local Digital Twins (LDTs), data spaces, and sectoral platforms through shared standards, coordinated governance, and sustained political support to form a common European data and analysis infrastructure enabling Transnational Digital Twins.

This report analyses the status quo and explores the to date unstructured field of Transnational Digital Twins in mobility, infrastructure, and cities; provides empirical evidence; identifies practice-oriented perspectives, challenges, and good practices for (future) cross-border projects; and enables knowledge transfer.

1. Introduction

In the course of the data-based transformation of public infrastructure, Digital Twins are establishing themselves as key integration, control, and steering mechanisms for infrastructure systems. As digital representations of physical objects, systems, and processes, such as transportation infrastructure, Digital Twins can support data-based planning, simulation, and decision-making. They are considered promising key technologies for public infrastructure and are becoming increasingly important particularly in mobility, transport, and urban governance, as well as data-based public administration.[3]

However, the potential benefits and possible usage areas of Digital Twins do not end at national borders and are not limited to isolated sectoral solutions and use cases. On the contrary, they can provide substantial efficiency gains, improved system control, and integrated, cross-border, and cross-sectoral planning; particularly in mobility and transport infrastructures such as rail networks, roads, bridges, and public transport networks, as well as in energy and water supply networks and other particularly critical infrastructure areas (see chapter 3). In these sectors, cross-border applications are structurally necessary because infrastructures are inherently intertwined across borders. For national actors implementing Digital Twins such as infrastructure operators, this means that developing a national solution with potential scalability and interoperability in mind can be a practical necessity in areas such as infrastructure and mobility to avoid duplicated efforts and remain compatible with cross-border systems, standards, and governance structures that the same infrastructures already require.

In order to leverage the potential of cross-border applications such as Digital Twins, an integrated data base and a harmonised data exchange between countries or sectors and individual data owners are required. The expansion of existing infrastructures such as European data spaces, i. e. the Mobility Data Space (MDS),[4] is an important step to build key components as a basis to implement data-based applications across boundaries. At the same time, the question arises as to what role open data can play within these data ecosystems for the conceptualisation, planning, and potential implementation of Transnational Digital Twins. However, systematic findings on their status quo and of comparable data-based applications regarding their structural characteristics, potential benefits, added value, and enabling factors, as well as the technical, organisational, and data requirements for their implementation, are still lacking.

Therefore, the aim of the research project "Open Twin", funded by the German Federal Ministry of Transport, is to investigate applications of Digital Twins across boundaries and comparable applications in the fields of transport and mobility, infrastructure, and cities with regard to their prospects of use and functions, data bases, and their specific added value and current challenges. Furthermore, special focus is placed on the role of open data in the planning and implementation of Digital Twins and their potential contribution to reducing access barriers and improving data availability. Therefore, this report addresses the following key questions:

[3] See Blüml et al. (2025).
[4] See the EU digital strategy at https://digital-strategy.ec.europa.eu/en/policies/mobility-data

1. *Which cross-border applications of Digital Twins in mobility, infrastructure, and cities are already planned or implemented? What is their purpose and what data bases are they based on?*
2. *What data bases do these Transnational Digital Twin applications in mobility, infrastructure, and cities use and (to what extent) are open datasets already contributing to their development and implementation?*
3. *What are the key challenges and enabling factors when developing and implementing Cross-Border Digital Twin applications and their data bases and what potential do they have for future implementation?*

To answer these questions, an introduction to the concept of Transnational Digital Twins as well as a working definition are developed (chapter 2) and potential added value, application scenarios, and concrete use cases of Transnational Digital Twins are outlined, particularly in the mobility and transport sector, in infrastructure, and in cities (chapter 3). Building on this, the status quo of existing cross-border applications and comparable projects is examined (chapter 4), followed by an analysis of challenges and enabling factors for implementing Transnational Digital Twins in seven key areas of action (chapter 5). This report concludes with an outlook on the future potential of Transnational Digital Twins.

Methodology

A systematic literature review and empirical analysis of Transnational Digital Twins and comparable cross-border initiatives was conducted, particularly in mobility, transport, and infrastructure as well as cities. The aim of the literature review was to gain a comprehensive overview of the current state of research, practice, and European discourse to identify existing approaches on cross-border, data-based applications, specifically Digital Twins. Particular attention was paid to technical, organisational, and data requirements, as well as to the role of open data in cross-border, use-case scenarios.

Secondly, in addition to this literature review, 77 thematically relevant research and application projects related to Transnational Digital Twins were identified, systematically categorised, and analysed with regard to their application contexts and areas of use, functions, data infrastructures, and cooperation structures. Due to the heterogeneous nature of the empirical use cases, this review was structured along seven key areas of action to develop and implement Cross-Border Digital Twins: strategic objectives, organisational and operational requirements, data and technical infrastructures, and legal requirements and overarching challenges.

A central element of the project involved 19 qualitative interviews with a total of 21 experts from 10 European countries. The interviews were conducted between November 2025 and January 2026, and the interviewees were selected based on an analysis of relevant stakeholders including experts from different institutional contexts and disciplines relevant to the topic. These included representatives from research, public administration, European and national institutions, and application-oriented projects in the field of Digital Twins and data infrastructure. The participants were grouped and prioritised according to their expertise to ensure sound and diversified data collection. The interviews were conducted using a modular guide based on the project's central research questions (see chapter 5). The findings of the qualitative analysis of the interviews were systematically evaluated in relation to the results of the literature review and condensed along the lines of the areas of action defined in this report.

2. Foundations of Transnational Digital Twins

There is still no common, cross-disciplinary understanding of the term Digital Twin.[5] Similarly, the concept of Transnational Digital Twins, that is, the cross-border dimension of Digital Twin applications, has not yet been systematically defined or consolidated in the literature. This applies both across sectors and specifically within the mobility sector, infrastructure, and cities.[6] This lack of understanding is due in no small part to the fact that in practice, there are only a few mature, truly cross-border-integrated Digital Twins planned or implemented (see chapter 3). At the same time, numerous transnational data-based projects and cross-border infrastructures are (being) established that can be considered functional precursors or approximations of Transnational Digital Twins. However, existing projects are often characterised by sectoral fragmentation, heterogeneous areas of application, and divergent stakeholder groups (see chapter 5). Thus, the conceptual complexity of cross-border Digital Twins clearly exceeds that of national, regional, and local Digital Twins, for example, with regard to data interoperability requirements, institutional embedding, and governance structures.[7]

Against this backdrop, a working definition of the concept Transnational Digital Twin is needed as a foundation for the subsequent empirical analysis of existing use cases and for evaluating the expert interviews. When defining the concept of Digital Twin as a central element of Transnational Digital Twins (see section 2.1), this chapter approaches the transnational dimension from two complementary perspectives: first, the institutional and strategic contexts of the EU, which provides both enabling conditions and potential definitional elements (see section 2.2) and second, existing technical architectures that enable Transnational Digital Twin applications in practical and technical terms (see section 2.3). Finally, these perspectives converge in a working definition of Transnational Digital Twins (see section 2.4). In brief, Transnational Digital Twins can be defined as follows:

Transnational Digital Twins can be understood as decentralised, cross-border, digital representations of physical objects, processes, or systems that extend across national and sectoral boundaries. Transnational Digital Twins are typically designed as decentralised, federated systems in which data remains within its original legal and organisational contexts while being exchanged in a sovereign, secure, and an interoperable manner.

[5] This is the conclusion of a comprehensive study by Think Tank iRights.Lab and authors Blüml et al. (2025), funded by the former Federal Ministry of Digital and Transport (BMDV), which analysed the status quo of Digital Twin applications in Germany, particularly in infrastructure, construction, and municipalities and provides among others a definition of the concept of Digital Twins and their technical components.
[6] There are journal articles that examine cross-border twin projects, for example, Jorgensen & Ma (2025) on the European project TwinEU https://www.mdpi.com/2076-3417/15/12/6475. But even reviews that describe cross-border areas of application for Digital Twins, such as the logistics sector or aviation, do not conceptualize the term Transnational Digital Twins. See, among others, Botín-Sanabria, D. M., Mihaita, A.-S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. d. J. (2022). Digital Twin Technology Challenges and Applications: A Comprehensive Review. Remote Sens., 14(6), 1335. doi: 10.3390/rs14061335 or Attaran, M., & Celik, B. G. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. Decision Analytics Journal, 6, 100165. doi: 10.1016/j.dajour.2023.100165.
[7] See Blüml et al. (2025), chapters 2 and 5.

This condensed definition is further elaborated throughout the chapter and outlines the different levels and definitory criteria in more detail, synthesising them into a comprehensive working definition at the end of this chapter.

2.1 From Digital Twins to Transnational Digital Twins

Determining the defining criteria and potential fields of application for Transnational Digital Twins first requires an understanding of the concept Digital Twin. Even if there is no uniform definition of the concept in the related literature or in practice,[8] in recent years, experts across disciplines have established sector-specific understandings of Digital Twins,[9] which, however, predominantly focus on the national scope and rarely integrate a cross-border or an international perspective.[10] Although sectoral and, in some cases, cross-sectoral definitions exist at the European and international levels, these do not yet provide a conceptual basis for the systematic definition of Transnational Digital Twins.[11]

As part of the project Digital twins for infrastructure, construction, and housing: from theory to design, funded by the Federal Ministry for Digital and Transport (BMDV),[12] a working definition of Digital Twins for infrastructure and in municipalities was developed based on a systematic literature review, expert discussions, and empirical analysis. This definition also provides the basis for this report that will be expanded for cross-border application in the following chapters.[13]

> *Digital Twins are virtual, dynamic representations of physical objects, processes, and systems (reference object) and their interrelationships. The properties and behavioural changes of the reference object are captured and reflected using sensors. The virtual model and the physical representation are linked by a permanent, bidirectional data exchange. The reference object can be influenced using aggregated data from a variety of sources such as sensors or models (e. g. building information modelling (BIM) and control units (actuators).*[14]

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[8] Overviews of various definitions and understandings of Digital Twins in the related literature can be found in Barricelli et al., (2019); Sharma et al., (2019); Jones et al., (2020); Liu et al., (2021); Yao et al., (2023).

[9] These include the Federal Ministry of Transport (BMV) for the transport sector in the area of federal highways (see the framework document of the former Federal Ministry of Digital and Transport (BMDV) Digitaler Zwilling Bundesfernstraße Fazekas, 2024 and for bridges see the BMDV paper Digitaler Zwilling von Brücken Wenner et al., (2024) as well as DIN Spec 91607 (2024) for the municipal sector of urban Digital Twins (see DIN SPEC 91607, 2024).

[10] For example, the DIN Spec 91607 for urban Digital Twins requires that *"international standardisation work on digital twins [...] should enable cross-border use [authors' translation]".* See the DIN SPEC 91607, 2024: 10. Although there are also sector-specific or cross-sectoral approaches to define Digital Twins in related European and international literature, there are no indications for the definition of Cross-Border Digital Twins.

[11] At the international and European levels, there are also sector-specific approaches to Digital Twins for transport and urban infrastructure, e. g. Masterplan Bundesfernstraßen and DIN SPEC 91607. However, these mainly relate to industrial applications, such as Internet of Things (IoT)-based twins, logistics/supply chain, and International Organisation for Standardisation (ISO) standards in the smart city sector that reference Digital Twins (ISO 30146 Smart City Indicators). See the Digital Twin Hub website at https://digitaltwinhub.co.uk/iso-and-digital-twin-definitions/?

[12] Former name of the ministry. Since 2025, it has been called the Federal Ministry of Transport (BMV).

[13] For comprehensive definition criteria, differentiation from related concepts and technical components, functions, and maturity levels, as well as the prototypical structure of a Digital Twin, see Blüml et al. (2025), pp. 4–22.

[14] See Blüml et al. (2025), p. 5.

2.2 Institutional context of the European Union

In addition to understanding the core concept of Digital Twin, it is crucial to outline the institutional framework for cross-border data exchange and the political–strategic relevance of implementing complex, cross-border cooperation projects within the EU.[15] The reason for this is that existing institutional and political contexts, notably the EU's funding programmes and initiatives, provide the backdrop for implementing Transnational Digital Twins and allow for conclusions to be drawn about the implementation status as well as definition criteria of Transnational Digital Twins and comparable data-based initiatives. Due to the data-based nature of Transnational Digital Twins and the project's research focus, open data constitutes a potential enabling foundation for their implementation, which will be analysed below.

Potential of open (mobility) data

Transnational Digital Twins are particularly dependent on interoperable, cross-border data bases. The more heterogeneous legal jurisdictions, administrative structures, and technical systems are, the more the data integration costs due to semantic ambiguity, structural differences, and licensing constraints (see sections 5.4 and 5.5). Against this backdrop, the principle of open data takes on particular significance: as standardised, legally unambiguous, and machine-readable datasets, open data can reduce integration barriers, promote interoperability, and form a common basis for Transnational Digital Twin applications.[16]

Open data refers to publicly accessible, free, machine-readable, and freely licensed information that can be used and reused without restrictions.[17] It often originates from the public sector (e. g. weather, geographic, and research data) and excludes sensitive, confidential, and protected content. The fundamental principles of open data entail that the data is open by default, is provided in a timely and comprehensive manner, is accessible and machine-readable, is comparable and interoperable, promotes transparency and citizen engagement, and fosters innovation and inclusive development.[18] Open data is of considerable importance as an economic driving factor for innovation and can serve as a raw material for innovative products and services, for example, in traffic control, route optimisation, logistics, and energy supply.[19][20] Figure 1 shows an overview of the six Open Data Charter principles.

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[15] There are numerous Digital Twins globally in a variety of countries. However, the geographical focus of this research project is largely limited to cross-border projects within the EU research framework.

[16] See the Federal Ministry of the Interior. (2025). Open Data Strategy of the Federal Government. https://www.bmi.bund.de/SharedDocs/downloads/DE/publikationen/themen/moderne-verwaltung/BMI21030-open-data-strategie-der-bundesregierung.html

[17] See the Open Definition website at https://opendefinition.org/; BMV: https://www.bmv.de/SharedDocs/EN/Articles/G/open-data.html

[18] See the Open Data Charter website at https://opendatacharter.net/principles/

[19] See the Federal Ministry for Digital Transformation and Government Modernisation (BMDS) at https://bmds.bund.de/themen/digitale-wirtschaft/daten/open-data

[20] The EU estimates the market potential for open data at €184 billion, with projections reaching between €199.51 billion and €334.21 billion by 2025. See Data Europe at https://data.europa.eu/de/veroeffentlichungen/open-data-impact

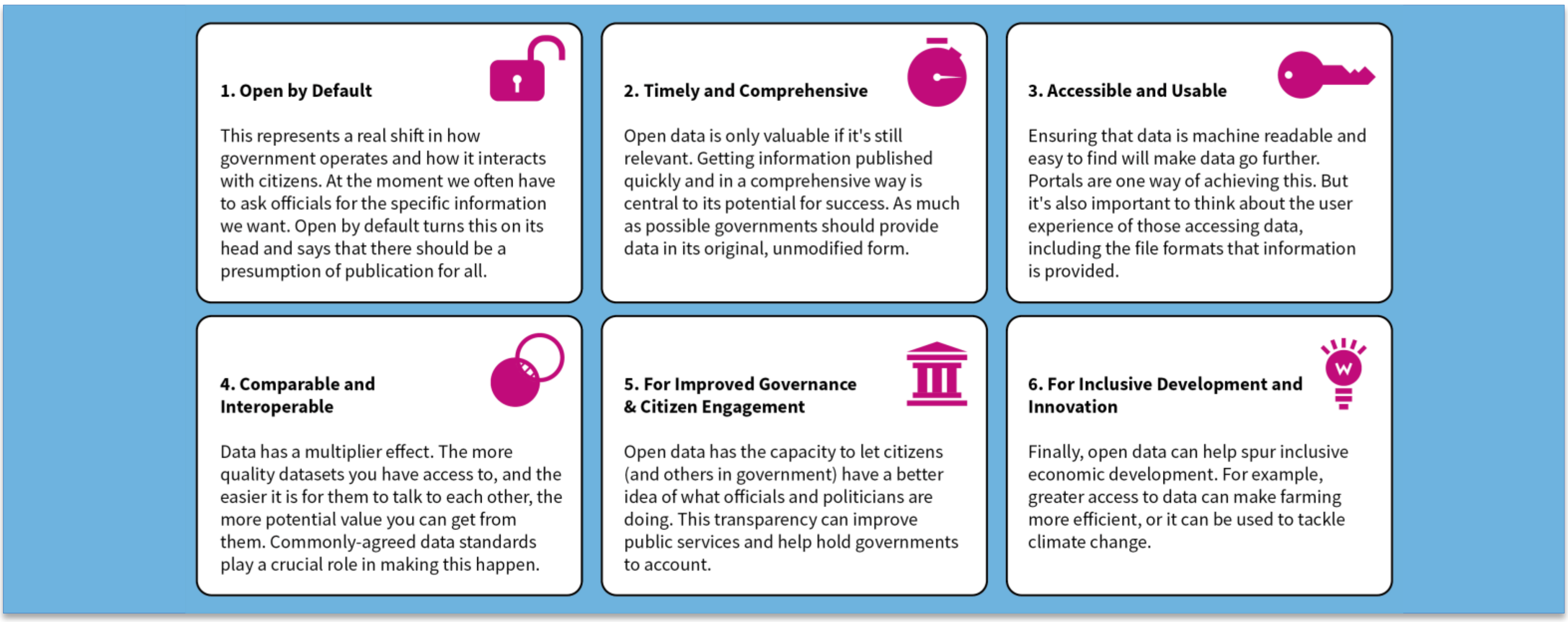

Figure 1: Overview of Open Data Charter principles. Source: Own representation iRights.Lab based on Open Data Charter principles.

In the context of Transnational Digital Twins, high-value datasets play a central role. Due to their socioeconomic potential, these are classified as particularly valuable by the EU Commission and must be made available in a machine-readable format and free of charge.[21] These datasets include the following six categories: geodata, Earth observation and environment, meteorology, statistics, business (including business ownership), and mobility. Geodata and mobility data in particular form a central infrastructural foundation for cross-border applications in the mobility, transport, and infrastructure sectors, as they make spatial, time-critical, and system-relevant information available in a standardised form. Open mobility data in particular can deliver significant added value in this context. It can contribute to more efficient traffic management and enable user-oriented mobility services, optimised infrastructure capacity utilisation, and the promotion of sustainable modes of transport.[22] EU strategies for the provision of open data in the mobility sector, such as the Sustainable and Smart Mobility Strategy,[23] initiatives such as the Mobility Data Space,[24] and standards such as DATEX II[25] aim to strengthen technical interoperability and thus support the cross-border usability of these datasets.

With regard to Transnational Digital Twins, open data can primarily be understood as a structural enabler for interoperability and scalability. Its actual added value depends not only on its legal accessibility but also and significantly on data quality, standardisation, and active use within interoperable system architectures (see sections 5.4 and 5.6).

[21] See the European Data Portal website at https://data.europa.eu/en/news-events/news/unlocking-potential-high-value-datasets-impact-hvd-implementing-regulation
[22] See Bruns, L. et al. (2020). Hochwertige Datensätze in Deutschland p. 66f. Retrieved from https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Publikationen/Studien/studie-hochwertige-datensaetze-in-deutschland.pdf?__blob=publicationFile&v=1
[23] See the EU mobility strategy at https://transport.ec.europa.eu/transport-themes/mobility-strategy_en
[24] See the EU Mobility Data Space website at https://mobility-dataspace.eu/
[25] See the DATEX III EU website at https://datex2.eu/

European data spaces

Another key enabling component are (sector-specific) European data spaces, also known as Common European Data Spaces[26] (see section 2.5 for conceptual distinction and below for its technical implications for Transnational Digital Twins). Planning and implementing Transnational Digital Twins are based on functioning cross-border data exchange mechanisms. As trustworthy, secure, and interoperable data infrastructures, data spaces can enable cross-border data exchange and thus form the basis for implementing Digital Twins in various sectors, for example, for optimised planning and monitoring and in infrastructure, industry, construction, urban development, and the energy sector.[27] This applies in particular to sector-specific data spaces such as the European Mobility Data Space, the European Health Data Space,[28] and the European Energy Data Space,[29] which can act as structural enablers of cross-border data-based applications. When focusing on enabling Transnational Digital Twins in the mobility sector, strategies such as the Sustainable and Smart Mobility Strategy[30] and initiatives such as the Mobility Data Space[31] are of particular importance.

The 2020 European Strategy for Data aimed to create a single European market for data to enable information to flow securely and freely across borders and sectors thereby increasing competitiveness.[32] *The Data Union Strategy*[33] published on 19 November 2025 further develops and strategically deepens this approach. It addresses structural deficits in the European data ecosystem by expanding access to high-quality datasets, especially for data-based innovations and artificial intelligence (AI) applications, to support a more coherent, previously fragmented, EU data law, and ensure fair and secure cross-border data flows in the long term.

While data spaces are already systematically established as European infrastructures (see Figure 2 for an overview of the data space support ecosystem), Digital Twins are currently predominantly conceived as thematically and spatially limited, i. e. to specific city services, application-oriented initiatives, as the interviewees also emphasise, often in the sense of specific tools rather than comprehensive solutions and rarely explicitly transnational in orientation (see section 2.2). With the exception of stand-alone flagship projects such as Destination Earth (see section 4.1.2) and the initiative Digital Twin Ocean[34] (see section 4.1.1), Transnational Digital Twins are not yet explicitly considered within thematically related European funding strategies. At the same time, the overall relevance of establishing cross-border and cross-topical applications and promoting shared frameworks such as data spaces in the future is emphasised both within the EU's institutional strategy and by experts.

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[26] See the Common European Data Spaces website at https://digital-strategy.ec.europa.eu/en/policies/data-spaces
[27] Ibid.
[28] See the European Health Data Space website at https://www.european-health-data-space.com/
[29] See the Common European Energy Data Space website at https://energy.ec.europa.eu/publications/common-european-energy-data-space_en
[30] See the European Commission website on sustainable smart mobility at https://transport.ec.europa.eu/transport-themes/eu-mobility-transport-achievements-2019-2024/sustainable-smart-mobility_en
[31] See the Mobility Data Space website at https://mobility-dataspace.eu/
[32] See the European Strategy on Data. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0066
[33] See the EU Data Union strategy at https://digital-strategy.ec.europa.eu/en/policies/data-union
[34] See the project website Digital Twin Ocean at https://digitaltwinocean.mercator-ocean.eu/

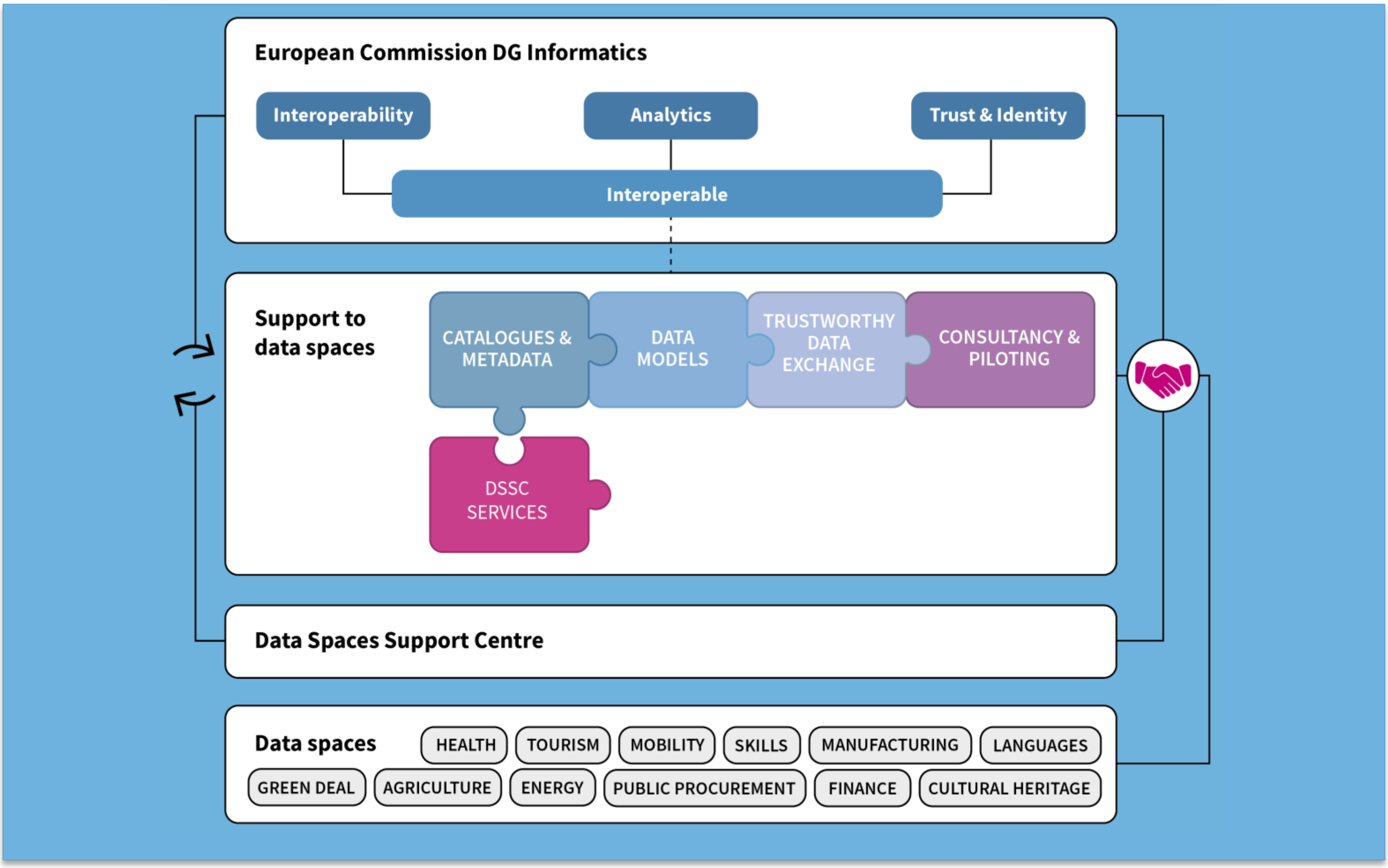

Figure 2: Overview of planned European data spaces and Directorate-General for Digital Services (DG DIGIT) strategic support services for their development. Source: Own representation iRights.Lab based on [European Commission, DIGIT offerings for the data spaces (2023)].

Institutional mechanisms to foster transnational cooperations

In addition to establishing European data spaces as an infrastructural basis, institutional mechanisms are needed to promote cross-border cooperations to implement Transnational Digital Twin applications. The EU's research and development funding programme Horizon (2021–2027, €93.5 billion), clearly emphasises the political–strategic importance of cross-border, data-based projects in the EU.[35] The 2025 work programme[36] highlights Digital Twins and European data spaces as "*key instruments*" of the digital transformation and the data economy. The 2026 work programme[37] focuses, among others, on horizontal, i. e. cross-sectoral funding. The practical

[35] The European research landscape is supported in a wide range of areas, from Excellent Science to Innovative Europe (business and innovation support) and through the funding of individual large-scale projects, such as research into fusion reactors. The majority of the budget (approx. 56%) is earmarked for research in six areas: health, culture, digitalisation, climate, energy, and mobility. See the European Commission. (14 May 2025). *Horizon Europe Work Programme 2025: Cluster 4 — Digital, Industry, and Space* (Entscheidung C (2025) 2779). Retrieved from https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/cluster-4-digital-industry-and-space_en
[36] Ibid.
[37] See the Horizon Work Programme 2026–2027 at https://www.horizont-europa.de/de/Horizont-Europa-Arbeitsprogramm-2026-2027-veroffentlicht-5282.html

relevance of this funding logic is exemplified by the Horizon-funded project Destination Earth, which concretely operationalises the conceptual and institutional prerequisites for Transnational Digital Twins.[38]

While Horizon primarily addresses the innovation and technology policy dimensions relevant to planning and implementing Digital Twins across borders, the European funding programme Interreg[39] offers a geographical and governance-related perspective. Projects and funding categories within this programme are thematically[40] insightful with regard to determining the defining criteria of Transnational Digital Twins, as it promotes initiatives and projects that address common and overarching challenges in neighbouring countries and (border) regions within the EU.[41] A distinction is made among the following four types of cross-border cooperation:

(1) Cross-border cooperations support cooperation between neighbouring countries, focusing on border regions[42];
(2) Transnational cooperations support cooperation in larger areas or sea basins;
(3) Interregional cooperations support regions in exchanging experience and knowledge, building capacity, and identifying good practices;
(4) Outermost regions support regions in the outermost regions in their cooperation with neighbouring, non-EU territories.[43]

In keeping with these definitions, cross-border projects and, in particular, (1) cross-border cooperations and (2) transnational cooperations, can thus provide valuable assumptions for a conceptual approach to Transnational Digital Twins due to their structural similarity. Especially in the mobility, transport, and infrastructure sectors, the assumption is that the physical object being mapped or modelled, for instance a railway line, may extend across at least two countries. This report adopts the Interreg programme's distinction and understands transnational as

[38] See the project website of Destination Earth at https://destination-earth.eu/
[39] In addition to Interreg, numerous other networks and associations, Directorates-General (DGs), especially the Directorate-General for Mobility and Transport and the Directorate-General for Communications Networks, Content, and Technology of the European Commission, EU research and innovation funding programmes, and European bodies are involved in Digital Twins and cross-border digitisation projects. There are also numerous thematic and supraregional networks dedicated to networking and implementing such projects. The following are particularly relevant for the implementation of Transnational Digital Twins: Eurocities; ERRIN: European Regions Research and Innovation Network; CCRE, Council of European Municipalities and Regions; Open and Agile Smart Cities & Communities (OASC); European Network of Living Labs; European Committee of the Regions; and Living-in.EU.
[40] Relevant thematic funding priorities include, in particular, the areas of smartness, connectivity, and governance, as these encompass the promotion of data-based innovations (smartness); cross-border digital infrastructures and interoperable mobility solutions (connectivity), as well as the removal of administrative and legal barriers and the development of institutional capacities (governance). Interreg EU (11 August 2025). Retrieved from https://interreg.eu/about/thematic-objectives
[41] Fogarasi, J. (2024). A review of the literature on cross-border cooperation in Europe. Deturope, 16(3), pp. 121–144.
[42] Besides Interreg, different institutions define so-called "cross-border infrastructure" projects, i. e. projects involving infrastructure across countries, that are structured in a similar way to Interreg project types. For instance, the European Investment Bank (EIB) defines these as "*fixed-asset investments that physically link two or more countries via infrastructure, including digital infrastructure, enabling the flow of people, goods, commodities, or data*." In addition to mobility/infrastructure projects (rail and road) and energy projects (electricity and gas), the EIB also specifically promotes data exchange enabled by digital infrastructures such as fibre optic networks and data centres. European Investment Bank. (2023). Cross-border infrastructure projects: The European Investment Bank's role in cross-border infrastructure projects. European Investment Bank. Retrieved from https://www.eib.org/attachments/lucalli/20230107_cross_border_infrastructure_projects_en.pdf
[43] Types of programmes — Interreg EU. (16 July 2025). Retrieved from https://interreg.eu/about/types-of-programmes

encompassing both cross-border and transnational cooperation in a broader sense. Consequently, the terms Transnational Digital Twin and Cross-Border Digital Twin are used synonymously in the following.

Interim conclusion

The examination of current funding programmes and cross-border projects highlights a range of existing transnational cooperation structures and project types within the EU as well as their diverging geographical, institutional, and functional characteristics. It also helps to differentiate between practical understandings of transnational and cross-border initiatives. Transnationality in this sense implies not only cooperation between at least two countries but also integration of previously separate systems, administrative structures, legal domains, datasets, and infrastructures across national, linguistic, organisational, and cultural boundaries. For conceptualising Transnational Digital Twins, this implies that they either digitally model a physical system with cross-border extension, such as a transport corridor, or integrate data, actors, organisations, and services from multiple national contexts into a common data model and architecture. Transnational Digital Twins are thus conceptually designed to operate across different legal and administrative frameworks and to synchronise them functionally.

2.3 Application-oriented architectures for implementing Transnational Digital Twins

In order to develop criteria to define and identify a prototypical technical structure to conceptualise Transnational Digital Twins, existing application-oriented architectures are examined with regard to their technical structure and functional scope.

For cross-border applications, two architectures are particularly relevant: a) federated architectures (of Digital Twins) and b) data space-based architectures, as the literature review and expert interviews show. Both approaches are conceptually recognized and practically applied in concrete use cases. In addition, data spaces in particular are a central priority in European strategy and funding logic, as shown in section 2.2.

A) Federated architectures (of Digital Twins)

Federated Digital Twins (FDTs) or Distributed Digital Twins[44][45] describe systems in which several decentralised Digital Twin instances cooperate to create a comprehensive digital representation, for example, of a cross-border rail connection, a multimodal logistics corridor, or an urban–regional mobility ecosystem. An FDT is therefore a federated system of several autonomous Digital Twins that (can) work together based on interoperability and coordination rules. This is ensured by common standards and interoperability, data governance, security rules, and synchronisation mechanisms. FDTs thus act as a kind of system of systems. The overarching purpose of FDTs is achieved through the linked insights of the individual Digital Twins.[46]

[44] Czekster, R. M., Perez, A. G., Kavakli-Thorne, M., Nasri, S. A. E. M., & Shaikh, S. (2024). Cyber–physical and business perspectives using Federated Digital Twins in multinational and multimodal transportation systems. arXiv, 2410.08479. Retrieved from https://arxiv.org/abs/2410.08479v1

[45] Vergara, C., Bahsoon, R., Theodoropoulos, G., Yanez, W., & Tziritas, N. (October 2023). Federated Digital Twin. In *2023 IEEE/ACM 27th International Symposium on Distributed Simulation and Real Time Applications (DS-RT),* pp. 115–116. IEEE.

[46] See Vergara et al. (2023).

FDTs can thus model complex systems using multiple Digital Twins and, thanks to their federated approach, comply with different regulatory frameworks, political and cultural systems, and requirements such as data protection and data security, as the data can remain within its respective (legal) framework.

Such a federated architecture could be utilised to implement Transnational Digital Twins, for example, in the mobility sector in which federated Digital Twins can optimise multinational and multimodal transportation systems (MMTSs).[47] Potential benefits of federated Digital Twins in MMTSs relate in particular to predictive maintenance, route optimisation, and fleet management across national borders and systems. In addition, federated Digital Twins could support mobility operators in the implementation and reporting of regulatory requirements such as safety (e. g. operational safety requirements for hazardous goods) and environmental regulations (country-specific noise and emission limits). Against the backdrop of increasingly complex global supply chains, the potential benefits of federated Digital Twins are steadily increasing. In addition to technical challenges, the integration of various international and national standards and regulations is emphasised as a key challenge in this context[48] (see sections 5.4 and 5.6).

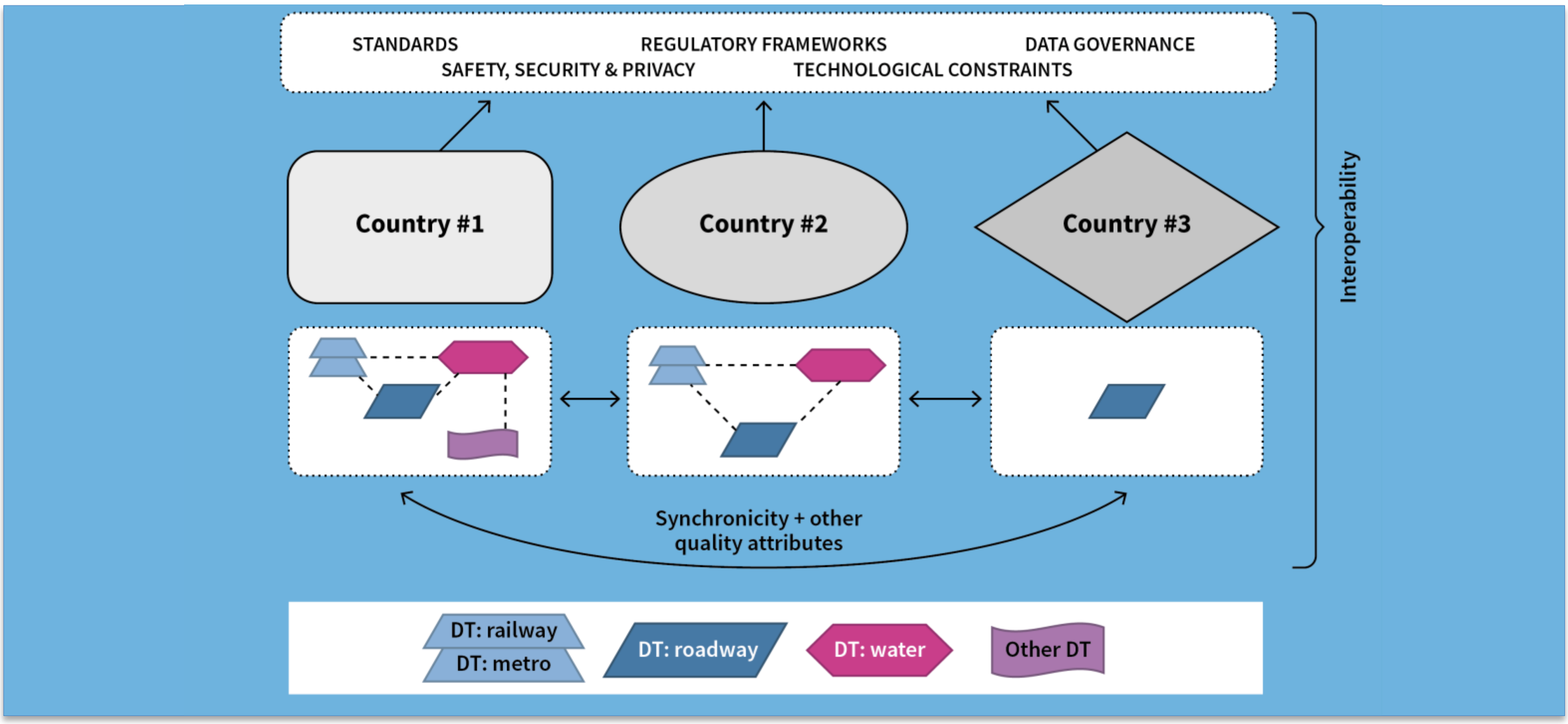

Figure 3: Overview of an FDT in an MMTS context. Source: Own representation iRights.Lab based on Czekster et al. (2004).

[47] See Czekster et al. (2024).
[48] See Czekster et al. (2024).

B) Data space-based platform architectures

In addition to FDTs, data space-based architectures offer a conceptual and technical framework for a sovereign, secure, and an interoperable data exchange across organisational units and actors[42] and are being promoted nationally and internationally through initiatives such as the International Data Space Association (IDSA)[49] and various European data spaces.[50] Data spaces, such as the planned European Mobility Data Space (EMDS),[51] do not create centralised data bases or platforms themselves, but rather harmonise and federate different data ecosystems, for example, in the mobility sector, thus linking heterogeneous data that is difficult to find and retrieve for various actors (see section 2.5). According to the European Commission's Sustainable and Smart Mobility Strategy and European Strategy for Data, the EMDS is intended to link essential data from all modes of transport, such as national timetables and traffic information in accordance with the Intelligent Transport Systems (ITS) Directive.[52]

Data spaces achieve harmonisation and interoperability of data through technical and governance measures. Governance measures include, for instance, building trust, verifying the identity of actors (authentication), defining authorisation, meaning who has which rights and responsibilities, the business model of the data space, and responsibility for operating the data space.[53] Technical interoperability is ensured by the specification of the data space protocol, which regulates, for example, the findability of data (Catalogue Protocol) and the negotiation of access and usage conditions (Contract Negotiation Protocol).[54] In addition, connectors implement governance requirements such as access requirements, thus enabling trust-based data exchange.[55]

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[49] See the International Data Spaces website at https://internationaldataspaces.org/

[50] See Möller, F., Jussen, I., Springer, V., Gieß, A., Schweihoff, J. C., Gelhaar, J., Otto, B. 2024. Industrial data ecosystems and data spaces. Electron. Markets, 34(1), 41–17. doi: 10.1007/s12525-024-00724-0.

[51] See the EMDS website at https://transport.ec.europa.eu/transport-themes/smart-mobility/creating-common-european-mobility-data-space_en

[52] Ibid.

[53] For more information see, e. g. the International Data Spaces position paper at https://internationaldataspaces.org/wp-content/uploads/IDSA-Position-Paper-Governance-for-Data-Space-Instances-Aspects-and-Roles-for-IDS-Stakeholders.pdf or the Gaia-X website at https://gaia-x-hub.de/wp-content/uploads/2024/03/WP-GX-Governance-Datenraeume.pdf

[54] https://docs.internationaldataspaces.org/ids-knowledgebase/dataspace-protocol

[55] See the IDSA Data Space Connector Report. Retrieved from https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Space-Connector-Report-1_October_2025.pdf

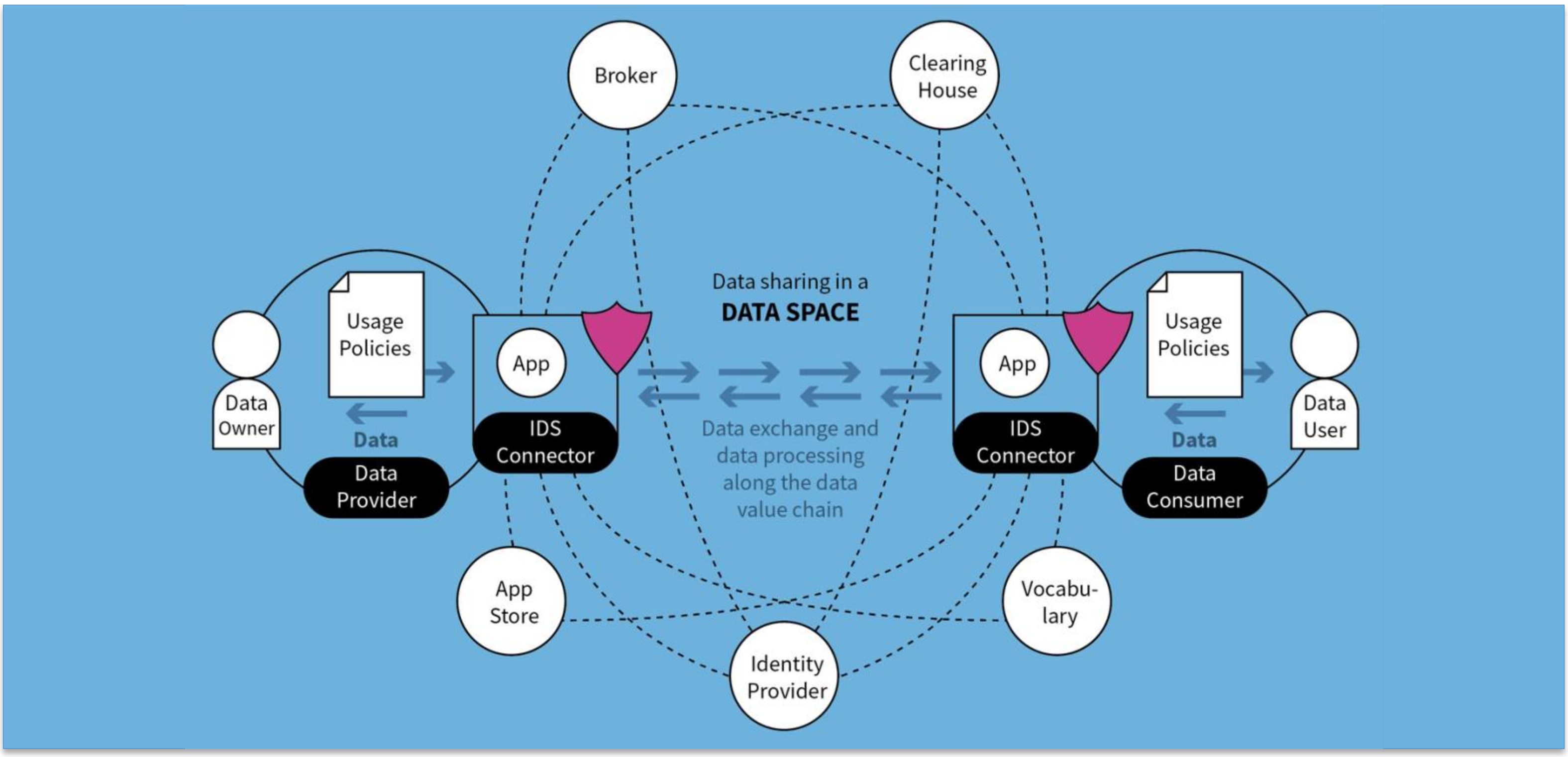

Figure 4: Schematic architecture of a data space. Source: Own representation iRights.Lab based on IDSA.

Both architectural approaches demonstrate how cross-border data exchange, interoperability, and data sovereignty can be technically designed and implemented, thus providing valuable starting points for conceptualising Transnational Digital Twins. In addition, architectures like these provide opportunities to create and (further) develop semantic (i. e. understanding of data) and syntactic (i. e. structuring of data) technical standards for data exchange and to design governance and business models for cross-border or multi-country collaboration.

2.4 Developing a working definition of Transnational Digital Twins

Drawing on the institutional and political–strategic frameworks and existing application-oriented architectures to technically implement Transnational Digital Twins as well as insights from expert interviews, a working definition of Transnational Digital Twins is developed in the following, based on the core definition of Digital Twins in infrastructure and municipalities (see section 2.1).

Across interviews and the literature review, a Transnational or Cross-Border Digital Twin is described less as a single, centralised, or even monolithic, all-encompassing digital model and more as a federated digital infrastructure that enables digital representations of physical systems, processes, and objects to function continuously across boundaries that currently fragment data, systems, and meaning.

Like Digital Twins, Transnational Digital Twins are not a technology as such, but should be understood as an open concept whose implementation is based on different components such as digital models, sensors, data platforms, and applications. They connect multiple local, regional, and national Digital Twin instances without replacing them and interlink them at a higher level of digital communication in order to represent, analyse, and manage cross-border physical systems, objects, and processes. Cross-Border Digital Twins can therefore function as an instrument to enable the integration of heterogeneous data within one "single source of truth" and resources between and across local entities for a common goal or challenge. The functions and added value of Transnational Digital Twins vary, depending on the areas of application, concrete use case, and maturity level[56] of the Digital Twins (see chapter 3).

Dimensions of the term cross-border

In this report, the term "cross-border" or "across boundaries" is used in two, complementary senses. First, it refers to the geographical scope in which Transnational Digital Twins represent a reference object that extends across national borders or operates within a transnational space, such as border regions or shared basins, e. g. cross-border transport corridors, energy grids, environmental monitoring systems, and maritime areas like the Baltic Sea. In this context, cross-border denotes a physical reference object located in the border region of at least two countries, while transnational refers to systems acting across a broader multi-country space, following the definitory distinction of Interreg (see section 2.2). Second, it refers to administrative and jurisdictional boundaries, i. e. at the city, regional, federal, and European levels, as experts state. A researcher specialising in Urban Digital Twins[57] and sustainable infrastructure elaborates that the meaning of cross-border in this regard should be understood beyond geographical attributes, as going into different data spaces and domains. It thus includes a cross-sectoral or transversal dimension, integrating heterogeneous datasets from different domains (e. g. mobility, geographical information systems (GISs), environment, energy, waste, and demographics) into coherent digital representations that enable systemic, cross-topical analysis. For example, a concrete use case in mobility could be to integrate public transport supply data with GISs for routing and contextual data like demographics into a single digital representation applicable at city, region, and country scales.[58] The common conceptual thread is that objects, processes, and services should not "break" at these borders in the digital realm, but that Transnational Digital Twins often overcome existing system and platform boundaries.

System architecture and technical interoperability

This analysis shows that a prototypical architecture of a Transnational Digital Twin mostly follows a federated logic. To function technically, a Transnational Digital Twin requires an overarching layer for the structured exchange of data, models, simulations, and analytical results towards a previously defined specific problem within a defined use case (see section 5.1). A Transnational

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[56] Digital Twins, as well as Transnational Digital Twins, can be systematically categorised into six different maturity or complexity levels, from descriptive, informative, and prescriptive to simulative, decisive, and overarching Digital Twin functions. See the complexity model in Blüml et al. (2025) pp. 15ff.

[57] See Schubbe, N. et al. (2023). Urbane Digitale Zwillinge als Baukastensystem: Ein Konzept aus dem Projekt Connected Urban Twins (CUT). *zfv – Zeitschrift für Geodäsie, Geoinformation und Landmanagement*, (1/2023), pp. 14–23. https://doi.org/10.12902/zfv-0417-2022

[58] In the scope of cross-border projects relevant to this research focus, cross-domain mostly also implies a cross-organisational dimension: This is because the central function and added value of Digital Twins (see Blüml et al. (2025)) and similarly of data infrastructures such as data spaces lies in the integration of data from heterogeneous sources, which in most cases implies the integration of data from different organisations.

Digital Twin typically requires a high level of technical interoperability, among others (see chapter 5 for dimensions of interoperability). Such an architecturally federated Digital Twin relies on distributed data storage, allowing data to remain within its legal and organisational contexts while being made interoperable through shared infrastructures. Transnational Digital Twins mostly integrate not only open data but also confidential and private data requiring appropriate governance. The analysis shows that Cross-Border Digital Twin applications mostly require hybrid models of both open and proprietary data, especially in mobility operations, infrastructure assets, and other critical infrastructure. Here, data is often sensitive with restricted access for security reasons or data is often non-open and owned by the private sector, public transportation companies, vehicle fleets, or energy producers (see section 5.4). Hence, interview partners point to the importance of shared exchange mechanisms and standards (e. g. *X-Road*[59]–like approaches and geodata standards[60]) and to non-proprietary, modular architectures, such as open-source components and solutions that should be commonly implemented in Transnational Digital Twins to make them transferable and reusable across use cases. Data spaces can play a key enabling role as basic infrastructure of Cross-Border Digital Twin applications, since they can provide trusted environments for sovereign, secure, and interoperable data exchange. They increasingly function not only as data marketplaces but also as a marketplace for models and analytical results generated, e. g. by Transnational Digital Twins.

Organisational structure: multi-stakeholder consortia

Organisationally, Transnational Digital Twins often combine technical and social dimensions as their cross-border nature is not purely physical or infrastructural, but often also crosses established national procedures, standards, and administrative working cultures. Therefore, Cross-border Digital Twins are typically embedded in and implemented by multi-actor consortia as their inherent cross-border project scope requires cooperation among different municipalities, national authorities, infrastructure operators, research institutions, and private technology providers across cities, regions, and nation states (see section 5.2).

Implementation mostly in target state

There is consensus among interview partners that Cross-Border Digital Twin applications are not yet realised in practice as a fully integrated system of mature Digital Twin instances, but rather as a target state or vision: a convergent, federated, semantically aligned, digital ecosystem built upon shared data bases, open standards, and coordinated governance, in which digital representations of transnational or cross-sectoral reference systems, processes, or objects remain continuous across borders and capable of supporting higher-level system goals, such as traffic analyses across different countries. Currently, to conceptualise and implement Transnational Digital Twins, considerable challenges remain with regard to organisational, semantic, and technical interoperability, non-compatible standards across but also within sectors; divergent data

[59] See the X-Road Global website at https://x-road.global/

[60] See the Arbeitskreis Geodaten. (2025). *Interoperabilitätskonzept für Geodaten in der GDI-DE* (Version 2.2) [Konzeptdokument]. Koordinierungsstelle GDI-DE, Bundesamt für Kartographie und Geodäsie. https://www.gdi-de.org/download/AG_Geodaten_Interoperabilitaetskonzept_Geodaten_GDI-DE.pdf

structures, and regulatory constraints, especially concerning data protection, security, and sovereignty (see chapter 5). Based on these considerations, the following working definition of a Transnational Digital Twin in the mobility and infrastructure contexts can be formulated, which can be adapted to specific application contexts:

A ***Transnational or Cross-Border Digital Twin*** *is a digital representation of a physical object, process, or system, which extends across national borders or operates within a transnational geographical space. Unlike a single centralised model, a Transnational Digital Twin functions as an overarching and a federated digital infrastructure that interlinks Digital Twin instances at local, regional, and/or national levels for objects, processes, and services to remain continuous across geographical, administrative, sectoral, and system boundaries. Thus, the cross-border scope of Transnational Digital Twins is not purely physical or infrastructural; it also includes the consolidation of established national procedures, standards, and administrative cultures, therefore integrating both, technical and social dimensions. Hence, Transnational Digital Twins have the potential to integrate different technical, legal, administrative, and cultural systems and contexts through shared governance frameworks and semantically aligned data models.*

Organisationally, a Transnational Digital Twin usually requires close cooperation among public authorities, implementing actors such as infrastructure operators, research institutions, and private actors at municipal, national, and European levels. Technically, Transnational Digital Twins are typically designed as decentralised, federated systems in which data remains within its original legal and organisational contexts while being exchanged in a sovereign, secure, and an interoperable manner, often via data space infrastructures and common standards. The central added value of a Transnational Digital Twin lies in enabling coherent cross-border and cross-domain integration of heterogeneous data. This enables precise condition monitoring as well as simulation and forecasting functions that offer considerable potential for control and planning across boundaries, such as for predictive maintenance, thereby improving data-based decisions, coordination, and governance of transnational and transversal systems and infrastructures. In doing so, it provides a shared analytical layer and "ground truth" for informed decision making in complex multi-country or multi-domain contexts.

2.5 Distinction to related technologies and concepts

To give implementing actors an understanding of the concept of Transnational Digital Twins, their possible areas of application, and implementing requirements, it is useful to conceptually distinguish them from related concepts. This differentiation sharpens the conceptual definition and clarifies its added value relative to established approaches.[61] In the following, Transnational Digital Twins are distinguished in particular from data platforms, data spaces, and federated architectures. Since this report focuses on the cross-border nature of Digital Twins, the distinction is made primarily in relation to technical or data infrastructures that can perform similar functions to Transnational Digital Twins.

[61] The core concept of Digital Twins must also be distinguished conceptually from related concepts, depending on the application context in which they are considered, in particular building information modelling (BIM), geographic information systems (GISs), and digital shadows. See Blüml et al. (2025), p. 8.

Data platform: Data platform is the collective term for all digital infrastructures that store, provide, and make data available for processing, from open data portals and so-called National Access Points (NAPs) to sectoral marketplaces and data spaces. They can be organised centrally (as a national platform such as the German Mobilithek[62]) or federated–decentralised (as data spaces) and range in function from data storage to analytical services and complex integration and exchange layers. They are a necessary but not sufficient prerequisite for cross-border applications. Transnational Digital Twins are often based on data platforms, but also require explicit governance mechanisms for cross-border data access and multi-level interoperability and for a federated architecture (see section 2.3). They are, therefore, a specific manifestation of data platforms.

Operational digital platform: In the context of Transnational Digital Twins, especially in the transport and infrastructure sectors, Operational Digital Platforms (ODPs) are particularly relevant. The term was coined by the European Commission and refers to a specific type of digital platform in the energy and transport sectors. ODPs are intended to "retrofit" existing infrastructure and to advance the digitalisation of these sectors, improve interoperability and standardisation, and stimulate investment in cross-border digital infrastructure.[63] Although not fully standardised in practice, an ODP can be understood as an infrastructural and organisational basis for transnational data use, on which Transnational Digital Twins can be built as a specific application or service. An ODP thereby aims to improve interoperability across sectors and countries in Europe, as the head of operations of a pan European project developing an ODP in the energy sector emphasises.

Data space: Data spaces such as the Common European Data Spaces driven by initiatives such as GAIA-X[64] and the IDSA[65] are concepts that could potentially support Transnational Digital Twins. The core element of data spaces is an established, standardised, and legally secure mechanism for a sovereign data exchange across organisational and legal boundaries. The technical and semantic interoperability provided by data spaces can significantly reduce the integration effort of heterogeneous data that was previously required as the basis for a Transnational Digital Twin. At the same time, data spaces are increasingly becoming marketplaces for data sets and are also offering so-called "added services", which enable, for example, analyses of data made available via the data spaces, as an expert in the field of data spaces emphasises. Transnational models and simulations could thus be understood as a future service in the sense of a Transnational Digital Twin.

[62] See the Mobilithek website at https://mobilithek.info/

[63] See the European Health and Digital Executive Agency. (26 June 2025). *Operational Digital Platforms* (Version 1.0, Issue CEF-DIG-2025-PLATFORMS). Retrieved from https://hadea.ec.europa.eu/programmes/connecting-europe-facility/about/operational-digital-platforms_en and https://www.euro-access.eu/_media/file/902_call-fiche_cef-dig-2025-platforms_en.pdf

[64] See the Gaia-X website at https://gaia-x.eu/

[65] See the International Data Spaces website at https://internationaldataspaces.org/

Attribute	Data Platform (Overarching Category)	Operational Digital Platform (ODP)	Data Space	Transnational Digital Twin (TDT)
Function	Data storage, data provision, and data processing	Efficient flow, storage, processing, and analysis of data for transport or energy infrastructure or both	Confident and interoperable data exchange	Digital representation of physical systems; simulation, analysis, and control across national borders
Architecture	Centralised or decentralised	Centralised or decentralised	Federated/ decentralised	Comprehensive Digital Twin with partially autonomously acting twins (centralised or decentralised)
Data storage	Centralised or decentralised	Centralised or decentralised	Decentralised; data remains with the data owner	Uses external data sources; includes models and simulations
Governance	Variable depending on platform type	Variable depending on platform type	Core components: access rights, identity management, and terms of use	Implemented through its underlying architecture
Interoperability	Variable	Designed for seamless integration with existing and emerging digital platforms, data exchange frameworks, and EU-supported initiatives	Standardised (connectors, protocols, and semantic models)	Dependent on source data and underlying data infrastructure
Cross-border Orientation	Possible, depending on platform design	Explicitly cross-border focus	Explicitly cross-border/ overarching focus	Intrinsically transnational orientation; can be built upon federated Digital Twins and/or data spaces
Relation to Transnational Digital Twins	Necessary but insufficient infrastructure: TDTs build on data platforms but extend beyond them in governance, interoperability, and federated architecture	Infrastructure upon which TDTs can be built	Enabling infrastructure providing the technical and legal exchange environments required for cross-border data access in TDTs	

Table 1: Comparison of data platforms, ODPs, data spaces, and Transnational Digital Twins. Source: Own representation iRights.Lab.

3. Added Value and Functions of Transnational Digital Twins

As digital representations of physical objects, processes, and systems such as infrastructures, Transnational Digital Twins can enable new forms of cross-border data integration and coordinated governance. In areas of application, such as planning and operation of transport networks, urban planning, and public services that expand across borders, they can support the development of shared data infrastructures, thereby fostering interoperability through standards and system-level analytical capacities that support visualisation, simulation, forecasting of the physical reference object, and evidence-based decision making across domains and jurisdictions. This added value is particularly relevant at national and local levels when Digital Twins reach their limits because the physical system, data base, and operational responsibility do not end at one administrative boundary, but instead extend across countries, sectors, and governance levels.

There are generally two analytical levels used to determine the added value of (Transnational) Digital Twins[66]: Firstly, Digital Twins can offer *overarching* benefits, for example, for cities, infrastructure operators, and administrations at the national or European level, such as resource efficiency of urban infrastructure planning. On a national level, this typically refers to improved planning processes, monitoring, operation, and maintenance within one institutional or geographical framework, for example, for a federal road system or a municipal Urban Twin. Secondly, *function-specific* benefits of Digital Twins can be described, for example, predictive maintenance of infrastructure objects. For this purpose, different levels of complexity of a Digital Twin and the resulting benefits and technical requirements can be differentiated along a complexity or maturity model.[67] As most Transnational Digital Twins are still at an early planning or an early demonstrator stage compared to the implementation status at a national level[68] (see section 2.4), assessing the detailed, function-specific benefits is mostly preliminary.

The following section thus focuses on the *overarching* benefits of Transnational Digital Twins, especially for implementing actors such as infrastructure operators and in the transport, mobility, and infrastructure sectors. Furthermore, added value that can already be achieved through national Digital Twins is distinguished from added value that only emerges when data, actors, and processes are connected across borders.

From national to transnational: Added value of Digital Twins across borders

The interviewees broadly agree that scaling Digital Twins across geographical or sectoral borders is strategically highly relevant within the EU (see section 2.2), particularly where physical infrastructures and services are inherently transnational such as in traffic planning and infrastructures in border regions. The transnational added value lies not only in the larger spatial scope, which initially increases complexity, but also in the possibility of representing interconnected systems as one functional whole despite being governed by different national and administrative systems, institutions, and technical standards. The relevant functional space is thus defined less by administrative borders and more by the actual system logic of the infrastructure.

[66] See Blüml et al. (2025), pp. 11–22.
[67] Ibid., p. 15.
[68] Ibid., pp. 23–38.

Transport corridors, electricity grids, and commuter networks, for example, do not cease to function at national borders, but rather continue across them as physically and operationally connected systems. Transnational Digital Twins, thus, can provide a more realistic and holistic representation of complex, cross-border systems to better analyse interdependencies and provide more reliable information about the overall system.

Similarly to Digital Twins on a national level,[69] Transnational Digital Twins vary in function and added value depending on application domain, concrete use case, and maturity level; they are not an end in themselves but rather highly context-dependent. This means that a Cross-Border Digital Twin is only warranted when a genuinely shared problem exists and services, processes, and objects require shared governance and representation because their functionality would otherwise be limited as in the case of coordinated traffic management, corridor planning, and the coupling of mobility and energy systems across borders (see chapter 4). Experts emphasise that if traffic analyses should include commuter flows from neighbouring countries or cities, a Digital Twin representing this reality would need to be transnational thereby justifying the added layer of complexity of scaling individual Digital Twin applications. Furthermore, as an assistant professor and director of a research centre on smart cities underlines, the public value of the Digital Twin concept is another relevant factor for measuring the benefit but also suitability of Cross-Border Digital Twins, especially in urban contexts. This could be, e. g. enhancing transparency across domains of decision-making processes by using Digital Twins as an instrument of communication (see below). A Digital Twin at the national level can improve communication within one entity, e. g. a city, system, or country, but transnationally, a Digital Twin can also make cross-border interdependencies visible, for example, regarding commuter flows, freight routes, energy demand, and environmental impacts. However, measuring the concrete impact of Transnational Digital Twins, such as the transparency achieved, can be challenging and costly, as experts point out.

The head of operations of a pan-European project in energy and mobility highlights the consensus about the benefit and need for shared data platforms and Digital Twin applications in mobility on a European level. This is particularly relevant because mobility constitutes a highly interconnected system and thus illustrates that transnational use cases are especially meaningful where national systems are already functionally linked, for example, through cross-border traffic, rail corridors, and interconnected energy networks. To support the development of Transnational Digital Twin applications, national solutions form a logical starting point for cross-border endeavours, but should be designed early on with scalability and interoperability in mind to subsequently enable horizontal (cross-border) and vertical (multi-level) integration if needed.

In other words, a Digital Twin on a national level should not be designed as a standalone solution or application if the referenced system, object, or use case is likely to extend beyond sectoral, administrative, or national borders in the future. Instead, it could be useful to be conceived as a scalable and reusable component that can be integrated later on into a federated and an interoperable Digital Twin architecture. For instance, a Digital Twin for rail infrastructure and asset management at the national level should ideally be designed from the conceptual stage with

[69] Ibid., p. 11.

standardised and interoperable components to allow the reference object to be extended and integrated later into larger, potentially Cross-Border Digital Twin systems.

Furthermore, it is important to enable cross-cutting use cases, i. e. approaches that are replicable in other cities, topics, and sectors like an approach for collecting and evaluating urban mobility indicators (mandated by the EU) in Digital Twins that work for all cities. Here, the specific transnational benefit lies in reuse and comparability across locations, not in replacing local solutions, but rather in connecting them through shared standards and transferable architectures. Compared to Digital Twins at the national level, the added value is therefore not so much the creation of a single “domestic” source of truth as the creation of a shared analytical layer across multiple jurisdictions. The main areas of potential for Transnational Digital Twins are summarised below.

Promoting cross-border data sharing and interoperability

Project responsibles for implementing Digital Twins and experts widely agree that a core function and an added value of cross-border applications lie the ability to promote interoperability, thereby contributing to greater consistency, harmonisation, and integration of data across the EU and the development of European data spaces (see section 2.2). This is especially relevant because the same type of infrastructure often has different data representations, metadata structures, and operating routines from one country to another, making direct reuse difficult without a transnational framework (see section 5.4). Transnational Digital Twins can help to aggregate this heterogeneous data from multiple domains such as transport data, GISs, demographics data, and more, allowing system-wide, cross-domain assessments of planning decisions, such as new urban districts and rural mobility redesigns (see chapter 5.4 for current hurdles). A Digital Twin can already integrate several datasets; a Transnational Digital Twin adds value where the datasets originate from different legal systems, institutions, and technical environments and therefore need to be made interoperable before they can be jointly used. In the mobility sector, for instance, insufficient and fragmented data often hinders cross-border transport planning. This means that a Cross-Border Digital Twin could support coordinated rerouting, harmonised passenger information, and joint traffic management in a border region when a disruption occurs on one side of the border but affects both sides operationally. Furthermore, in cities, (urban) Digital Twins, provided they are conceptualised for potential scalability across borders, can function as a tool to integrate and cross-reference heterogeneous data sources, enabling a more comprehensive analysis and thereby making infrastructures more resilient and reaction times quicker in times of crisis, like a pandemic.

Resource efficiency and sustainability

Similar to Digital Twins at the national level, resource conservation and sustainability in infrastructure, mobility, and urban planning are major drivers for the adoption of Transnational Digital Twins. In a transnational setting, this resource efficiency is not only about saving material, time, and energy within one system but also about avoiding duplicated planning, inconsistent investments, and fragmented capacity use across multiple systems that actually operate as one interdependent network. Across the mobility, transport, and energy sectors, experts emphasise the added value Digital Twins have to use resources more efficiently by integrating heterogeneous datasets, visualising system interdependencies, and enabling simulation-based optimisation of real-world processes.[70] Potential use cases include cross-border traffic management, where one incident can trigger coordinated responses in several countries, and coordinated planning of charging infrastructure, where transport demand, grid capacity, and spatial planning data are analysed together (see sections 4.1.3 and 4.1.4).

In transport and infrastructure contexts, Transnational Digital Twins can contribute significantly to carbon dioxide reduction and energy efficiency by digitally tracking goods, services, and their carbon footprints across supply chains and borders. This is particularly relevant for international freight corridors, rail logistics, and port systems (see section 4.1.1) that cannot be assessed functionally within one national boundary alone. By aggregating and harmonising data across jurisdictions and multiple domains such as mobility, energy, environment, and spatial planning, Cross-Border Digital Twins can make emissions and energy consumption visible in their full system context and reveal effects that would otherwise remain hidden in single-country analyses, such as emissions shifting between corridors and congestion displacement across borders. This enhances transparency and supports compliance with climate targets and regulatory requirements that increasingly operate at a European scale. By combining data from multiple domains, the added value of Transnational Digital Twins extends beyond the benefit at a national level because the relevant planning question often lies in the interaction between systems rather than in the optimisation of a single system in isolation. Cross-domain sustainability assessments, for instance, show how decisions in one sector affect resource demand and environmental performance in another, e. g. how the electrification of mobility influences electricity demand, grid load, and renewable energy needs across regions. A technical manager of a European energy project notes that cross-border architectures for Digital Twins are particularly relevant for maximising resource sharing to achieve outcomes that surpass what individual nations or actors can accomplish alone. Architectures like these enable coordinated management of interconnected systems at the European level, supporting not only market integration but also a more efficient and balanced use of shared and existing resources across member states. In this sense, the sustainability benefits commonly associated with national Digital Twins extend logically and structurally to Transnational Digital Twin frameworks.

Efficiency gains and resilience

Efficiency improvements, particularly operational gains, are especially evident in transport infrastructure. Digital Twins can offer efficiency gains across the full lifecycle of transport infrastructure: planning, construction, maintenance, and operation. For national infrastructure operators, this means that transnational solutions can reduce duplication of development work, improve comparability of methods, and allow them to benefit from shared standards and reusable modules developed together with partners in other countries. Concrete use-case scenarios include the coordination of maintenance windows across borders, the harmonisation of infrastructure condition data, and the shared evaluation of construction impacts on international corridors. Analyses and simulations based on integrated data enable more informed decisions and support cost-efficient, predictive maintenance as well as optimised operations of assets such as bridges,

[70] See Blüml et al. (2025), p.13.

tunnels, rail tracks, and road corridors, as a project lead in railway infrastructure research and development states. Compared to a Digital Twin at a national level, the transnational benefit arises when such assets are part of a continuous cross-border corridor and one operator's decision directly affects the capacity, reliability, and safety of the system as a whole. A key contribution, as stated by experts, lies in improving monitoring and asset management. By continuously integrating condition and operational data, Digital Twins help reduce unplanned downtime, enhance availability, and strengthen infrastructure resilience. In transnational systems, this becomes especially relevant for corridors in which a fault, delay, or maintenance measure in one country immediately affects traffic, capacity, or service quality in neighbouring countries. This is particularly relevant for interconnected, cross-border corridors, where the reliability of each segment affects the overall system.

Digital Twins can also reduce inefficiencies caused by fragmented information flows, inconsistent documentation, and coordination gaps among stakeholders. This is not only an efficiency issue within one entity or system but also a transnational coordination issue, because different national documentation practices, interfaces, and data standards can slow down or distort decision making across borders. Providing standardised and shared data environments helps minimise delays, avoid redundant processing, and improve collaboration among planners, operators, and public authorities. A practical example would be a shared incident or view of disruptions that can be used by infrastructure operators in adjacent countries to coordinate rerouting or service adjustments without having to process the same information separately. For instance, in cross-border traffic management, a traffic jam or accident in one country could automatically trigger a standardised data exchange, co-ordinated rerouting, and aligned traffic information in neighbouring countries. Beyond operational efficiency, continuous traffic monitoring and data-driven simulations — frequently cited as core use cases by implementing actors — enable more responsive and resilient planning. For national projects, this may already support better planning within one system; for transnational projects, it can also enable scenario analysis across interdependent systems whose effects cannot be captured inside a single national view. By combining cross-domain and cross-border datasets, Transnational Digital Twins can support systemic impact assessments by, for example, examining how mobility planning interacts with environmental or demographic developments, thereby strengthening adaptive governance in times of disruption. This is particularly valuable for border regions and international corridors, where disruptions, climate events, and supply bottlenecks produce spill-over effects across jurisdictions.

Communication, reuse, and scalability

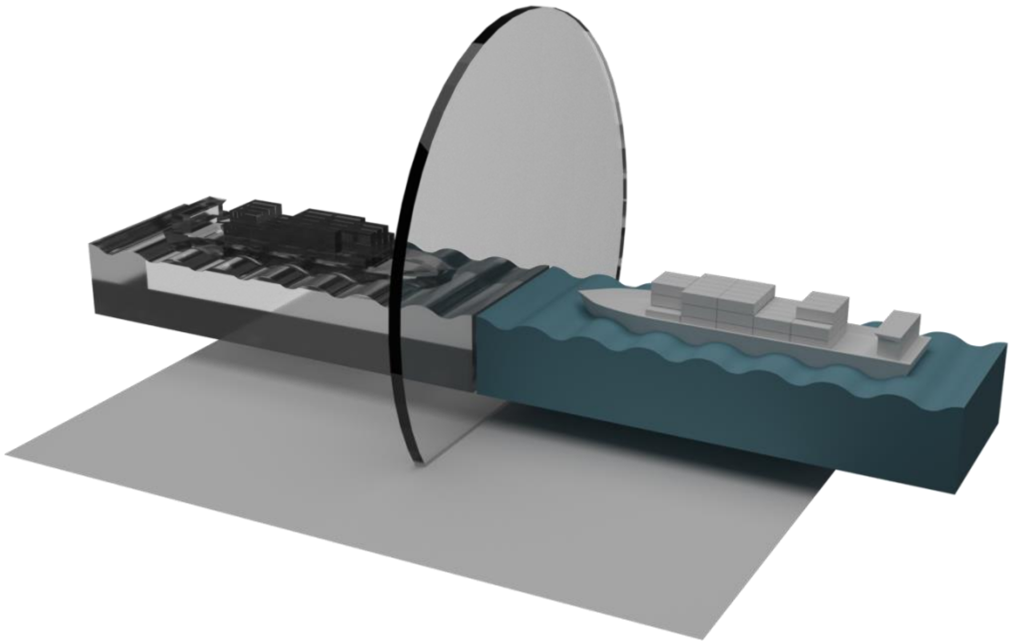
Enhancing communication, reuse, and scalability are central added value of Transnational Digital Twins, particularly due to the predominant stakeholder structures of multi-country projects, which typically involve large consortia, diverse stakeholder groups, and cross-sectoral collaboration (see section 5.2). Compared to Digital Twins, the transnational added value lies less in the communication effect itself and more in the possibility of transferring solutions, governance structures, and technical building blocks across countries and sectors. This requires structured communication both internally among project partners and externally towards target groups, with a strong emphasis on knowledge transfer and long-term usability of results. In practical terms, this means that outputs should not remain project-specific prototypes, but rather should be designed as reusable modules, shared standards, or transferable reference implementations (see section 5.5). In particular, a key motivation for implementing actors from both the public and private sectors to engage in Transnational Digital Twin initiatives lies in avoiding duplication of work and parallel structures, which is currently visible especially in cities (see sections 4.1.3 and 5.7). Across Europe, municipalities face comparable challenges, ranging from climate adaptation and sustainability targets to the operation, monitoring, and optimisation of transport infrastructures and mobility services.[71] According to several experts, the needs of European cities are largely similar, and a convergence of requirements across municipalities is visible. They often seek non-proprietary, modular, and extensible solutions. Although solutions are not directly transferable one-to-one, system architectures can be adapted and reused across contexts. This is relevant for national actors, because modularity and openness reduce vendor lock-in and make later scaling across borders or into adjacent sectors easier. This adaptability enables inter-municipal and cross-border cooperation, helping to overcome language barriers and differences in administrative systems while fostering mutual learning. In a national setting, the same modular logic helps with replication among federal states, municipalities, and agencies; in a transnational setting, it also enables alignment among different legal, technical, and organisational frameworks. Similarly, national infrastructure actors face comparable problems that are often solved repeatedly in separate institutions, sectors, and regions instead of being coordinated through common architectures or by using common building blocks. In both application cases, local contexts differ, but many underlying problems are shared. Transnational Digital Twins are therefore seen by experts as instruments to ensure that results of pilot projects remain usable beyond project lifetimes and that digital assets persist. The transnational benefit is that local use cases can be designed from the outset to be interoperable and comparable, so that one city's or one country's findings can inform another's without complete redevelopment. As a leading expert and deputy chair of several European initiatives on (Urban) Digital Twins notes, cities often experience that *"when the pilot finishes […] very few digital assets remain"*, which creates a strong incentive to participate in European-level initiatives that support lasting infrastructures and shared benefits.

This replicability is enabled and therefore closely connected to interoperability standards and semantic data models. As a professor in the field of open data and Digital Twins in the public sector emphasises, if Digital Twins are structured in interoperable layers that can be adopted by neighbouring cities (or sectors) using the same standards and tools, they form a shared infrastructure capable of addressing multiple problems simultaneously. Beyond isolated monitoring platforms, for instance, for mobility or environmental variables, Transnational Digital Twins can enable cross-topical analyses, such as assessing interactions between mobility systems and environmental impacts. Existing use cases show that at the moment, it is mostly correlations among transport, energy, environment, and spatial planning data and the integration of traffic flows, charging-point availability, energy grid capacity, and spatial planning data into cross-border charging infrastructure planning that are targeted in a cross-topical analysis.

[71] Chovancová, J., Petruška, I., & Pata, U. K. (2024). A Cross-National Study on Sustainable Smart City Indicators and Their Influence on Life Expectancy—A Cluster Analysis of EU Countries. Urban Science, 8(4). Doi: 10.3390/urbansci8040164.

4. Areas of Application and Use Cases of Transnational Digital Twins

Transnational Digital Twins are becoming increasingly important, particularly in the areas of mobility, transport, and critical infrastructure and especially in the energy sector, as central planning, operational, and steering mechanisms in these areas typically do not end at national borders. Traffic flows, supply chains, energy and data networks, and environmental and climate phenomena have inherent regional and cross-border effects. Digital Twins have the potential to model complex systems based on data, visualise interactions, and support decision-making processes. At the same time, Transnational Digital Twins clearly have significantly higher requirements than local or national Digital Twin applications. For national infrastructure operators, this also means that a Transnational Digital Twin is not simply a larger version of a local twin, but rather a different coordination effort with more actors, more interfaces, and more potential legal and organisational constraints. There is a high level of technical integration, fragmented data infrastructures, institutional requirements (see chapter 5), and project complexity, as evidenced by the fragmented empirical landscape of Transnational Digital Twins. This is summarised below as the status quo of the implementation of Transnational Digital Twins and then systematically analysed according to five categories. A total of 77 thematically relevant research and application projects were identified, systematically categorised, and analysed with regard to their application contexts and areas of use, functions, data infrastructures, and cooperation structures (see Appendix I for project overview of use cases). The range of these projects shows that the transnational field is still heterogeneous and not yet consolidated into one dominant model and that it tends to develop through sector-specific and geographically limited use cases.



4.1. Key application areas for Transnational Digital Twins

Based on this analysis of existing use cases, desk research results, and interviews, several key areas of application can be identified, which are considered particularly relevant for the potential implementation of Transnational Digital Twins. Within the EU, a total of 77 projects and initiatives in the areas of mobility, infrastructure, and cities were identified that deal with various aspects of Cross-Border Digital Twins, data spaces as possible preliminary stages or foundations for Transnational Digital Twins, and similar data-based projects (for methodology, see chapter 1).

Figure 5: Overview of use cases of Transnational Digital Twins and similar initiatives in Europe. Source: Own representation iRights.Lab created with kepler.gl.

For the systematic analysis of relevant use cases, the existing projects were divided into five categories covering different application areas: Mobility: Transport management and planning; Environmental and climate research; Cities and urban governance; Energy and crisis prevention; and the overarching category of Border regions.

The category **Mobility: Transport management and planning** results from this research project's thematic focus on mobility and infrastructure (see chapter 1). This category covers applications in rail, water, and road transport infrastructures, including operational control and planning applications and also projects whose implementation and research goals can further develop the structural prerequisites for transnational applications. Within this category and in addition to specific relevant application projects, mobility-related data space initiatives and National Access Points were also taken into account, as they can help establish a standardised and an interoperable data base for cross-border traffic control, simulation, and planning.

The category **Environmental and climate research** reflects the high technical and structural potential of this area for Transnational Digital Twins. This category is analytically useful because environmental phenomena such as climate, weather, and marine areas are not bound by political and administrative borders and are typically considered in transnational and international contexts. Furthermore, there are already numerous Digital Twin use cases in this field with a comparatively high degree of maturity, as relevant research and technical infrastructures are often already well developed.

The category **Cities and urban governance** comprises projects that digitally model and represent urban infrastructures and planning processes, thus representing a central operational implementation level. In particular, this category encompasses the development of Urban Digital Twins, which are used for strategic planning support, mobility management, and energy and environmental analyses in urban regions. This category acknowledges that use cases in cities and regions as well as funding for Urban Digital Twins are currently key drivers within the EU for scaling Digital Twins, with cities acting as integration spaces for various sectors and central drivers. In particular, use cases in planning, simulation, and resilience as well as initiatives for the development of federated architectures and interoperable toolboxes are included.

The category **Energy and disaster prevention** arises from the inherent cross-border nature and strategic importance of energy and supply systems. It covers, in particular, applications for resilience, reliability, and fault-tolerance simulation, load and flexibility management, and the integration of energy and mobility systems. Furthermore, platform approaches that enable the cross-border exchange of network and supply data are taken into account, as they are a functional prerequisite for Transnational Digital Twins.

The overarching category **Border regions** considers projects that are located in functionally interlinked but administratively distinct areas. Although the category entails use cases related to mobility, urban, and energy aspects, a separate category is useful, as challenges related to interoperability, governance harmonisation, and data coordination are particularly prominent here. Border regions thus serve as practical testing grounds for Transnational Digital Twins, where technical and institutional integration requirements become clearly visible.

Some of the identified use cases and projects overlap with several categories. In these cases, the category that best suits the focus of the project was selected. For example, the Begonia[72] project aims, among other things, to optimise the supply chain in the context of e-mobility (charging infrastructure, utilisation, route planning, etc.), but its central focus is on cross-border energy systems, so it was assigned to the **Energy and disaster prevention** category. Assigning projects was not based exclusively on sectoral criteria, but rather on the primary application focus in the context of transnational integration.

4.1.1 Mobility: Transport management and planning

Based on this analysis and the evaluation of the interviews, the mobility sector[73] was identified as a particularly suitable field of application for transnational digital applications such as Digital Twins, as the ever-increasing global movement of goods and people necessitates the need to maintain and

[72] For the Begonia project website, see https://www.begonia-project.eu/

[73] Due to a lack of publicly available information on projects and strategies in this area, the field of aviation can only be touched upon in this analysis.

optimise underlying infrastructure. Mobility and transport, like climate phenomena, are inherently cross-border in nature and have high scaling requirements and potential. For national actors, the added value lies in better domestic planning and operations; for transnational actors, it lies primarily in coordinated corridor management, harmonised information flows, and shared responses to disruptions. In the context of data space initiatives, mobility-related use cases were frequently cited in expert interviews as prototypical examples of cross-border applications. For example, disruptions and irregularities in traffic can be detected and remedied at an earlier stage, and operational management, i. e. of public infrastructures, can be made more resilient to the effects of climate change. Concrete application scenarios include cross-border traffic and congestion management, simulation of traffic flows at border crossings and junctions, rail operation applications for timetable and disruption analysis, and interoperable ticket and information systems across national providers. Accordingly, the transportation and mobility sector has the highest maturity level and potential for creating, operating, and scaling Digital Twins across borders. This does not mean that the sector is already mature in an operational sense, but it does offer the clearest structural rationale for transnational scaling. The monitoring and automated management of traffic offers enormous potential for reducing friction points resulting from different national governance approaches, regulations, and bilateral agreements. An evaluation of existing application scenarios and use cases for mobility shows that the following functions and use cases of Transnational Digital Twin or preliminary stages are currently the most relevant:

- Cross-border traffic and congestion management;
- Simulation of traffic flows at border crossings and junctions;
- Rail operation applications for timetable and disruption analysis;
- Asset and process Digital Twins in rail transport;
- Multimodal mobility services;
- On-demand transport;
- Interoperable ticket and information systems across national providers.

Mobility Data Spaces and National Access Points

The large number of data space initiatives in the field of transport and mobility demonstrate their high potential and the demand for transnational (data) cooperation. For national infrastructure actors, these initiatives are relevant because they offer a way to connect existing national data ecosystems to a broader European architecture without fully centralising data ownership or operational responsibility. Initiatives such as the European Mobility Data Space (EMDS),[74] national mobility data spaces,[75] and Eona-X[76] aim to facilitate the interoperable and trustworthy exchange of mobility data in areas such as logistics and private mobility, thereby contributing to the creation of the European data economy (see section 2.2). Their role in the transnational context is to provide the data foundation on which Cross-Border Digital Twins can later operate, especially when operational, proprietary, or sensitive data is involved. In this sense, EMDS is a particularly ambitious and comprehensive EU initiative as it is cross-border in nature; it is relevant not as a Digital Twin in

[74] See the deployEMDS website at https://deployemds.eu/
[75] See the Mobility Data Space Website at https://mobility-dataspace.eu/
[76] See the Eona-X website at https://eona-x.eu/

itself, but rather as an enabling environment for a federated data exchange, shared use cases, and interoperable mobility services.[77] As part of EMDS, specific use cases such as multimodal route planning, traffic-related environmental monitoring, and barrier-free mobility are being implemented at nine European locations. The overarching goal is to enable data exchange and reuse as the foundations for a common European Mobility Data Space.[78] The project is creating a federated, cross-border data space that can serve as a central prerequisite for Transnational Digital Twins in the mobility and transport sector, as it facilitates the integration of heterogeneous data sources, the simulation of multimodal scenarios, and the development of scalable, sovereign applications.

Furthermore, the creation of new central platforms for open mobility data highlights the importance of mobility as a key area of application for Transnational Digital Twins. In addition to existing open data portals, the EU requires the creation of National Access Points (NAPs) in its member states.[79] These platforms, such as the German Mobilithek and more than 30 others,[80] collect and publish mobility-related datasets, thereby creating an essential prerequisite for interoperable, cross-border data infrastructures and strengthening the development and implementation of transnational applications in the mobility sector by increasing the availability of mobility data (see section 5.4). These NAPs are particularly relevant for national actors because they create a standardised entry point for mobility data. With regard to specific areas of application and functions, they already include data on the road network, traffic and operating conditions, travel planning, location search, passenger services, and secure truck parking areas. In the future, vehicle-generated data, cooperative intelligent transport system (C-ITS) services,[81] and shared mobility data, for example, are to be integrated as well. For Transnational Digital Twins, this means that NAPs are an important but insufficient building block: they improve discoverability but not automatically semantic alignment and controlled cross-border integration. NAPs alone do not yet guarantee full interoperability, because differences in interfaces, data formats, access conditions, and implementation maturity persist among member states.

In the following, the sub-areas of mobility along the rail, water, and road transport infrastructures are systematically analysed with regard to their potential and existing use cases for Transnational Digital Twins. These subsectors differ in maturity and in the degree to which cross-border coordination is already structurally necessary.

Rail infrastructure and operations

[77] European Commission. (2025). *Unlocking the potential of mobility data | Shaping Europe's digital future*. Retrieved from https://digital-strategy.ec.europa.eu/en/policies/mobility-data

[78] European Commission. (19 March 2024). *DeployEMDS, der gemeinsame europäische Mobilitätsdatenraum beginnt Realität zu werden | Gestaltung der digitalen Zukunft Europas*. Retrieved from https://digital-strategy.ec.europa.eu/de/news/deployemds-common-european-mobility-data-space-starts-become-reality

[79] Based on the ITS Directive 2010/40/EU and its delegated regulations. See https://digital-strategy.ec.europa.eu/en/policies/mobility-data

[80] A complete list of all NAPs can be found here at https://napcore.eu/

[81] Cooperative intelligent transport systems (C-ITSs) are communication-based transport systems in which vehicles, roadside infrastructure, and other traffic participants exchange real-time information to improve road safety, traffic efficiency, and driving comfort. For instance, a roadside unit can transmit a warning about roadworks ahead to approaching vehicles, allowing drivers to reduce speed and adapt their route in advance. Retrieved from https://www.car-2-car.org/about-c-its/

Most of the potential applications for Transnational Digital Twins that have currently been identified can be found in the area of rail infrastructure, either as pilot projects or as “true” Cross-Border Digital Twins, albeit at a low level of maturity. This is because rail network infrastructure is inherently cross-border in nature, and its planning, operations, and control and steering mechanisms already require the coordinated exchange of timetable, capacity, and operational data among national infrastructure operators.

Currently, potential areas of application and functions of Transnational Digital Twins can be identified primarily in predictive maintenance, asset and process management, and, to a limited degree, in cross-border traffic management. Further possible use-case scenarios for Transnational Digital Twins include digital representations of rail vehicles and rail fleets as well as routes and assets such as switches and signals.

The objectives and possible applications of Transnational Digital Twins extend far beyond the optimisation of day-to-day business through early warning and fault detection. Comprehensive digitisation of asset management is intended to create transparency in border regions, for example, regarding how individual routes are equipped, and to facilitate cross-border coordination of maintenance measures. In addition, extensive static asset Digital Twins are widely used to digitally model infrastructure elements such as track networks, signals, bridges, and tunnels. In addition, sensor data is increasingly being used to model the condition of individual assets. The transnational scaling consists in linking these asset Digital Twins with operational process data and standardising the meaning of the data across operators and countries. However, cross-border simulations of disruptions, cascade effects, and operational variants are still a vision and not established in practice.

Overall, similar to German Digital Twin initiatives,[82] Transnational Digital Twins of rail infrastructures mainly focus on asset management, while their use for operational applications such as traffic management, timetable coordination, and other operational processes with real-time data remains limited. This suggests that many countries and cross-border projects are currently building comparable Digital Twin capabilities. A stronger coordination of these developments could therefore lead to national infrastructure operators benefiting from synergies in Digital Twin development through shared learning, common standards, avoidance of duplicate implementation efforts, and reduced interface problems. In the longer term, this could lead to greater interoperability between Digital Twin initiatives across borders and could promote the development of Transnational Digital Twins that represent a more integrated European system view. Such integration could improve European timetable creation and construction coordination and better align infrastructure planning across countries.

Rail4Future[83] is a national research and development project in Austria that aims to increase the resilience, availability, and reliability of rail infrastructure and create a Digital Twin of the rail infrastructure system by linking measurement data, simulation models, and AI applications. It focuses on representing the condition and behaviour of key infrastructure elements such as

[82] See Blüml et al. (2025).
[83] See the Rail4Future project website at https://www.rail4future.com/

switches, rails, bridges, and tunnels throughout their life cycle and across rail transport processes for predictive maintenance and operation and management. However, as a project lead in railway infrastructure research and development points out, the functional maturity of the applications varies depending on the type of asset. For instance, the project developed simulation and predictive capabilities for switches, whereas more complex assets such as tunnels remained in the monitoring stage. Overall, the Digital Twin will not only model the condition of individual components but also enable the virtual evaluation of operating scenarios, wear and tear, maintenance requirements, and innovations. This opens up a range of applications for Digital Twins and potential cross-border applications, from condition-based monitoring and model-based analysis to advanced predictive simulation approaches, depending on the respective asset and use case. Rail4Future therefore provides important conceptual foundations for subsequent cross-border applications in the area of rail infrastructure. The interviewees explicitly emphasise that a Transnational Digital Twin can only be realistically implemented if uniform data formats and harmonised models are available. Hence, Rail4Future is less a Transnational Digital Twin in the narrow sense and more a key component showing how Digital Twins can be functionally constructed in the rail sector at the national level and what requirements must be met for later transnational scaling.

In the cooperation project Railbaltica[84] involving the European countries of Estonia, Latvia, Lithuania, Finland, and Poland, approximately 870 km of new rail lines are being built to convert the Baltic rail network from Russian broad gauge to European standard gauge. In addition to the construction of this cross-border rail infrastructure, a Digital Twin of the entire operating infrastructure is also being developed. During the construction phase, this will make it easier to coordinate construction progress and further planning. The data collected during the planning and construction phases will form the basis for a Transnational Digital Twin that will map the entire cross-border infrastructure in the Baltic states. This will facilitate traffic control across three national borders and the simulation of traffic flows at border crossings and junctions in the future.[85] The project is one of the few “genuine” Transnational Digital Twin pilots, although it is in an early stage of implementation. Its new rail lines will span across three countries: Lithuania, Estonia, and Latvia. Following the definitory characteristics (see section 2.4), Railbaltica meets the criteria of a Cross-Border Digital Twin with the data currently being stored in one country, while the physical railway assets are being built in three countries. When the time comes for each country to maintain and use the infrastructure, the data will be split and given to each respective country.

The European funding project Flagship Project 1 MOTIONAL is part of the research and innovation programme Europe’s Rail Joint Undertaking (EU-Rail)[86] and aims to implement a digital, Europe-wide, harmonised control logic for railways, both technically and organisationally, and to support the development of the Single European Railway Area (SERA).[87] It aims to develop a future European Traffic Management System that is interoperable, resilient, and highly digitised, providing digital enablers such as Digital Twins with a multimodal environment. One interviewee makes it clear that

[84] See the Railbaltica website at https://www.railbaltica.org/
[85] See the Railbaltica website on virtual design and construction at https://www.railbaltica.org/virtual-design-and-construction/
[86] Europe’s Rail. Retrieved from https://rail-research.europa.eu/about-europes-rail/
[87] Europe’s Rail. Single European Railway Area. Retrieved from https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/single-european-railway-area-0

MOTIONAL is intended to create digital foundations for interoperable, cross-border applications in particular. To this end, common data models are created for infrastructure objects such as signals and converted into digital representations. These representations then serve as the basis for the Transnational Digital Twin. In addition, the Flagship Project 3 IAM4Rail,[88] which focuses on rail asset digitisation using Digital Twins, and Flagship Project 5 TRANS4M-R,[89] which focuses on the digitisation of freight transport, are working on other areas of digitisation and harmonisation of European rail transport.

Road infrastructure and operations

In addition to rail infrastructure, road infrastructure offers considerable potential for the planning and implementation of Transnational Digital Twins, as the existing infrastructure and processes are also inherently cross-border. At the same time, road traffic is already more harmonised, for example, through largely standardised traffic signs and the absence of central technical interoperability barriers, such as those that exist in rail transport due to different signalling systems, track gauges, and increased requirements for route-specific local knowledge. As a result, the need for transnational harmonisation in the road sector has been less pronounced to date, which is also reflected in a smaller number of practical Cross-Border Digital Twin use cases.

However, there is substantial potential for application scenarios, particularly in cross-border traffic management, predictive maintenance, and the coordinated planning of maintenance measures in border areas, such as new infrastructure measures, e. g. the Fehmarnbelt. Another key area of application lies in cross-border support for electromobility, particularly in the logistics sector. With the increasing prevalence of electric vehicles, the importance of cross-border charging infrastructure, data-based route optimisation based on traffic flow and availability of charging points, and coordinated integration into the energy grid is growing.

Overall, national infrastructure operators could benefit from stronger cooperation and knowledge exchange with their European counterparts as operators face similar challenges in traffic management and maintenance optimisation and increasingly pursue Digital Twin approaches to address them. The currently limited practical implementation of road infrastructure Digital Twin initiatives (for example, see Blüml et al. (2025), pp. 28–39) may further suggest that closer collaboration with other European operators could support more practice-oriented progress. This kind of cooperation appears especially important in areas shaped by European regulations, particularly Cooperative, Connected, and Automated Mobility (CCAM) and systems such as Cooperative Intelligent Transport Systems (C-ITSs). In these fields, harmonised data standards, interoperable systems, and aligned procedures are likely necessary to ensure reliable operation across borders. Moreover, border regions may benefit most, as infrastructure operators there regularly need to cooperate across different technical systems, languages, and administrative contexts. Common standards and improved exchange mechanisms, potentially enabled by

[88] Europe's Rail *Flagship Project 3: IAM4RAIL - Intelligent & Integrated Asset Management*. Retrieved 29 April 2026, from https://rail-research.europa.eu/rail-projects/fp3-iam4rail/

[89] Europe's Rail *Flagship Project 5: TRANS4M-R - Sustainable Competitive Digital Green Rail Freight Services*. Retrieved 29 April 2026, from https://rail-research.europa.eu/rail-projects/fp5-trans4m-r/

Transnational Digital Twins as the common infrastructure, could therefore reduce coordination efforts and improve cross-border collaboration.

As shown at a national level, tunnels and bridges could serve as potential flagship reference objects for Transnational Digital Twins, as many current projects are focusing on these asset types. A prominent national example is smartBRIDGE Hamburg, while the planned Digital Twin of the Fehmarnbelt Tunnel between Germany and Denmark provides a visible example of a transnational application.[90]

X4ITS (Cross for ITS)[91] is a large-scale implementation and harmonisation project for cross-border intelligent transport systems (ITSs) in road traffic. It standardises, synchronises, and links digital traffic and infrastructure services across six EU member states (Austria, Czechia, Croatia, Hungary, Romania, and Slovenia). The project has two central goals: The first one is to improve the cross-border coordination of traffic management plans. The aim is for traffic disruptions to trigger coordinated measures across national borders, for example, when a traffic jam in one country triggers early detours in neighbouring countries by means of standardised, machine-readable messages (e. g. DATEX II[92]). The second goal is to promote the implementation of cooperative intelligent transport systems. These are digital systems in which vehicles, road infrastructure, and traffic control centres can communicate with each other in real time. In practical terms, this means that information on accidents and recommended detours, for example, can be transmitted directly to appropriately equipped vehicles. C-ITS is also being promoted in other European projects such as c-roads[93] and the Meridian[94] project. The former focuses on the standardisation and further development of standards, while the latter concentrates on the implementation of C-ITSs in the Connecting Europe Facility (CEF) core network corridors[95] along the Scandinavian–Mediterranean and North Sea–Baltic.[96]

X4ITS focuses on the prerequisites for interoperable, cross-border data and communication structures, which can then be used to develop further data-based applications, such as the Transnational Digital Twin. According to project participants, a Hungarian motorway operator is planning to implement a Digital Twin within the project, which was still in the tendering and preparation stages at the time of the interview. Overall, X4ITS appears primarily as a transnational enabler structure for future data-driven applications, including potential Digital Twins, rather than as a fully developed Transnational Digital Twin project.

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[90] For the Fehmarnbelt Tunnel project, see https://femern.com/de/

[91] For the X4its project, see https://x4its.eu/

[92] DATEX II is a European data standard for exchanging road traffic and travel information among traffic authorities, service providers, and mobility systems, enabling consistent and interoperable data sharing across transport networks. See https://datex2.eu/

[93] See *C-Roads*. (12 April 2026). C-Roads.Eu. https://www.c-roads.eu/

[94] See *Meridian Corridors*. (19 June 2023). Meridian Corridors. https://meridian-corridors.eu/

[95] Core network corridors are strategic multimodal transport routes within the EU that coordinate infrastructure development and investment to remove bottlenecks, strengthen cross-border links, and improve interoperability across the European transport network. See https://transport.ec.europa.eu/other-pages/transport-basic-page/corridors_en

[96] For short- and long-term goals of Meridian Corridors and project overview see https://meridian-corridors.eu/news/short-term-and-long-term-goal-of-meridian/ and https://transport.ec.europa.eu/other-pages/transport-basic-page/corridors_en

Waterways and port management

In the field of water management, including ports, waterways, and international freight and passenger shipping, there is considerable potential for the use of Transnational Digital Twins, as maritime areas extend across borders and are inherently beyond national boundaries. The field of water and marine research is characterised by large-scale international research initiatives such as the Digital Twin Ocean[97] and the European Digital Twin Ocean (EDITO)[98] (see section 4.1.2*)*. Although the primary purpose of these applications is to model environmental influences, they also offer considerable added value for the mobility and infrastructure sector. Potential exists, for example, in the planning of maritime infrastructure such as wind turbines and submarine cables, in the simulation of climatic changes, and in the assessment of their impact on shipping routes, traffic control, and operational decisions.

In addition to large-scale projects related to seas and oceans, there are specialised projects that focus on specific sub-areas and application logics of water-related Digital Twins, e. g. TrilaWatt[99] and Ports & Waterways Digitalization Lab.[100] The latter aims to digitally model the condition and usability of shipping lanes, port connections, and traffic flows, thereby supporting operation, monitoring, and maintenance on a cross-border data base.

Furthermore, Digital Twins are used in cargo shipping mainly to improve navigation. Since important nautical conditions such as water depth, ice conditions, weather conditions, and hazardous situations are constantly changing, they are based on continuously updated environmental and traffic data. By linking sensor data, remote sensing, automatic identification system (AIS) information, and simulation models, Digital Twins can thus contribute to route planning, risk detection, and traffic management.[101]

One major field of application for Digital Twins in Germany[102] and other European countries is the port sector. Although ports are within individual nations, their effects extend beyond national borders. Ports are central hubs of international supply chains, and their operational performance influences not only local processes but also cross-border transport and logistics processes. This is precisely why port-related Digital Twins offer considerable potential to more efficiently manage infrastructure, traffic flows, and operations (e. g. Begonia[103]). Existing national projects aim to

[97] For the Digital Twin Ocean project website, see https://digitaltwinocean.mercator-ocean.eu/
[98] For the EDITO project website, see https://www.edito.eu/
[99] For the TrilaWatt project website, see https://trilawatt.eu/
[100] See TU Delft. *Ports & Waterways Digitalization Lab (PWD Lab)*. Retrieved 29 April 2026, from https://www.tudelft.nl/citg/over-faculteit/afdelingen/hydraulic-engineering/sections/rivers-and-ports/research/ports-waterways-digitalization-lab
[101] Further use cases can be found in the 2025 PIANC report. *Digital Twins for Operation and Monitoring of Inland Waterways and Infrastructure*. PIANC – The World Association for Waterborne Transport Infrastructure. https://izw.baw.de/publikationen/pianc/0/ToR%20InCom%20WG%20257%20-%20Digital%20Twins%20for%20Operation%20and%20Monitoring%20of%20Inland%20Waterways%20and%20Infrastructure.pdf
[102] See Blüml. et al. (2025), p. 31.
[103] For the Begonia project website, see www.begonia-project.eu/

increase the efficiency of port operations (e. g. TwinSim[104]) and improve the communication between ships and maritime infrastructure (e. g. DAVE[105]).

4.1.2 Environmental and climate research

Another area of application with considerable potential for implementing Transnational Digital Twins is environmental modelling and climate impact research. There are already several use cases in this field with a comparatively high degree of maturity, as relevant research and technical developments are often already well advanced. Furthermore, environmental analysis, research, and modelling are inherently cross-border activities. This is particularly evident in large international research initiatives such as Destination Earth (DestinE)[106] and the European Digital Twin Ocean,[107] which model natural systems such as climate, marine areas, coasts, tidal flats, and river landscapes that are not along national borders and therefore must regularly be considered in a transnational or international context. The aim of these initiatives is to better understand and predict cross-border environmental changes and to integrate them into planning and decision-making processes. These range from the simulation of sediment and current changes to the planning of coastal protection measures and the evaluation of long-term climate adaptation strategies in cities and regions.

A characteristic feature of applications in the environmental sector is the close cooperation among large European institutions and services (e. g. European Space Agency and Copernicus). Comparatively favourable conditions already exist in terms of data availability and data quality (e. g. on weather conditions, water composition, and climatic developments); interoperability; institutional cooperation; and available resources (e. g. large computing capacities and scientific modelling expertise) for the development of Transnational Digital Twins.

A noteworthy project in the context of Transnational Digital Twins is Destination Earth, which is developing two specialist Digital Twins: Weather-Induced Extremes Digital Twin and the Climate Change Adaptation Digital Twin. While the first supports in responding and adapting to extreme events such as floods, the latter simulates long-term climate scenarios to support adaptation and mitigation planning.[108] The project can be considered a special European case and one of the most advanced and ambitious Transnational Digital Twin projects to date as it is not focused on a single sector or a limited project duration, but rather is institutionally and strategically embedded in the European Green Deal, the Digital Strategy, and the European Data Strategy.[109] The aim of DestinE is to build a highly accurate digital model of the Earth system on a global scale that monitors, simulates, and predicts the climate, weather, oceans, land surfaces, atmosphere, and interactions with human activities. A Digital Twin data infrastructure manager of a global twin project emphasises that this analysis and these considerations are inherently transnational in nature since

[104] For the TwinSim project website, see https://www.innovativehafentechnologien.de/wp-content/uploads/2021/11/Projektsteckbrief_TwinSim_2021-11-04_ma-1.pdf
[105] For the DAVE project website, see https://www.bmv.de/SharedDocs/DE/Artikel/mFUND/Projekte/dave.html
[106] For the Destination Earth project website, see https://destination-earth.eu/
[107] For the EDITO project website, see https://www.edito.eu/
[108] For the Digital Twins of Destination Earth, see https://destine.ecmwf.int/digital-twins/
[109] For the European Commission Communiqué, see https://digital-strategy.ec.europa.eu/en/policies/destination-earth

climate- and weather-related modelling cannot be meaningfully undertaken at the level of individual countries; rather, these models operate on a global or world scale, from which local-scale applications are then derived.

From an explorative research perspective on Transnational Digital Twins, DestinE can be characterised as a mature reference architecture for Cross-Border Digital Twin infrastructures. With its large-scale modelling of the Earth system, DestinE creates not only a scientific infrastructure for climate, weather, and environmental simulations but also a scalable methodological and technical basis for cross-sectoral and local applications, such as mobility behaviour and energy systems. DestinE can serve as a useful reference not only for Transnational Digital Twins but also for national actors implementing Digital Twins as it may provide both technical and organisational guidance when developing similar projects. Technically, it illustrates how highly complex systems, such as the global climate and weather system, can be modelled in a structured, scalable, and operationally relevant way. This could offer useful insights for infrastructure operators seeking to represent similarly complex systems in domains such as mobility and energy (see also sections 5.4 and 5.5). Organisationally, DestinE also shows how Digital Twin initiatives representing complex systems may require cooperation across multiple institutions and stakeholders (e. g. political, scientific, and public authorities), with different actors contributing data, expertise, and governance input. In this regard, DestinE may offer valuable lessons for managing these broad stakeholder networks with their partly diverging interests (see also chapters 5.1–5.3).

4.1.3 Cities and urban governance

An important stimulus for research and development of Cross-Border Digital Twin applications is currently coming from cities and regions. Similar to the national level, cities play a central role in the European context when developing Transnational Digital Twins in their capacity as implementing actors and operators of these applications, since a large number of use cases converge within their areas of responsibility. The findings from this analysis show that the development of Urban Digital Twins has been increasingly promoted across Europe in recent years.[110] Typical use cases include, apart from the planning and management of buildings and the implementation and monitoring of environmental and climate protection measures, the optimisation of transport infrastructure, particularly with a view to supporting strategic planning. This includes, for example, the simulation and analysis of traffic flows such as commuter traffic and the management and optimisation of local road infrastructure.

Major EU initiatives in the mobility sector such as EMDS and Living in.EU are currently focusing primarily on urban applications. The ACUMEN[111] project, which is being implemented by the Luxembourg Institute of Science and Technology[112] is developing a Digital Twin architecture for mobility-related issues that will address traffic management, mobility planning, and energy

[110] For a project list of use cases, see Appendix I, especially Barcelona, Hamburg, Helsinki, Zürich, Aachen, Bologna, Sydney, Shanghai, London Underground, Aimsun Live, MOVE21, FinEst Twins, LDT4SSC, LDT Toolbox, CitiVERSE, DS4SSCC, Twin4Resilience, BIPED, ExPEDite, Amsterdam LIFE, Singapore DUCT, and EMDS.
[111] For the ACUMEN project website, see https://acumen-project.eu/
[112] For the Living-in.EU LIST website, see https://living-in.eu/smartcommunities/luxembourg-institute-science-and-technology-list-digital-twin-innovation-centre

demand analyses across Europe. Strategically, this project fits into the vision of a Federated Digital Twin that is intended to be compatible with European architectures in the future (see section 2.3). The systems are intended to enable monitoring, forecasting, simulations, and operational control support. Experts currently see the greatest potential for Cross-Border Digital Twins in this area in climate adaptation, in particular as instruments for fulfilling climate protection measures such as CO_2 neutrality and air quality assurance, disaster control, and resilience promotion in crisis situations in cities, for example, in the event of extreme weather events (heat and heavy rain adaptation, microclimate simulation, and flood prevention).[113] Furthermore, visualisations and monitoring, for example, of traffic flows, data-based planning support, and simulations and analyses of urban processes are central functions of Digital Twins in the urban sector, which could also support analyses of cross-border processes in the future. An architect and expert in the field of digitisation and urban planning explicitly describes the need to link static maps (hazards and heat) with dynamic movement and usage data as a step towards cross-city applications. Furthermore, experts cite improved decision making in urban planning as a key function of potentially urban Cross-Border Digital Twins.

This analysis shows that there are significant convergences among European cities in terms of requirements and the characteristics of use cases, for example, with regard to the need for modular, non-proprietary system architectures and data bases, even if there is no 1:1 transferability. At the same time, there are significant differences in maturity levels between cities and sectors within the EU. While some municipalities have high-resolution 3D models with integrated geodata, other applications are limited to sectoral dashboards or representing individual process models. A leading expert and deputy chair for several European initiatives on (Urban) Digital Twins systematically categorises these maturity levels. Simple static twins (3D geometry and basic inventory) already exist in most European cities, e. g. the Digital Twin Zurich[114] and the Digital Twin Helsinki 3D+.[115] There are also use cases for dynamic Digital Twins based on real-time data, including in Barcelona[116], Hamburg,[117] and Shanghai with the Yangpu Bridge.[118] Predictive Digital Twins (simulations and forecasts) are utilised in projects such as Amsterdam LIFE[119] and Singapore DUCT.[120] Prescriptive Digital Twins (recommended actions and strategic control), such as parts of the Sydney Twin,[121] are less common (see project list of use cases for details in Appendix I). According to this expert, high levels of maturity are not an end in themselves, but always depend on

[113] See Blüml et al. (2025), pp. 13 and 53ff.
[114] For the website of the Digital Twin Zurich, see https://www.stadt-zuerich.ch/artikel/de/klick/digitaler-zwilling.html
[115] For the City of Helsinki, Helsinki 3D project website, see https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d
[116] For the Barcelona Supercomputing Center (2023), see https://bsc.es/news/bsc-news/barcelona-tests-digital-twin-developed-bsc-if-it-15-minute-city
[117] See *Connected Urban Twins*. Freie und Hansestadt Hamburg at https://www.hamburg.de/politik-und-verwaltung/behoerden/behoerde-fuer-stadtentwicklung-und-wohnen/themen/stadtentwicklung/stadtwerkstatt/forschung-und-entwicklung/connected-urban-twins-187056
[118] See Shanghai Municipal People's Government. *Yangpu Bridge digital twin information page* at https://service.shanghai.gov.cn/sheninfo/specialdetail.aspx?Id=6530e08a-9de4-4667-8580-17b9007d23a3.
[119] For the LIFE project website (TU Delft Ports & Waterways Digitalisation Lab), see https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/intelligent-electrical-power-grids-iepg-group/projects/current-projects/life
[120] For the Singapore-ETH Centre website, see https://sec.ethz.ch/research/cs.html
[121] See the University of New South Wales. Liveable City Digital Twin project website at www.unsw.edu.au/arts-design-architecture/our-schools/built-environment/our-research/clusters-groups/grid/projects/liveable-city-digital-twin

the application and context. This implies that the added value of a Digital Twin depends less on reaching a higher maturity level and more on whether its level of development is appropriate for the intended planning, operational, and management tasks or specific challenge. Cross-sectoral, cross-topical, and even transnational linkages between such Urban Digital Twins are rare and have so far mainly been limited to pilot and research projects. Moreover, fully integrated, real-time twins have not yet been established at the national and cross-border levels.

Key EU-funded initiatives in European cities that foster Cross-Border Digital Twin applications include the Local Digital Twin for Smart and Sustainable Cities and Communities (LDT4SCC),[122] Local Digital Twin Toolbox (LDT Toolbox),[123] and European Digital Infrastructure Consortium (EDIC).[124] The EDIC aims to establish a central catalogue of interoperable tools for cities and regions. Itis a legal and institutional framework for enabling a European digital ecosystem for Urban Digital Twins. The main goal is to facilitate multi-country projects among member states and cities in Europe and enable structured cross-border networking of existing Digital Twin initiatives. Instead of isolated local twin entities, the EDIC aims to make sectoral solutions comparable and interoperable. Therefore, the EDIC also addresses a governance deficit. While many initiatives (e. g. Living-in.EU) bundle political interests, there has been a lack of joint operational coordination of involved stakeholders to date. The aim is, therefore, to provide a central catalogue of services that offers interoperable solutions that cities can use to develop their Digital Twins, while also bringing existing projects together within a common organisation framework.

CitiVERSE[125] is a specific instance of the EDIC framework which, unlike a central platform, aims to connect existing local approaches, such as tools, data spaces, and reference models, via common standards and interoperability mechanisms (IMs) and to enable the convergence of sector-specific Urban Digital Twins into an interoperable network for cross-border and multi-city applications.

Apart from EDIC, the LDT Toolbox and LDT4SSC,[126] which are funded by the European Commission, are currently a pioneering initiative dedicated to the structured deployment of interoperable tools especially for Urban Digital Twins. Rather than developing a new technological infrastructure, the aim is to bundle existing solutions, preferably open-source tools, into a multi-layered architecture and make them operational for cities. The toolbox integrates components at the data, orchestration, and visualisation levels and is scheduled for delivery by 2026.

Initiatives and frameworks such as the EDIC and the LDT Toolbox are not Digital Twin applications. Instead, they strategically focus on the reuse and replicability of such Local Digital Twins. They are being developed in cooperation with numerous member states and, unlike many implementation projects, focus on an overarching European perspective that is intended to take into account the specific needs of individual nation states and cities in equal measure (for the integration of local needs, see section 5.2). According to experts, this is the reason why cities as testing grounds provide great potential for the implementation of Transnational Digital Twins in the future, as the jointly

[122] For the LDT4SCC, see https://ldt4ssc.eu/
[123] See the European Commission, LDT Toolbox at https://interoperable-europe.ec.europa.eu/collection/ldttoolbox
[124] See the European Commission, EDIC at https://digital-strategy.ec.europa.eu/en/policies/edic
[125] See the European Commission, LDT CitiVERSE at https://ldtcitiverse-edic.eu
[126] See the Open Agile Smart Cities, LDT Toolbox at https://oascities.org/european-local-digital-twin-toolbox-project/

developed, systematic, institutional, and structural requirements for cross-cutting architectures are created. Exchange between cities (peer-2-peer) is seen as an important driver, as cities can learn from each other and adapt some solutions. The use of common tools and standards is the focus of the further development of urban Digital Twins, with the aim of simplifying cross-border cooperation.[127]

4.1.4 Energy and crisis prevention

A complex application domain for Transnational Digital Twins is the energy sector and crisis prevention and management, as this area is often cross-border in nature and, at the same time, places high demands on governance, security, and regulation.[128] In this area, existing Transnational Digital Twin projects and other cross-border data-based projects show a comparatively high degree of maturity (e. g. projects like TwinEU, Begonia, Twin4Resilience, Offshore For Sure (O4S), and Omega-X*;* see project list in Appendix I). Their scope ranges from hazard prevention and resilience planning through simulation-based preparation for heavy rain, flooding, heat events in urban areas, and offshore wind park operation right up to resilience and failure simulations and load and flexibility management in the power system. In an urban context, this is illustrated by the Twin4Resilience project,[129] which models climate and risk scenarios across six European countries and also serves as an important component of local Urban Digital Twins.

The energy sector appears to be particularly advanced, as it already has highly integrated cross-border network structures in place. On the one hand, in this domain, Digital Twins across borders are used to increase efficiency and improve cross-border network planning in the context of increased integration of renewable energies. On the other hand, Digital Twins are increasingly being used as instruments for more robustness, ensuring security, and strategic system planning. Here, scenario-based analyses can help to identify cascade effects of infrastructure failures, develop joint response strategies, anticipate potential cyberattacks on networked energy systems and assess their impact, and test recovery strategies under realistic conditions. This is particularly evident in the example of TwinEU, which aims to develop a Federated Digital Twin ecosystem that connects national and regional twins via a common, federated architecture with open interfaces such as an Application Programming Interface (API) to improve network operation, planning, and demand and generation forecasting; enable new business models in the energy sector; and increase cyber–physical resilience.

In addition, Begonia[130] should be highlighted as another advanced project. Although it is developing an operational digital platform and not a Transnational Digital Twin (see distinction in section 2.2),

[127] In addition to LDT4SSC, LDT Toolbox, and CitiVERSE, MOVE21 (Cascade Cities), MetaCities Hub, and DS4SSCC are exemplary projects and initiatives in this area (see Appendix I: Project Overview of Use Cases).
[128] See the Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. (n.d.). *Kritische Infrastrukturen: Sektoren- und Brancheneinteilung*. Retrieved from https://www.bbk.bund.de/SharedDocs/Downloads/DE/KRITIS/kritis-sektoren-brancheneinteilung.pdf?__blob=publicationFile&v=7; and Organisation for Economic Co-operation and Development. (2019). *Good Governance for Critical Infrastructure Resilience*. Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2019/04/good-governance-for-critical-infrastructure-resilience_7d5a9993/02f0e5a0-en.pdf
[129] For the Twin4Resilience project website, see https://t4r.nweurope.eu/
[130] For the Begonia project website, see https://www.begonia-project.eu/

it is laying essential groundwork for future Transnational Digital Twin architectures, particularly in the field of cross-border energy applications, by identifying, analysing, and preparing concrete, data-based, modular, and interoperable use cases for implementation. In the energy sector, this includes platform approaches for distribution network operators that provide a Digital Twin of the network with functions such as network planning, predictive maintenance, and solutions for increasing network stability through demand-side flexibility and early detection of vulnerabilities. Overall, these examples show that Transnational Digital Twins in the field of energy and crisis preparedness have a dual character: they can increase the resilience and protection of physical infrastructures, but at the same time they become part of the critical infrastructure as they grow in importance for operations, security, and crisis response.

Moreover, the strong interconnection of the European energy grid suggests that interoperable digital solutions such as Digital Twins are of particular importance. At the same time, the still limited digitalisation of parts of the German grid for instance, may point to a continued need for learning, coordination, and practical exchange. Although individual projects have already advanced the digitalisation of selected grid segments,[131] closer engagement with European initiatives such as TwinEU could be especially valuable for national grid operators. This could help them better understand emerging standards and implementation approaches at the European level and support closer alignment with ongoing developments.

4.1.5 Border regions as test fields for Transnational Digital Twins

Border regions, such as neighbouring countries, adjacent municipalities in different national territories, and closely interlinked areas such as the Baltic states, are repeatedly cited in interviews and analyses of existing application projects as natural test fields for Transnational Digital Twins and are thus of particular relevance as an overarching category for analysing their implementation status. Although there are numerous overlaps with other categories, it is useful to consider them separately in order to highlight the fundamental challenges of cross-border cooperation in mobility, infrastructure, and cities.

These border areas are characterised by an inherent need for harmonisation and coordination, which arises from, among other things, geographically and functionally interlinked (mobility) infrastructures, while administrative structures and cultures, political responsibilities and resource allocation, and levels of maturity in terms of data infrastructures remain fragmented along national borders. Precisely because key areas such as traffic management, disaster control, energy supply, and environmental and climate issues are most effectively organised across borders, harmonisation "*cannot really be achieved by one municipality alone*," which not only motivates cross-border cooperation but also makes it inevitable in many cases, as an architect and expert in the field of digitalisation and urban planning emphasises. This makes border regions the most common geographical contexts for implementing existing Cross-Border Digital Twin pilot projects (see section 2.1).

[131] See Blüml et al. (2025), p. 33.

Use cases such as the German–Polish city cooperation Guben/Gubin[132] and the regional network Freiburg–Basel–Mulhouse[133] illustrate the potential and the structural barriers of such approaches. In Guben/Gubin, the Resi.Form resilience platform was developed as part of the smart city model projects[134] as an application to support cross-border, resilience-oriented urban development processes, enabling the joint evaluation of spatial data via planning, analysis, and simulation modules.[135] This revealed considerable challenges due to differing administrative structures, responsibilities, data standards, and decision-making processes. In this context, governance-related incompatibilities often outweigh technical differences, making technical solutions difficult to implement without functioning governance structures.[136]

Similar efforts to harmonise geodata and digital infrastructure across national borders are ongoing in the Freiburg–Basel–Mulhouse tri-border region as part of the TriRegio Data Space[137] initiative, which aims to facilitate the structured exchange of municipal data and establish joint governance and infrastructure among the cities. The project focuses on commuter traffic, public transport, energy, urban development and environmental and climate topics.[138] Within the project, the bordering cities utilise workshops and collaborations to systematically explore data exchange among them, with a focus on shared smart city data, digital infrastructure, and the development of initial use cases. Here, too, the long-term goal is to network existing digital solutions into a Transnational Digital Twin; this is usually a gradual development that starts with limited use cases and on a voluntary cooperation basis.

Currently, most use cases in border regions can be found in the areas of mobility and transport, particularly, cross-border traffic and rail operations. In addition, there is an energy and mobility nexus, for example, in improved route and supply chain planning in the context of e-mobility, such as charging infrastructure, utilisation, and route planning, as addressed in the Begonia project. Cross-border passenger transport, such as accelerated connections, e. g. Berlin–Paris, and tourism are also mentioned by the interviewed experts but are less pronounced. Other relevant fields include hazard prevention and resilience promotion, as demonstrated by the intercity cooperation Guben/Gubin. Often, there is an overlap among these domains, as mobility, energy, and the environment have both urban and regional dimensions.

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132 See the City of Guben at https://www.guben.de/de/wirtschaft-stadtentwicklung/wirtschaftsstandort-guben-gubin/item/307-gemeinsame-wirtschaftsfoerderung-in-der-eurostadt-guben-gubin-die-doppelstadt-macht-weiteren-schritt

133 See Smart City Dialog, *Connected in Europe: Basel, Freiburg, Mulhouse work on cross-border data sharing*. https://www.smart-city-dialog.de/en/inform/news/connectedineurope-basel-freiburg-mulhouse-work-cross-border-data-sharing

134 See Smart City Dialog, Modellprojekte Smart Cities at https://www.smart-city-dialog.de/ueber-uns/modellprojekte-smart-cities

135 More projects exist in other Interreg region such as in the Meuse–Rhine region see https://digital-twin-academy.eu/

136 See Smart City Dialog, Resi.Form*:* Resilienz-Plattform Guben at https://www.smart-city-dialog.de/wissen/massnahmen/resiform-resilienz-plattform-guben-0

137 For the Canton Basel-Stadt, TriRegio Data Space website, see https://www.bs.ch/pd/kantons-und-stadtentwicklung/triregio-data-space

138 In addition, the Eurodistrict Region Freiburg – Centre et Sud Alsace (Eurhena) provides an institutional framework for cross-border cooperation. Established in 2006 as a European Grouping of Territorial Cooperation, it provides structural support for cross-border cooperation between local authorities in Germany and France. For more information, see https://eurhena.eu/de/verstehen/der-eurodistrict/

4.2 Interim conclusion: Current implementation status of Transnational Digital Twins

The analysis of the use cases and evaluation of the expert discussions show that, given the current state of implementation, Transnational Digital Twins are still predominantly in early testing and development phases. Local or national Digital Twins[139] already exist in numerous European countries, particularly in the mobility and infrastructure sector and in cities. However, these applications mostly focus on monitoring, visualisation, and analysis functions and only occasionally achieve higher levels of maturity, such as predictive or simulation-based decision support.[140]

While many national Digital Twins already exist as prototypes or even as operational systems, with their main challenge being implementation and scaling, Transnational Digital Twins are still often considered a future vision. Projects are primarily conceptual in nature or are currently developing their first demonstrators. Although national Digital Twin applications show to be overall more advanced, several interviewees emphasise that current efforts still focus on progress at the national or local level before cross-border perspectives (and their increased complexity) can be addressed. Therefore, experts consider the maturity of existing applications and pilot projects that can be considered preliminary or “genuine” Transnational Digital Twins to be low, although there are exceptions, mainly large EU flagship projects such as DestinE. The biggest challenge here is the transition from vertical (sector-specific) to transversal (cross-sectoral) use cases (see chapter 5). At the same time, this analysis and the expert interviews clearly illustrate the importance of establishing the foundations for scaling Digital Twins today through common components in order to enable interoperability and, over time, transnational applications in the future. A characteristic feature of the Transnational Digital Twin landscape is the strong EU funding focus of many projects; more advanced pilot projects are almost without exception anchored in large European project consortia that serve as flagship projects.

Digital Twins across borders can create significant added value, particularly where physical infrastructures, data flows, and governance structures are intertwined across borders and, for example, in the areas of mobility, energy, and transportation. By aggregating and harmonising heterogeneous data from different countries and domains, they can enable improved data interoperability, more informed planning and decision-making processes, more efficient infrastructure operation and maintenance strategies, and greater transparency and resilience of complex systems through, for example, simulation-based analyses and integrated monitoring along cross-border infrastructure corridors. With advancing standardisation, interoperability, and expansion of European data spaces, scaling Digital Twins opens up future potential to model transnational systems holistically and analyse them across sectors, which could enable coordinated governance approaches, system-wide sustainability assessments (e. g. of emissions or energy flows), and more efficient and balanced use of shared resources at the European level.

The current empirical project landscape is highly heterogeneous in terms of maturity levels, application types, and areas of application. There are four main types of projects that are especially relevant for the development of Cross-Border Digital Twins: data space initiatives or projects, Urban Digital Twins, cross-sectoral data platforms, and “genuine” Transnational Digital Twins, such as

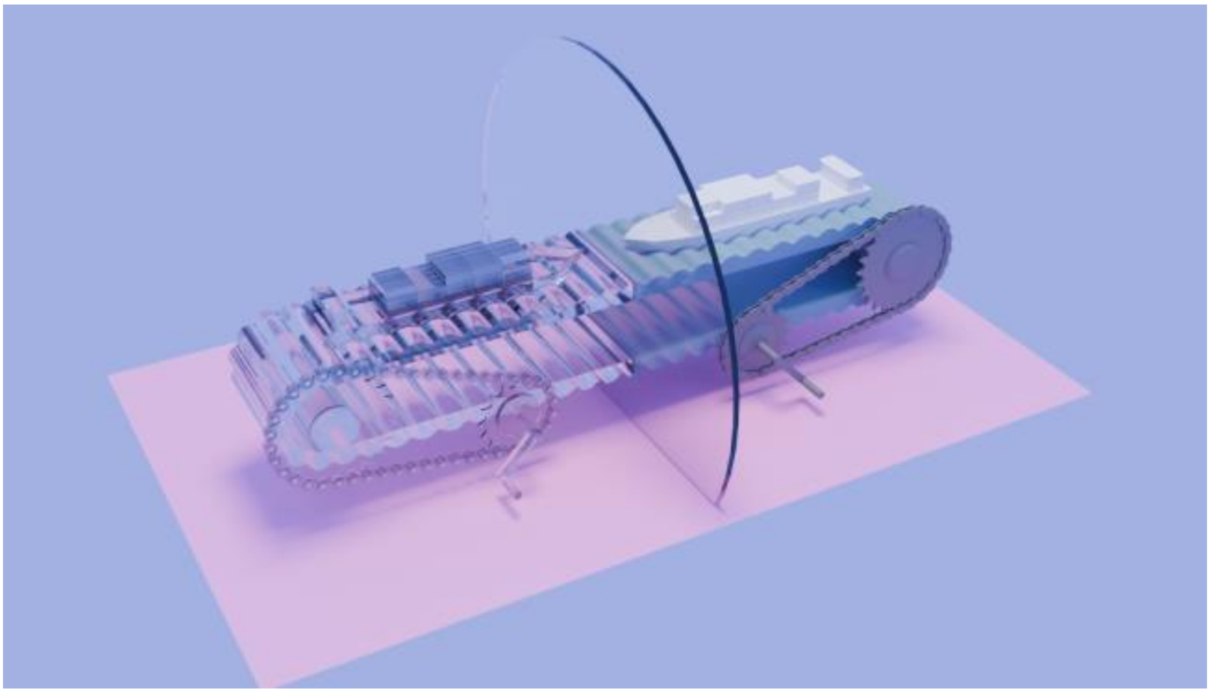
[139] See Blüml et al. (2025), pp. 11–14.
[140] Ibid.

DestinE, TwinEU, TrilaWatt, and Digital Ocean, which are institutionally designed for operation. While data space projects promote the structured accessibility and interchangeability of data, European Urban Digital Twin initiatives are fostering the implementation and usage of interoperable and reusable solutions, while also promoting peer-to-peer exchanges among cities. Cross-Border Digital Twins conceptually extend this by modelling and analysing cross-border system relationships. Their focus is on the transport sector, in particular rail infrastructure and its harmonisation, as this is where issues of common standards, interoperability, and cross-border operating logic are central.

Furthermore, the empirical analysis shows that in addition to large EU flagship pilots and data spaces, important impetus for the potential implementation of Transnational Digital Twins currently stems from cities and border regions. In recent years, there has been a strong focus on developing Urban Digital Twins. There is increasingly strong networking among cities as well as financial support from EU initiatives such as the LDT Toolbox, which explicitly focus on reusable blueprints and infrastructural foundations, such as service catalogues and technical and data infrastructures for facilitated inter-city replicability of Digital Twins and use cases, in order to enable cross-border analyses in the future.

Overall, this evaluation shows a diverse, extensive landscape of EU initiatives and pilot projects in preliminary stages, as well as considerable progress in creating uniform technical foundations in specific sectors, with standardisation and interoperability recognised as key success factors. Transnational Digital Twins are strategically considered to be useful and expected to add considerable value across various areas of application; conceptual and political initiatives at the EU level are increasing, and numerous local projects such as urban Digital Twins, European flagship and lighthouse projects, and good practices, mostly within the framework of large multi-country European consortia, already exist. At the same time, implementation remains predominantly isolated among sectors, dependent on funding, and only in exceptional cases designed for long-term scaling. The projects are for the most part not systemically integrated and have so far shown only limited structural reuse, so that scalability is often limited to the respective project context. Transnational Digital Twins therefore mainly unfold their potential where there are clearly defined benefits, step-by-step scaling, standardisation, and institutionally secured cooperation.

5. Key Challenges and Enabling Factors for Planning and Implementing Transnational Digital Twins



What are the key challenges faced by actors and bodies responsible for planning and implementing Cross-Border Digital Twins or similar projects in mobility, infrastructure and cities? What organisational, technical, and procedural causes underlie these challenges? Which factors promote the feasibility of Transnational Digital Twin projects? These key questions are addressed below in seven topic areas, which provide initial answers to major challenges, implementation barriers, and enabling factors relevant to promote cross-border cooperations and the scaling of Digital Twins across borders.

The following findings are based on the analysis of selected areas of application and qualitative data collected in the form of guided interviews with 21 experts (for methodology, see chapter 1). A semi-structured interview guideline was developed covering six topics, which were weighted and applied differently depending on the expertise and prior experience of the experts interviewed.

- **Module 1: Foundations and added value of Cross-Border Digital Twins:** This module explores the experiences of the interviewees with (Transnational) Digital Twins, their conceptual understanding, technological features, and specific added value of Transnational Digital Twins, especially in mobility, transport, and infrastructure.
- **Module 2: Application areas and potential:** Questions cover current and potential application areas of Cross-Border Digital Twins across Europe, including added value, data bases, perceived benefits, and limitations.
- **Module 3: Potential and role of open data:** This module investigates the relevance of open datasets for the development and implementation of cross-border applications such as Digital Twins. It examines open data initiatives, data portals, implementation obstacles,

conditions for successful use, and political action needed related to open data for Transnational Digital Twins.

- **Module 4: Implementation status and empirical projects:** This module targets the specific Transnational Digital Twin or Digital Twin project of the interviewee (if applicable), focusing on its functions, use cases, actors, technological components, data base, interoperability and standards, financing, current stage, next steps, and long-term vision.
- **Module 5: Challenges and enabling factors in key areas:** This module addresses key challenges and enabling factors in implementing Cross-Border Digital Twin projects, especially foundations, organisational and operational requirements, data and technical infrastructure, and open data and legal frameworks.
- **Module 6: Future potential:** This module looks at future pathways and prototypical applications of Transnational Digital Twins and the strategic role of Cross-Border Digital Twins in digital transformations across Europe.

After the interviews were transcribed, a detailed content analysis was performed, keeping the participants anonymous. In the course of this analysis and based on a comprehensive review of the related literature and application projects, existing implementation barriers and promising solutions were condensed into six key areas and one overarching area where there is a significant need for action for the development of Digital Twins according to the implementing institutions and actors, such as infrastructure operators, cities, and those responsible for projects on national and European levels.[141]

Interoperability as an overarching challenge

The evaluation of the expert interviews and the empirical analysis of use cases clearly indicates that interoperability is a central prerequisite and currently one of the major challenges for the planning and implementation of cross-border applications such as Transnational Digital Twins. Without sufficient interoperability, cross-border data exchange, cross-sectoral integration, knowledge transfer, and reuse of Digital Twin use cases remain limited and cannot be scaled effectively. The views of the interviewed experts align with the European Commission's definition of interoperability.[142] The experts consistently stress that interoperability is not solely to be understood in technical terms but is multi-dimensional and involves legal, organisational, semantic, and technical layers:

- **Technical interoperability**: through compatible interfaces and exchange mechanisms and standards (Application Programming Interfaces (APIs); protocols; data exchange

[141] Due to the diverse fields of application in which Transnational Digital Twins and similar projects are implemented in the mobility and infrastructure sectors, the role descriptions of the interviewed actors in the project teams and organisations vary. It is therefore not possible to uniformly define the exact responsibilities for implementing a Cross-Border Digital Twin within an organisation or proj
ect. For this reason, the following analysis is limited to a general description of the roles.

[142] For the European Commission, Level of Interoperability, see https://interoperable-europe.ec.europa.eu/collection/iopeu-monitoring/solution/european-interoperability-framework-eif-toolbox/levels-interoperability For a comprehensive discussion about interoperability dimensions see also Bertelsmann Stiftung "Der Standard of Standards". (2025). Retrieved from https://www.bertelsmann-stiftung.de/de/publikationen/publikation/did/der-standard-of-standards

mechanisms; security mechanisms, e. g. X-Road–like approaches; and geodata standards) (see sections 5.4 and 5.5);

- **Semantic interoperability**: common meaning through shared vocabularies, ontologies, data models, and harmonised metadata standards ensuring that equivalent data fields, attributes, and concepts are defined and interpreted consistently across jurisdictions and sectors and supported by frameworks such as the INSPIRE Directive and Data Catalog Vocabulary (DCAT) (see sections 5.4 and 5.5);
- **Organisational interoperability**: alignment of responsibilities and workflows across departments and organisations so data exchange becomes operationally possible, not blocked by internal silos (see sections 5.2 and 5.3);
- **Legal interoperability**: through aligned frameworks that regulate data ownership, access rights, liability, and responsibilities, including for confidential and private data, enabling data sharing, especially cross-border (see section 5.6).

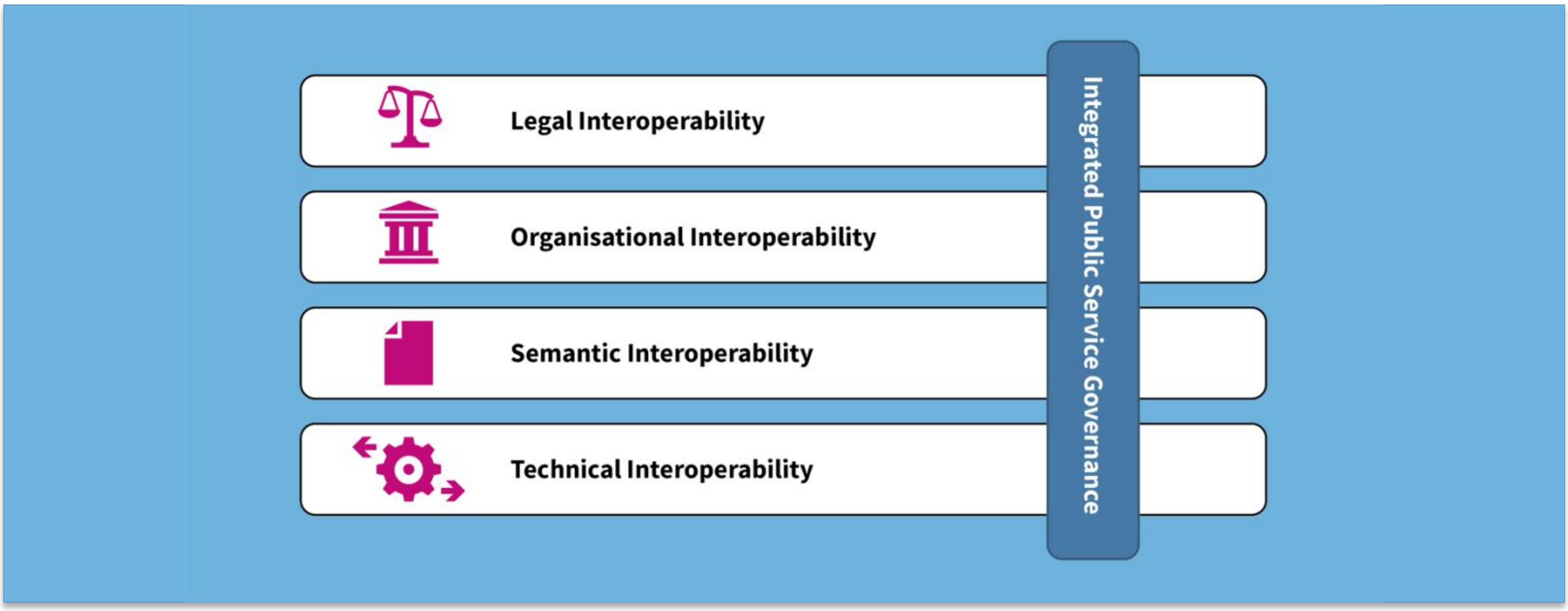


Figure 6: Dimensions of interoperability according to the New European Interoperability Framework. Source: Own representation iRights.Lab based on European Commission.

The different dimensions of interoperability and the related challenges and enabling factors emphasised by implementing actors, project responsibles, and experts are presented below within the respective key areas of action.

5.1 Objectives and prerequisites for Transnational Digital Twins: Shared understanding of concept and added value

The basis for planning and implementing Cross-Border Digital Twins for infrastructure measures in the transport sector, in mobility and in cities is a common understanding of the definition and objectives of the Digital Twin. Furthermore, it is necessary for stakeholders to specify the concrete use cases and the scope of functions. The project stakeholders develop a concrete analysis of requirements or problems. Based on this, a solution approach can be defined in the next step, thereby establishing the framework for the project. Once there is basic agreement on the challenges and solutions, those responsible are in a position to clarify the project and its associated objectives. This enables them to assess whether the Digital Twin is indeed an effective problem-solving tool or whether other, potentially less complex applications are more suitable.

Accordingly, the interviewed experts emphasise that planning and implementing Transnational Digital Twins is not primarily challenging due to technological issues but rather due to a lack of strategic clarity and shared understanding of the concept regarding the added value and the specific objectives of the transnational cooperation. Across domains, the main challenge as implementing actors underline is not only to define a technical architecture but also to establish an initial minimum consensus among all involved parties regarding the technological and definitional implications of the concept of the Transnational Digital Twin that is supported politically, administratively, and technically (see chapter 3 and section 5.7).

The interviewed experts highlight that the complexity and heterogeneity of the concept (see chapter 2) and the to date few existing mature practical use cases (see chapter 4) are currently significant hurdles among the involved stakeholders when it comes to agreeing on a shared understanding of a Transnational Digital Twin and its added value. The limited number of reference projects is another challenge for project responsibles when it comes to convincingly demonstrating the added value and thus the suitability of the concept for funding: *"It is still difficult to explain the investment needs if you cannot clearly show the benefits,"* as a professor in the field of open data and Digital Twins in the public sector states. Thus, additional good practices for Transnational Digital Twin applications are needed that clearly demonstrate the added value compared to other solutions. Furthermore, the distinction between similar concepts and technological infrastructures such as data spaces, data platforms, and ODPs (see section 2.5) is often blurred, since the multiple context-specific denominations of those terminologies vary considerably, as a European standardisation expert in transport and mobility points out. For example, an expert in the field of AI technologies, smart cities, and local Digital Twins, as well as project managers of European twin initiatives, differentiate between an ODP as a strategic framework and a Digital Twin as a possible service within the ODP. In addition, the interviewed experts observe a convergence of the concepts, which further blurs the distinction (see chapter 2). This conceptual ambiguity presents a major challenge when developing a common vision and goal of the transnational cooperation and aligning different perspectives and interests, as a data strategy architect in railway digitalisation sums up, *"You need a common understanding of the objective; otherwise, every partner will interpret the Digital Twin differently, and then you will not converge."*

To develop a shared understanding of the added value of Digital Twins across borders, project responsibles suggest that it is helpful to first assess whether the concept or the scaling of national or local Digital Twins across borders, domains, or systems is the most suitable solution for the specific problem in question. This analysis indicates that assessing the suitability of Transnational Digital Twins, and thus their added value, varies considerably across application areas and subsequently stakeholder perspectives. While for example researchers in the field of open data and Digital Twins in the public sector explicitly confirm the added value of cross-border pilot projects, an asset manager of a rail infrastructure operator argues that a Digital Twin initially designed for national purposes is usually not developed with a cross-border orientation, as the added value of Digital Twins is typically anchored in the more immediate local use case. As discussed in detail in chapter 3, application areas with high potential for such transnational use cases in the mobility sector include cross-border rail operations and corridor management, cross-border road traffic management, and projects at the mobility and energy infrastructure nexus, for example, in charging infrastructure planning.

Overall, this analysis suggests that Transnational Digital Twins are considered conceptually and strategically useful and potentially valuable, but their added value is highly context-dependent and must be communicated in a politically and economically convincing manner, especially when compared to related approaches.

Experts further emphasise the importance of a shared overarching sectoral vision of cooperation and project governance at the intergovernmental level to develop a common understanding, such as the concept of a Single European Railway Area (SERA) pursued in the MOTIONAL infrastructure project (see section 4.1.1).
A shared project vision is particularly necessary to promote the intrinsic motivation of all involved stakeholders, often multinational and multisectoral, and to build up the project structures needed to develop and implement complex endeavours such as Transnational Digital Twins (see section 5.2). The overarching goal should be jointly developed by all participating units and stakeholders, and clearly established from the outset in order to align all partners, as a data strategy architect in railway digitalisation emphasises. This can help clarify how different national solutions and interests relate to one another, which forms of coordination are required, and which national barriers, such as differences in data infrastructures, governance, and administrative processes, a Transnational Digital Twin approach is expected to address. With such an overarching vision, project consortia can collaborate more efficiently despite their large size and leverage synergies to successfully develop Transnational Digital Twin projects. The head of operations of a pan-European energy and mobility project emphasises this:

> *They have very strong links among each other [...] quite lively exchanges of ideas because they are all trying, from their different perspectives, to work towards the same goal. (Head of operations of a pan-European project in energy and mobility)*

Large EU projects, through which transnational cooperations are often implemented, create part of this clarity of objectives through their funding logic. In such European consortia, the objective, project vision, and implementation milestones, as well as work packages, are often contractually defined a priori, taking into account the interests of the respective stakeholders. This can support a stronger alignment, a clearer focus on common goals, and a more efficient implementation, making an early definition an important condition for creating transnational projects (see section 4.2), as an expert states:

> *There is a hierarchy – project coordinators, project managers, and so on. Whenever you want to do something, you look at the process and ask what is the process that has been defined? Then, you go through the process and obtain the required permissions from people. All those things are already mentioned in the contracts. So, all the foundations and governance are already there. It carries a lot of weight for partners as well, because they have signed the documents and the contracts. So, the whole process is in front of you. If you want to do something, you look at the process and then you go through the hierarchy of what has to be done. (Data strategy architect in railway digitalisation)*

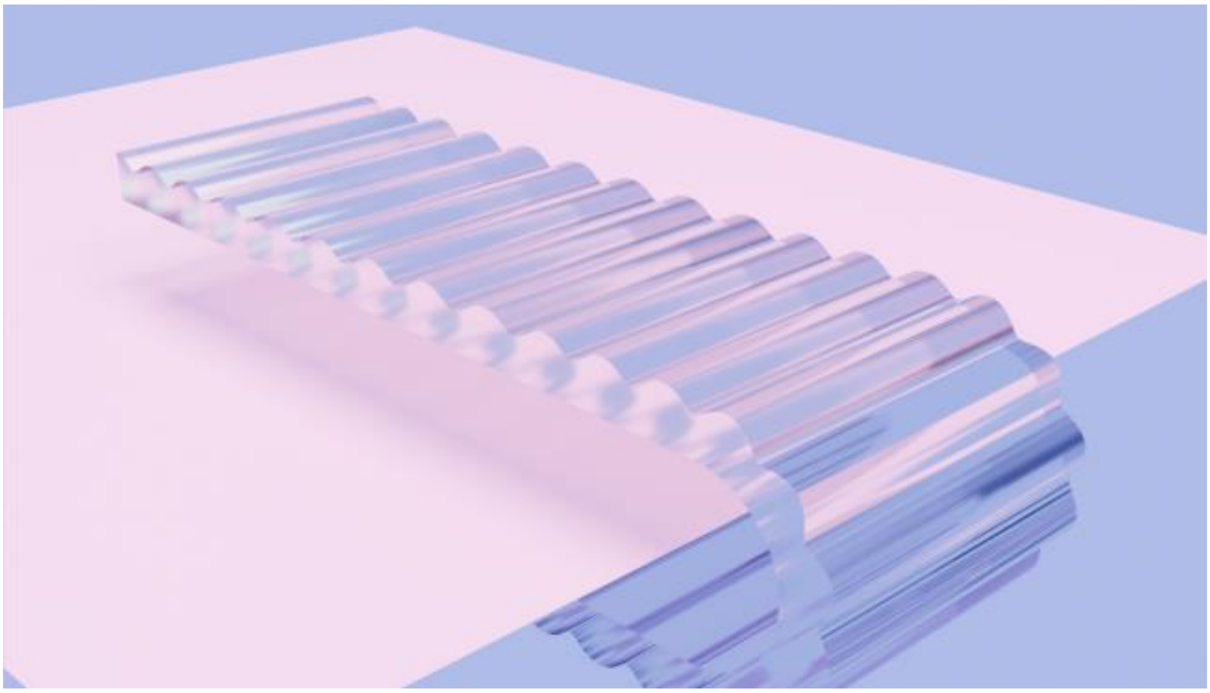
Moreover, the alignment of partners depends on whether national and local interest are adequately considered. As a leading expert and deputy chair in several European initiatives on (urban) Digital Twins emphasises, *“Each partner needs to see their own benefit in participating. Otherwise, motivation will decrease over time.”* If countries or cities do not perceive a clear added value in participating in implementing a Digital Twin across borders, they will not invest resources in the long term. In urban contexts, a leading expert and deputy chair of several European initiatives on (Urban) Digital Twins emphasises that European structures such as the EDIC can strengthen participation of local actors by linking transnational projects to shared funding, combining European funding with financial contributions from the cities themselves. This may foster a stronger commitment and help align local interests with broader transnational goals.

In practice, it has proven useful to begin the planning phase of a Cross-Border Digital Twin with specific problems and narrowly defined use cases rather than with an overly broad project architecture (see sections 5.2 and 5.3). The interviewed experts emphasise the importance of demonstrating tangible early success stories to users of the Transnational Digital Twin and implementing actors or bodies, such as local authorities, to jointly identify the specific added value and intended use of the Transnational Digital Twin: *“Success stories are extremely important to convince local stakeholders,”* as a leading European expert and deputy chair in the field of (Urban) Digital Twins states. Moreover, the same expert emphasises that an iterative approach in various stages also proves to be very beneficial in operational implementation: *“If municipalities do not see how it helps them in their daily work, they will not engage”* (see section 5.3).

Key Takeaways:

1. **Shared goal and tangible project vision as key prerequisites:** A shared project vision that takes into account local needs, specific problems, and the tangible potential benefits for the stakeholders involved is a key prerequisite to develop Transnational Digital Twins. Specified use cases with an initially limited scope and reliable success stories are crucial for demonstrating practical relevance and ensuring political and funding legitimacy.
2. **Conceptual clarity:** Viable transnational projects require a clear and common terms and concepts for (Transnational) Digital Twins. Currently, conceptual ambiguities and inconsistent distinctions between Transnational Digital Twins and related concepts such as data spaces, platforms, and ODPs challenge cooperation among project partners.
3. **Definition of context-related added value**: Digital Twins across borders are considered conceptually and strategically useful, particularly in the mobility and energy sectors. However, their additional benefits compared to simpler solutions for cooperation or data exchange are highly dependent on the specific use case and domain and are often difficult to demonstrate convincingly to political decision makers and funding bodies due to a lack of robust reference projects. This requires further good practices from Transnational Digital Twins in real-world operation. To this end, implementation partners should, if possible, include objectives and indicators for measuring their impact in the project’s objectives to achieve transparency about the results and resources used for the project’s target group.

5.2 Organisational requirements



Establishing a shared project vision, agreeing on a common understanding of the analysis of requirements or problems, and assessing if the Digital Twin is the most effective problem-solving tool or if other applications are more suitable are key implementation prerequisites for defining suitable organisational processes and structures to meet the complex requirements of governing multinational or cross-border use cases and projects. In this context, project governance on the one hand, refers to the strategic steering of the transnational consortium, including the allocation of responsibilities, decisions-making structures, coordination mechanisms, and the institutional embedding of the project. Project management, on the other hand, refers to the operational coordination of work packages, timelines, resources, and implementation steps within this governance framework.

Typically, the planning and implementation of a Transnational Digital Twin is embedded in multi-actor and multi-country consortia structures involving municipalities and national authorities such as infrastructure operators, research institutions, and private technology providers (see section 2.4). Because these different actors stem from different sectors, administrative contexts, and national systems, effective cooperation depends not only on technical integration but also on well-aligned organisational structures, roles, and working processes. These complex multi-level constellations result in specific organisational requirements for developing Transnational Digital Twins, which are discussed below.

Creation of a multi-level project governance structure

The central challenge is not only how to organise work processes and structures internally within a project consortium but also how to establish strategic coordination across institutional, national, and sectoral boundaries. Often, there is *"a little bit too much of a technocratic perspective,"* as a professor in the field of open data and Digital Twins in the public sector observes. The real difficulty lies in organising *“collaboration on multiple levels”* in such a way that it fits together seamlessly.

The evaluation of the interviews and analysis of existing application projects show that consortium structures of Transnational Digital Twin projects and relevant initiatives, such as European data spaces, are typically organised in multi-level, multi-stakeholder partnerships that connect local, national, and European levels.
These project consortia usually consist of many project partners, sometimes up to 70, from public implementation bodies at national and European levels ranging from cities, administrative authorities, and infrastructure operators to transport and mobility providers, research institutions, technology companies, and analytics providers. This results in a characteristic mix of implementing actors in Transnational Digital Twins that makes coordination demanding because of technical or content complexity and divergent institutional logics and expectations. In addition, operational objectives must be aligned. Successfully built projects and use cases often combine the research-based expertise of academia, the technological capabilities from private firms, and the problem-specific and regulatory knowledge of public authorities, as this empirical analysis shows. Often, overarching sectoral bodies or coordinating European institutions, such as Europe’s Rail Joint Undertaking,[143] are involved to review, test, and validate approaches.

To successfully establish such complex multi-stakeholder project consortia, different incentive structures need to be set up in order to secure the participation of partners. As Digital Twins across borders are currently planned mostly within the framework of EU funding programmes (see chapter 4), national actors are often incentivised to participate in transnational settings as it also generates reusable components and knowledge for their own regional, urban, or national applications. Participation can thus advance transnational interoperability and help co-finance domestic digitalisation efforts. Hence, several interviewed experts argue for a more targeted use of resources, fewer parallel solutions, and stronger coordination of existing approaches rather than duplicating similar systems across administrative levels.

Involving private-sector actors, on the other hand, can be particularly challenging as an assistant professor and research centre director in smart city studies emphasises, as this mostly implies a financial commitment: *“Convincing the private company to change its technological roadmap, which impacts its cash flow, to jump into a two-year pilot or 18-month pilot is more difficult.”* At the same time, private partners are particularly valuable for developing transnational use cases, especially in the mobility sector as much of the relevant mobility data is held by private organisations (see section 5.4). Experts note that such projects can be especially attractive for companies if it allows them to develop interoperable solutions for different national contexts, which may later facilitate scaling, market access, and the adoption of their products across European markets.

Such initiatives or projects usually require several levels of governance. In addition to project governance, which usually regulates consortium agreements, steering committee and technical meetings, and structured coordination processes, the governance of data and technical

[143] For Europe’s Rail Joint Undertaking website, see https://european-union.europa.eu/institutions-law-budget/institutions-and-bodies/search-all-eu-institutions-and-bodies/europes-rail-joint-undertaking_en

infrastructures plays a central role. Particularly data governance, so the rules, roles, responsibilities, and processes for data access and use and the terms for how the shared technical systems are operated, maintained, and coordinated across institutions and countries, need to be defined (see sections 5.4 and 5.5).

In addition to internal project management and overarching project governance, stakeholder management beyond the project itself, for example, through external partners, user forums, working groups, or exchange formats among parallel EU projects, is another key success factor. These formats function as important feedback channels among users, technical experts, and political decision makers and can therefore improve the alignment, relevance, and practical applicability of the project. To manage these external stakeholders effectively, project managers report that a multi-level participation structure including operational, strategic, and political levels has proven helpful. To this end, a coordination group with representatives from various technical stakeholder groups and a strategic advisory group can be established, whose members are appointed by the respective groups. In addition, it has proven useful to establish and continuously maintain a project-related community. This kind of community can support continuous exchange and feedback with potential users of the Digital Twin, helping to identify practical needs and ensuring the long-term usability of project results. This can be supported through regular exchange formats such as conferences, organised workshops, and the active participation of project representatives in them. To ensure the long-term viability of these exchanges and the knowledge transfer, it may be valuable to formalise these activities in a stakeholder and partnership management plan, as a project responsible reports.

Work structures and integration of local needs and requirements

In practice, the translation of local specificities, requirements, and prerequisites into overarching project coordination and governance as well as the creation of incentives for the involved actors is often achieved through a bottom-up approach that starts from local needs and use cases. In the case of a European Digital Twin of an electricity system, for example, this means taking the requirements of local grid operators into account while ensuring that each national partner also contributes to the broader development of the shared European Digital Twin infrastructure. The director of a technical research institute and technical consultant for Digital Twins in railway infrastructure states that local teams or entities in every country know the distinct national characteristics and needs best and are able to integrate them into the overall project plan, thereby functioning as a link to central project governance.

Local counterparts like these can provide support in setting up project management structures to meet country-specific technical, regulatory, and governance-related requirements in the respective areas of application. Taking local conditions and circumstances into account comprehensively in the overall vision of the project structure and governance is one of the key prerequisites for establishing cross-border initiatives, as a researcher specialising in urban Digital Twins and sustainable infrastructure emphasises:

> *And if you then want to build up a Digital Twin between different cities in one country or different countries, a data exchange is not feasible. And then, of course, when you build up applications, software, and so on, and everyone stores and structures the data differently, you can’t really scale the different software or applications because at any time, you need to be able readapt it to the local*

conditions, local data structures, and so on. (*Researcher specialising in urban Digital Twins and sustainable infrastructure)*

In practice, as a project responsible points out, a recurring challenge regarding coordinating work structures and processes among local, national, and European levels is that often national implementing actors are hesitant to relinquish their scope for action within project consortia, which leads to creating mostly decentralised coordination units and less central authorities to enforce overarching project goals. However, such an authority with more comprehensive responsibilities could help to consolidate divergent political, legal, and normative frameworks and develop binding project-wide guidelines. Instead, this task usually falls to coordinating units that implement project goals across countries and actors without a direct mandate and are therefore heavily reliant on cooperative coordination. The interviews also show that such coordination becomes more difficult when local actors are overloaded, because the project's work competes with daily administrative work and existing bottlenecks; consequently, many respondents recommend a phased approach that starts with a limited, manageable scope.

Moreover, the working structure of EU-funded Cross-Border Digital Twin projects such as TwinEU, DestinE, and Begonia (see chapter 4) are usually characterised by clearly defined hierarchical and contractually agreed structures, milestones, outputs, and coordination structures between the stakeholders prior to actual implementation — often with independent *work packages* and an overarching cooperation or project management unit. Within these consortia, the often-mature governance is characterised by a) work in clearly defined work packages or use cases, i. e. vertical use cases that deal with specific applications or sectoral tasks; b) horizontal work packages, such as those providing shared technical data infrastructure, knowledge management, and governance strategies; and c) overarching coordination bodies that manage the interfaces between work packages and national and regional structures. The analysis shows that clear contractual arrangements and agreed milestones like these minimise conflicts among the parties. Building on this, the interviews indicate that these formally structured project architectures coexist with a more fragmented implementation reality at the European level.

Several interviewed experts stress that the project ecosystems often remain separated from one another and are governed within their own organisational logics. An expert in the field of AI technologies, smart cities, and Local Digital Twins notes that *"each project manages its own ecosystem"* and that there is currently no *"common governance of all the stakeholders of all these initiatives,"* while a European standardisation expert in transport and mobility points to overlapping initiatives, short project cycles, and repeated work on very similar topics across successive EU projects. In this sense, clear internal governance can reduce conflicts within individual consortia, but it does not automatically prevent duplication or fragmentation between projects. The challenge therefore lies less in the internal organisation of single consortia and more in the strategic alignment, continuity, and interoperability of multiple parallel initiatives across the European level. In addition, an organisational structure must be created that reflects the complexity of Transnational Digital Twins, which often requires a readjustment of existing role allocations and corresponding decision-making powers and responsibilities. It is therefore necessary to have clearly defined responsibilities, especially at the top level in combination with a comprehensive overall strategy that coordinates and brings together the individual activities, as highlighted by experts, researchers, and analysts in the field of urban mobility data and AI. The interviewed experts also emphasise that such coordination requires people with data competence inside the administration, because if this knowledge is externalised entirely, organisations lose the ability to steer, assess, and further develop the system themselves.

Heterogenous national contexts

In addition to the challenge to harmonise work processes and structures as well as the interests of the involved actors in multi-level project consortia, the nation states, cities, and regions have differing resource distribution and administrative and governance cultures and varying degrees of data governance and data infrastructure maturity and knowledge distribution, among others. These differences can complicate cooperation for implementing actors because often the foundations like viable data governance structures must first be created before complex projects such as Transnational Digital Twin projects can be planned. Even Digital Twin projects are often still in development or the subject of research projects at the national level.[144] For instance, in the rail infrastructure sector, data foundations like these must first be preceded by a modernisation of physical and digital infrastructures, as the interviews we conducted with implementing actors show. For example, automated condition monitoring of infrastructures can only be implemented once the necessary sensor technology has been installed in the individual countries, as a GIS team lead for Digital Twins in railway infrastructure states.

In the context of cities, Urban Digital Twins also diverge considerably in terms of the technical, personnel, and organisational capacities of municipalities. According to experts, many organisations lack the internal expertise required for the implementation of Cross-Border Digital Twins, particularly in regard to data management and data governance. A product lead of an open data portal points out that smaller municipalities in particular often do not have their own comprehensive data infrastructures and are therefore dependent on open data or additional supranational support mechanisms if a city cannot manage the full implementation effort on their own. In this sense, open data portals can have an important enabling function as data access infrastructures as they allow municipalities to work independently with datasets without having to build their own complete data architectures (see section 5.4).

Openness of organisational culture

The experts surveyed also emphasise that the cultural dimension within project governance depends heavily on the willingness exhibited in the early stages of the project to understand local needs and requirements, to listen to the stakeholders, and to incorporate these into concrete planning and implementation steps. As one expert critically questions, *"The cultural aspect, in particular the 'cross border', are we really open to work on it?"* (*Professor in the field of open data and Digital Twins in the public sector*)

Several experts emphasise that intercultural competence and an understanding of, for example, the administrative structures of other countries are essential prerequisites for successful cross-border cooperation. Existing know-how from other areas can serve as a catalyst, e. g. through preparatory workshops before the start of Digital Twin projects. Experts emphasise that this cultural openness

[144] See Blüml et al. (2025).

is not abstract, but rather operational and requires the ability to work across administrative boundaries, to understand how *"the other side"* functions, and to build on existing cooperation routines instead of starting from scratch:

> *The big challenges are not technological. The first challenge is really increasing the maturity level of the [cities], so, not only the technical capabilities but also the value that the local Digital Twin and data spaces can bring to them concretely. So, what we need is more of a cultural change. (Expert in the field of AI technologies, smart cities, and local Digital Twins)*

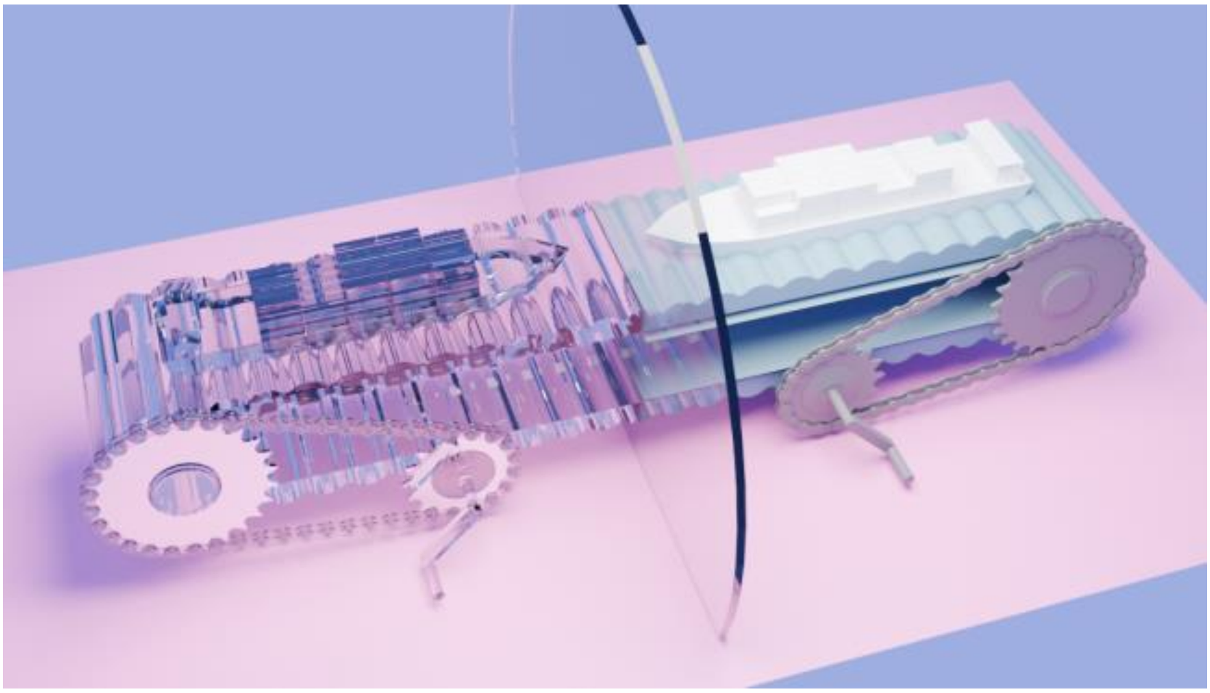
Several interviewees add that this change also depends on a realistic handling of expectations. Not every use case needs high-end, real-time functionality, and not every problem justifies a complex and costly architecture. What matters is that the organisational culture enables prioritisation, step-by-step implementation, and a (political) willingness to learn from pilot projects and good examples.

Key Takeaways:

1. **Robust multi-stakeholder governance structures:** The implementation of Transnational Digital Twins requires robust governance structures, because success depends on effectively coordinating diverse actors, responsibilities, and framework conditions across multiple levels. As these projects are typically embedded in complex multi-stakeholder consortia involving public, private, and research actors, effective implementation also requires a clearly structured organisation, coordinated work processes, shared objectives, vertical use cases, and horizontal work packages such as governance, technical architecture, and sustainability.
2. **Importance of coordinating structures and local counterparts:** Since national and local implementation bodies are often hesitant to limit their scope of responsibility or decision-making powers to higher levels, cross-border applications are particularly dependent on local counterparts, as they translate national peculiarities, regulatory requirements, and operational realities into the overall project implementation and act as a link between central control and local implementation.
3. **Diverging national contexts as organisational hurdle:** A major organisational challenge for implementing Transnational Digital Twins lies in the heterogeneous conditions of the different countries, cities, and institutions involved. Differences in data infrastructures, financial resources, funding experience, governance structures, institutional routines, and cultural and technical capacities make cooperation considerably more challenging. Fostering the development of cross-border projects such as twins therefore requires not only common objectives but also mechanisms to compensate for different levels of maturity and structural conditions among the partners.
4. **Cultural openness as enabling factor:** The successful implementation of Transnational Digital Twins requires an organisational culture that actively supports cross-border cooperation. Therefore, in addition to technical and formal structures, cultural openness, a willingness to cooperate, and intercultural competence are crucial. Different administrative structures, institutional routines, and national cooperation cultures must be understood and integrated into the project organisation so that cross-border cooperation becomes operationally viable.

5. **Ambivalence of European funding structures:** European funding and cooperation frameworks create important organisational prerequisites for cross-border applications while at the same time leading to new requirements for harmonisation and orchestration. On the one hand, EU-funded projects enable comparatively mature governance through contractually defined goals, work packages, and milestones and promote cooperation between large, transnational consortia. On the other hand, the large number of parallel initiatives, subprojects, and project-related governance structures create new fragmentation, which must be increasingly harmonised and strategically consolidated at the European level.

5.3 Operational requirements



Once a project consortium has developed a common understanding of a Digital Twin application in a transnational context and assessed whether the organisational prerequisites are in place, it can focus on the operational implementation. This involves defining and operationalising the specific use case and determining the user group for the application. Even though the potential added value of Digital Twins across sectors or borders is recognised by experts across domains (see chapter 3), practical implementation is highly complex, as the head of operations of a pan-European project in energy and mobility states:

> *Implementing [the Transnational Digital Twin] is extremely complicated, as we know. I mean, a Digital Twin, for instance, of an electricity grid, would mean that you can embed in the same Digital Twin different system operators or different countries that probably have different data-sharing standards and different characteristics. But the concept per se, I see quite clearly, and also the benefits that such a concept could actually bring. (Head of operations of a pan-European project in energy and mobility)*

Determining the use case and defining requirements

Digital Twins across borders do not arise in an institutional or national vacuum (see section 5.2). Different countries, cities, and infrastructure providers work with different technical solutions, organisational processes, and regulatory frameworks. If these differences are not taken into account in the planning phase of the Digital Twin project, solutions may work technically but might not be compatible with specific problems, existing resources (e. g. in a city), and other requirements of the specific context for which it is implemented. Requirements should therefore be developed in a user-centred manner based on existing practices, needs, and system logics of the implementing actors, as described by the technical manager of a European energy project:

> *But in order to propose something that could be applicable across Europe, first we have to listen carefully to what is happening. What are the needs? What are the approaches? And, of course, understand how to put ourselves in other people's shoes across Europe and then see how we can best serve the interest of everybody. (Technical manager of a European energy project)*

From the perspective of implementing actors, formulating the overall objective of a use case at an early stage supports the use case specification and later implementation of the Digital Twin, for example, by defining not only the purpose of open data provision for a mobility application but also and specifically the efficiency or performance in the respective area of application (e. g. transport system). In a large transnational energy project, this will be operationalised and modelled through Key Exploitable Results (KERs)[145] and measurable Key Performance Indicators (KPIs)[146] as well as midterm reports to the EU Commission. This allows suitable KPIs to be set and the means to achieve the goals to be provided in a targeted manner, as an expert, researcher and analyst in the field of urban mobility data and AI highlights. A clearly defined scope of work, describing activities, use cases, and pilots in detail, increases the efficiency of planning and implementing a Cross-Border Digital Twin. In the context of a European energy twin project, for example, around 50 use cases were developed in accordance with International Electronical Commission (IEC) 62559,[147] covering various areas such as system operation, planning, and asset management. According to IEC 62559, the structure serves to systematically record functional requirements, stakeholder roles, and interactions. The challenge here is to consistently document a large number of use cases and keep them compatible with each other.

Besides user orientation, use cases should be prioritised strategically, because financial, human, and technical resources are limited, as project managers across sectors emphasise. Determining the specific use case must therefore always include an assessment of economic efficiency. It is therefore useful not to pursue too many use cases simultaneously, but rather to focus on those that act as bottlenecks in order to address potential structural blockages and enable scaling of the use case in the long run. Because Cross-Border Digital Twin applications require considerable resources for computationally intensive simulation models, cost–benefit analyses can serve as a tool to assess

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[145] A KER refers to a key output identified in the project with high potential for exploitation, whether for further research, policy application, or economic exploitation. This includes both tangible results and knowledge or information products that are strategically selected and prioritised to generate real impact. See craft oa at https://www.craft-oa.eu/results/

[146] KPIs are quantifiable performance metrics used to measure and evaluate the success of activities or projects in achieving defined goals; they serve the purpose of objective control, comparability, and continuous improvement of processes. See Wirtschaftslexikon Gabler at https://wirtschaftslexikon.gabler.de/definition/key-performance-indicator-kpi-52670

[147] See the International Electrotechnical Commission at https://syc-se.iec.ch/deliveries/iec-62559-use-cases/

whether the expected added value justifies the investment in a Transnational Digital Twin project (see assessment of suitability of the concept in section 5.1).

Defining the target group

The analysis and the expert interviews reveal that Transnational Digital Twin projects address heterogeneous target groups with considerable differences in requirements, value propositions, and communication forms depending on the stakeholder group. Users range from technical and operational stakeholders such as national infrastructure operators (e. g. of the energy system) or technology manufacturers to political decision makers and citizens. The needs of the individual user groups should therefore be examined continuously during project phases and integrated early on into the project planning. For example, key stakeholders in the energy context, such as energy network technology manufacturers, require precise technical specifications, interoperable data models, and validated system mappings. Requirements arise here from system operation, planning, and asset management. This shifts the focus to standardisation, interoperability, and robust validation.

In contrast, policy makers as a target group are mostly less concerned with technical architectures and focus more on support for decision making, for instance, through simulations, scenarios, and transparency with regard to infrastructure conditions. Their focus is often on the political connectivity of the Transnational Digital Twin application, as experts highlight. From a research perspective, data used in Transnational Digital Twin applications is being developed, for example, as part of the DestinE project (see section 4.1.2) to conduct simulations and scenarios for research purposes, which often include political decision-making processes. Here, the focus is often on data quality, scalability, and international connectivity, as researchers involved in respective projects state. Citizens are often addressed as an indirect target group, since the planning and implementation of complex digitalisation measures such as (Transnational) Digital Twins across sectors, e. g. in mobility, energy, and urban development, mostly require social acceptance and therefore the early integration of citizen perspectives and requirements. Digital Twins across borders can serve as instruments to foster transparency of decision-making processes by using visualisations and scenarios to facilitate participation and make complex interrelationships comprehensible (see chapter 2).[148]

Target groups can shift over the course of a project, as project representatives point out. While administrative bodies and technical stakeholders often dominate initially in the design and planning phases, implementing actors, such as infrastructure operators and governance bodies become pertinent when it comes to implementing the Digital Twin application, and ultimately communication and knowledge transfer become viable when the project results are to be consolidated. Target group analysis is therefore an iterative process and not a one-time preparatory task. In order to implement user centricity, user communities are already being implemented on platforms such as Mobilithek.[149]

Roadmap for implementation

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[148] See Blüml et al. (2025).

[149] See the Mobilithek User Group at https://mobilithek-usergroup.de/

The analysis further indicates that complexity in the operational implementation of Transnational Digital Twin projects arises in particular from the confluence of local requirements, overarching European strategic goals, and often limited resources, all of which must be taken into account simultaneously. A structured roadmap can guide stakeholders step by step, as an expert, researcher, and analyst in the field of urban mobility data and AI states.

According to implementing actors, Transnational Digital Twin projects are often initiated bottom-up. Local requirements of end users, e. g. cities and system operators, are translated into an overarching consolidated project vision (see section 5.1). To integrate local tools and technologies, project managers must clarify at an early stage the responsibilities for the maintenance, integration, and further development of available and needed resources, such as technical infrastructures, to avoid fragmentation. This approach proves successful when it makes efficient use of local resources, which are often scarce, especially in smaller municipalities, and provides central infrastructure while implementation remains local.

A key enabling factor, as highlighted by experts on national and European levels across domains, is the step-by-step implementation of use cases. Large cross-sectoral, and cross-country projects cannot be planned purely conceptually, as illustrated by the director of the technical research institute and technical consultant for Digital Twins in railway infrastructure, but rather must be implemented iteratively and be use case-driven in order to make complexity manageable. Building trust, structures, and governance requires a step-by-step-approach and should be aligned with specific use cases.

This emphasises the importance for those in charge of projects to make benefits and added value visible to project participants and funding bodies and to avoid oversizing the scope of use cases too early in favour of focussing on interoperable, local solutions. Such bottom-up collaborations between cities already exist, as the interviewees observe. For instance, a technical coordinator of a European Digital Twin initiative describes the development of demonstrators at the national level as an intermediate step to enable transnational scaling:

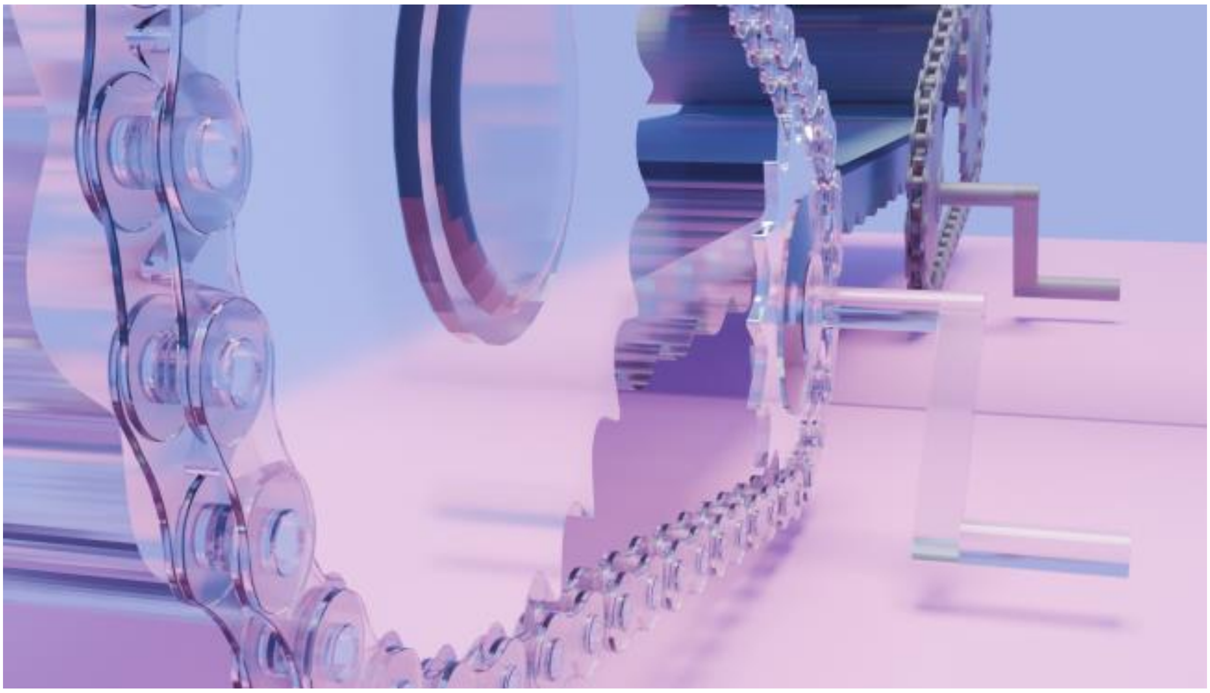
> *Because the ambition to go beyond a national twin is to have something all over the Earth. However, it's not that easy because each country has its own constraints and different problems. And so far, the scene is still quite young. And among the entities, we started to develop some demonstrators or precursors, which are at the national level. So, there are multiple cities and countries, regions, local twins [...] to show how it can work and how it can be then transposed to another region. However, each region has its own input data and all kinds of different climate shapes, you know? We're moving towards a different scale. I also think Digital Twin is a big word. In our project, there are multiple twins and there are maybe even twin cities, which are more than an application based on output of the climate twins or extreme twins. (Technical coordinator of a European Digital Twin initiative)*

The establishment of the European Digital Infrastructure Consortium can be highlighted as a practical example of the implementation of a roadmap for the consolidation of local Digital Twin units. Previous project experience and insights gained by LDTs are to be transferred into long-term governance and operational structures. Therefore, a roadmap should encompass technical, organisational, and institutional dimensions with the goal of creating operational structures and infrastructures, such as service catalogues, and governance regulations to focus on long-term consolidation. In this context, a leading expert and deputy chair in several European initiatives on (Urban) Digital Twins points to the trend that is also visible in the course of the deployment of EDIC, which is the increasing consolidation of past and existing projects to launch new projects based on previous insights and learnings.

Key Takeaways:

1. **Defining requirements as a success factor:** The early and precise determination and strategic prioritisation of user-centred use cases with smaller scopes, taking into account existing technical, organisational, and regulatory national contexts and cost-effectiveness, is crucial to ensure (future)connectivity, efficiency, and scalability of Cross-Border Digital Twins.
2. **Target group-oriented implementation:** Clearly defining the target groups is an important step to successfully build Transnational Digital Twins, as different stakeholder groups, from technical operators to political decision makers, researchers, and citizens, have specific requirements in terms of (technical) information needs, communication formats, and demands, and these requirements may change over the course of the project and must be re-assessed and integrated accordingly.
3. **Iterative implementation roadmap:** An iterative roadmap for implementing Transnational Digital Twins can be helpful in linking local requirements with European strategic goals, thereby increasing the chance of transferring project results into long-term governance and operational structures and taking changing requirements over time into account.
4. **Monitoring impact as operational steering tool:** The use of suitable KERs and measurable KPIs to achieve objectives can help increase efficiency, controllability, and adaptability of Transnational Digital Twin projects and strengthen structured project implementation as well as impact measurement to ultimately define and legitimate the added value of the Cross-Border Digital Twin.

5.4 Establishing the data infrastructure



Data infrastructure is consistently described as a foundational prerequisite for Transnational Digital Twin applications. Several interviewees note that many technical components and data already exist, but they are not implemented consistently or coordinated adequately. As a result, higher-level, interconnected Transnational Digital Twins can only be achieved across borders when data can be reliably identified, accessed, exchanged, and interpreted consistently across systems and contexts.

Data interoperability as a core prerequisite

Across interviews, experts identify data interoperability as the primary prerequisite for Cross-Border Digital Twins. In this context, data interoperability refers to the ability to exchange and interpret data across actors, systems, and national contexts, and interviewees commonly distinguish between syntactic and semantic interoperability. For instance, in a cross-border rail project, partners from across countries and contexts need to agree on a shared protocol for data sharing (syntactically and technically) and a shared understanding of the meaning of the data, i. e. creating a common data model (semantic) that works across borders and contexts. While both dimensions are essential, the interviewed experts agree that the latter is more challenging. This will be discussed in more detail below.

Common data models

Implementing actors describe the need for a common language to derive a common interpretation of the Digital Twin reference object:

> *The understanding of the replicated physical object must be aligned so that data acquisition, modelling, and 3D representation describe the same entity consistently across systems and borders. (Data strategy architect in railway digitalisation)*

However, in practice, a recurring theme across interviews is that the same physical object or process (e. g. rail infrastructure elements such as track switches) is often represented differently across countries and organisations. Aligning these representations is considered especially critical for transnational and transversal use cases and collaboration. Shared data standards and common data models are thus described as the key mechanism to scale an individual Digital Twin to a transversal and transnational dimension as the understanding of concepts and objects must be aligned across borders.

Common data models are further needed to enable replication. A researcher specialising in Urban Digital Twins and sustainable infrastructure argues that if city structure data from the same domain is different, applications cannot be reused without substantial rework, and cross-border data exchange becomes infeasible. The interviewees therefore link data interoperability directly to the reusability and scalability of local and national Digital Twin applications. In this sense, those applications designed for interoperability are more likely to scale into transversal and transnational use cases.

As a pragmatic pathway towards interoperability, several initiatives and experts refer to Minimal Interoperability Mechanisms (MIMs).[150] MIMs support gradual alignment between systems by defining a minimum set of interoperability rules for priority datasets. This stepwise approach enables initial interoperability while allowing progressive convergence towards higher interoperability levels. In urban data contexts, MIMs define minimum shared mechanisms for making city data accessible, understandable, linkable, secure, and reusable across systems and services, as Figure 7 shows.

[150] See the Publications Office of the European Union. (2024). *Minimal Interoperability Mechanisms: Advancing Europe's digital future*: https://data.europa.eu/en/news-events/news/minimal-interoperability-mechanisms-advancing-europes-digital-future

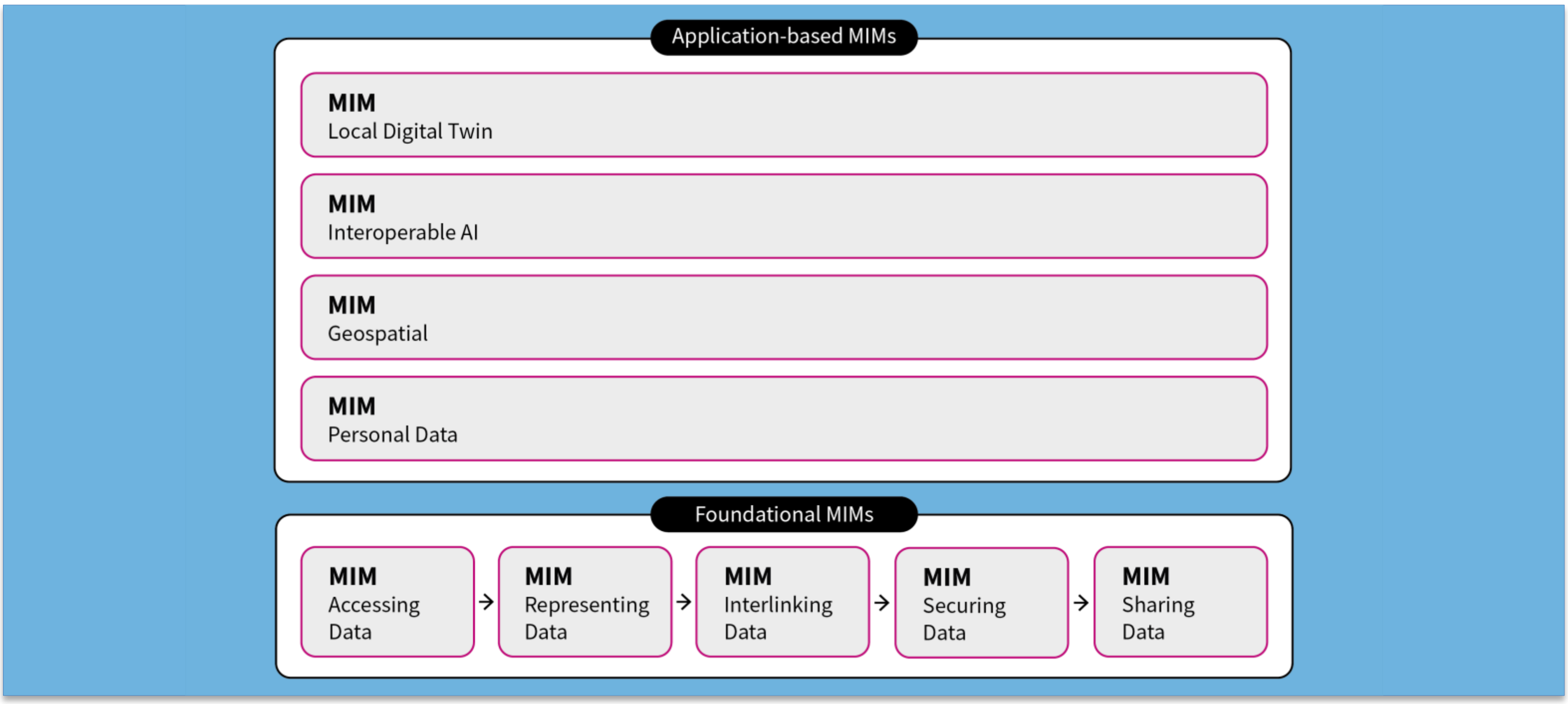


Figure 7: Overview of MIMs in urban contexts and related mechanisms. Source: Own representation iRight.Lab based on [Open & Agile Smart Cities](#).

Metadata standards to improve data interoperability

Experts describe metadata standards as a key mechanism to improve the interoperability and reusability of dataset in Transnational Digital Twins. They can align semantics and structure within and across actors, which supports a predictable data exchange and more efficient software development. As a European standardisation expert in transport and mobility summarises, metadata standards provide a shared *"dictionary and grammar"* for data exchange. Experts highlight that compared to a data model, which is a conceptual representation of data structures and relationships used to organise and manage data effectively, metadata standards define the rules and attributes for describing data, ensuring consistent interpretation and use across different systems.

In this context, open data efforts and European initiatives such as NAPCORE *(*National Access Point Coordination Organisation for Europe) push towards standardisation and contribute to the European harmonisation of metadata standards, for example, through the Data Catalog Vocabulary Application Profile (DCAT-AP) and its domain-specific extension for urban mobility data, mobility DCAT-AP[151]. In other mobility domains, such as long-distance travel, logistics, and railway, common standards like these are still nascent. For instance, experts from the rail industry report a lack of sufficiently established sector-specific standards for the digital exchange of infrastructure and rolling stock data, especially beyond local project contexts. Moreover, experts describe an environment in which many competing standards coexist, and actors select standards based on immediate project needs rather than long-term reuse potential.

[151] See the NAPCORE, mobility DCAT-AP website at https://napcore.eu/release-of-the-mobilitydcat-ap/

Furthermore, experts stress that European standardisation remains incomplete, even where formal standards exist because profiles are interpreted differently across countries and harmonised cross-country; cross-metadata-model translations are often missing, and enforcement of standard use is limited. Especially in transversal use cases, standard interoperability and translation mechanisms are not yet sufficient to achieve robust interoperability across standards and domains.

Interviewees, further, report a persistent gap between officially prescribed standards and standards used in practice. For instance, in the mobility sector, practitioners often rely on widely adopted industry standards such as General Transit Feed Specifications (GTFS)[152] because they are easier to implement and more flexible for operational use cases compared to the officially promoted standard called the Network Timetable Exchange (NeTEx).[153] Lastly, metadata quality is often insufficiently described, incomplete, or inconsistent, which reduces its practical value and makes it difficult for users to assess whether a dataset is fit for a specific use case. Key gaps include missing licensing information, unclear usage rules, and limited information on data quality leading to reduced interoperability and reuse because potential users cannot reliably determine whether data can be legally and technically used for their purposes.

Data findability and access as a central barrier for Transnational Digital Twins

In the mobility sector, experts note that data is abundant in principle, but ease of access by key stakeholders of Transnational Digital Twins especially by public actor-focused consortia are limited, especially for high-value behavioural and mobility data due to its high fragmentation. Experts highlight two key challenges: limited findability of data and limited data access.

Experts emphasise that organisations often lack a clear overview of who holds which data within and across actors and under which access conditions. This is especially true in the mobility sector with data distributed across multiple stakeholders that often remains fragmented within organisations. This makes data discovery a core prerequisite for improving practical access.
In this context, beyond the metadata standard itself, experts describe metadata infrastructure as a critical first step for increasing readiness for Transnational Digital Twins. By improving the visibility and traceability of datasets, metadata infrastructure helps project responsibles identify relevant data sources before full technical integration. Open metadata catalogues based on common European standards, such as the DCAT-AP and federated catalogues found in data spaces, are considered key enablers.

In the mobility sector, National Access Points are described as an important practical step to improve data findability and access. However, the interviewees also note major differences in maturity and implementation across member states. Some countries have developed operational data platforms (see section 2.5), while others provide only basic registries or lists of data-holding

[152] General Transit Feed Specification provides specification for public transport schedules and was originally developed by Google and named Google Transit Feed Specification.
[153] NeTEx (Network Timetable Exchange) is the European Committee for Standarization for public transport schedules and related data and can include more detailed information such as accessibility-related information. See https://transmodel-cen.eu/index.php/netex/

authorities. Where NAPs do not offer direct access through downloads or APIs, usability and reuse remain limited.

Even if data is findable, access to it is further constrained. For instance, experts from the urban mobility sector highlight that in many cities, private providers operate services on behalf of public authorities and deliver aggregated analytics, while the underlying raw data remains inaccessible to the public actors. Experts further note that procurement decisions strongly shape interoperability and raw data access. Cities that explicitly require open and exportable data in procurement processes achieve better interoperability outcomes. By contrast, private actors may restrict interoperability and data access to protect business models and monetise data assets, particularly in mobility. This limits independent analysis and reduces the ability to use the data in local or national Digital Twins and, in the future, in transnational or transversal Digital Twins for cross-sectoral analysis. Data access is further constrained because much of the most relevant mobility data is not covered by the EU High-Value Data Regulation as an open data expert highlights. Additionally, the interviewees indicate that access to sensible and valuable data is often met with scepticism and depends on trust building and institutional legitimacy.

Open data as a partial enabler of Transnational Digital Twins

The interviewees broadly describe open data as valuable for transparency, research, testing, and early interoperability work, and many experts state that they follow open data principles and try to use open datasets whenever possible. Moreover, open data is described as a practical way to identify gaps in standards and implementations. As an open data expert explains, open datasets can be used as a fast test bed to detect missing fields, overlaps, and divergent extensions across countries. In this sense, open data supports rapid exploratory analysis, even if it does not fully represent the complete data landscape.

On the other hand, experts also stress that in practice, Transnational Digital Twin projects cannot rely solely on open data to succeed as many relevant datasets are sensitive, proprietary, operational, or security-critical. This applies in particular to mobility operations, infrastructure assets, and other critical infrastructure data, as the interviewees stress. As a result, open data can support foundational work, but more advanced Transnational Digital Twin use cases require governed access to restricted datasets, which can be achieved via data spaces (see below).

The empirical picture is best described as a mixed data base. Project data sources are often project-specific and combine open data, partner-provided internal data from e. g. operational data from energy transmission system operators and other non-open datasets. In some cases, data stems primarily from consortium partners (e. g. internal operational and asset data) and external stakeholders or associated partners such as public authorities, research institutions, and other organisations outside the core consortium that support piloting and validation. But overall, interviewees emphasise that given the sensitivity of critical infrastructure, a balanced open–closed approach is required in which certain data remains protected while selected data and functionalities are made available for research and innovation.

Declining willingness for broad open data sharing
Furthermore, several interviewees report a shift away from broad "open-by-default" approaches. According to these experts, some actors increasingly view extensive data sharing as a competitive disadvantage, especially when non-European competitors may benefit from publicly funded European data resources. Experts stress that this concern is also articulated by their political leadership, which has become more reluctant towards unrestricted public data sharing and has placed greater emphasis on ensuring that publicly funded data primarily supports European research and industry. The interviewees further note that open data access is increasingly questioned because of dual-use risks. Infrastructure and mobility data can support legitimate uses such as traffic analysis and urban planning but may also contain security-relevant information. This makes public actors more cautious about releasing such data openly.

Overall, evidence from the interviews suggests that Transnational Digital Twin projects face growing tension between maximising open data benefits (reuse, innovation, transparency, and faster standardisation) and tighter political, economic, and security constraints, leading to more *"controlled openness"* rather than fully open-by-default publication as a professor in the field of open data and Digital Twins in the public sector states.

A pragmatic compromise currently evolving is a tiered access model that keeps high-risk datasets restricted while enabling free reuse for European research, industry, and citizens, supported by clear licensing, identity-based access where needed, and explicit dual-use risk assessment as a Digital Twin data infrastructure manager describes.

Data spaces as a concept for the use of sensitive data
Experts commonly describe data spaces as a promising future data infrastructure for Transnational Digital Twins because they combine several necessary layers within one structure. These include federated metadata catalogues, interoperable protocols and connectors for data exchange, semantic models, and governance mechanisms such as access control and usage rules. In combination, these elements can support cross-border data sharing and Digital Twin development. In this view, data spaces provide the backend data-sharing layer, while Digital Twins use this data infrastructure for transnational analytics and applications. Moreover, the interviewees stress that national and local data projects should be designed envisioning future interoperability with data space as a strategic necessity to enable future transnational projects.

Experts highlight that data spaces provide mechanisms for both technical and semantic interoperability making them most suitable for transnational use cases.[154] At the same time, domain-specific data models and shared standards remain necessary to ensure that exchanged data can be interpreted and reused across actors and contexts. This means that data spaces can provide the infrastructure for trusted exchanges, but interoperability still depends on common standards and models at domain level.

[154] For example, data connectors support standardised exchange and controlled access, including the possibility of machine-readable usage conditions and contracts. https://internationaldataspaces.org/data-space-connector-report/

A central advantage of data spaces is their potential to enable the controlled use of sensitive, proprietary, and grey-area data[155] that cannot be published as open data. The interviewees describe many relevant datasets as commercially sensitive, operationally critical, or constrained by privacy and legal requirements and therefore unsuitable for open release. In this context, data spaces are described as a governance-based alternative to open data. They can support controlled access, identity management, licensing, and enforceable usage rules, allowing authorised partners to securely access data under defined conditions, as a standardisation expert states:

> *There are other types of data that are usually on the bleeding edges of open data that are very sensitive. That is either because data can cause problems in terms of competition, in terms of the GDPR [General Data Protection Regulation], and in terms of other matters. And for me, that's where the data space is interesting because organisations, often private or even public ones, research institutes, for example, could sell, can sell, should sell, the bleeding-edge data. So, what I call a kind of grey data. And the data space, as I see it, should facilitate the understanding of if you buy that dataset, you know what the format is, what the quality level is, and you know that it would also fit what you are looking for before paying for it. (European standardisation expert in transport and mobility)*

Overall, the interviewees describe data spaces as a promising infrastructural approach for Transnational Digital Twins, especially for use cases that depend on sensitive or proprietary data. Their value lies in combining interoperability mechanisms with governance and controlled access, but their current impact is constrained by limited adoption, business immaturity, and policy uncertainty.

Toolboxes as a reuse-based architecture for interoperability

In addition to data space infrastructures, experts describe a second interoperability pathway based on reuse and integration of existing components through shared toolboxes. In this architecture, interoperability is supported less through federated data exchanges and governance layers and more through the coordinated reuse of common software components, tools, and implementation patterns across local or national Digital Twin projects. According to the interviewees, this approach is relevant for cross-border harmonisation as it can reduce duplication, support standardisation in practice, and promote interoperability by design in local implementations. A central idea of the toolbox approach is to avoid rebuilding core functions from scratch. Instead, existing tools are curated, combined, and made available in a structured form for reuse. According to an expert in the field of AI technologies, smart cities and Local Digital Twins, the Local Digital Twin Toolbox is an example of this model (see section 4.1.3). It is not primarily new technology, but rather a multi-layered aggregation of already existing tools across data, orchestration, and visualisation layers. This architecture is important because it shifts the focus from developing isolated solutions towards assembling interoperable component ecosystems.

Overall, evidence from the interviews suggests that toolboxes and data spaces represent different but complementary technological architectures. Toolboxes focus on component reuse and implementation support, while data spaces focus on trusted data exchange, governance, and

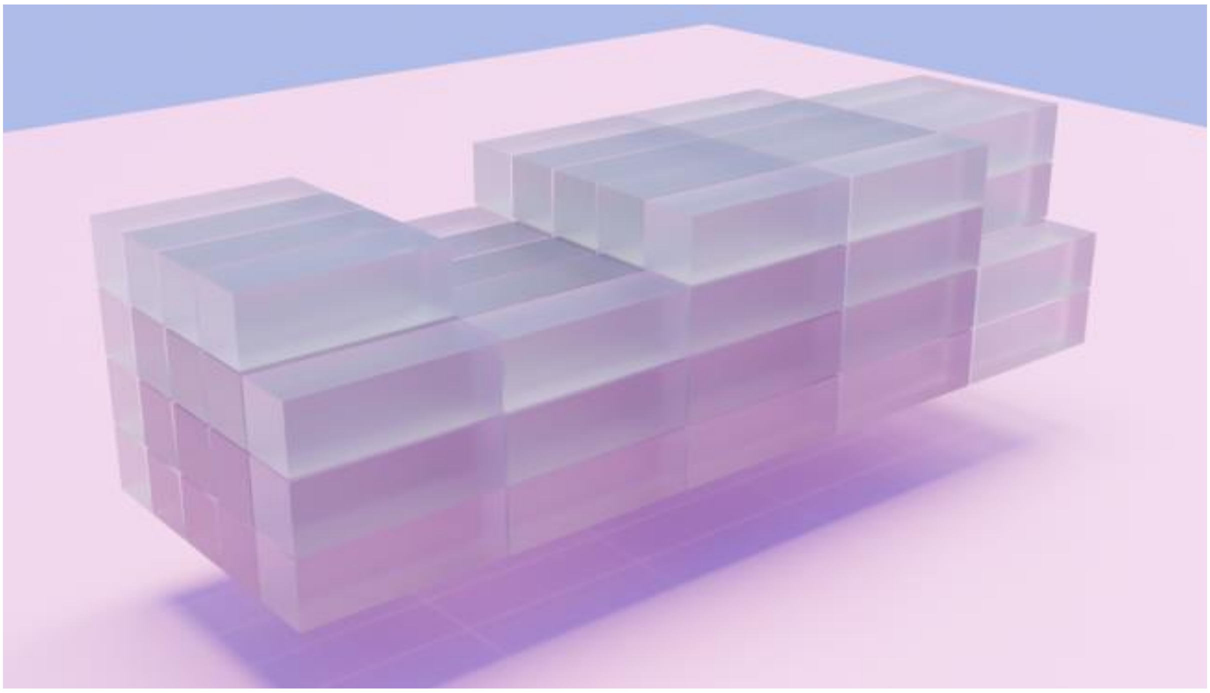
[155] "Grey data" was described by a European standardisation expert in transport and mobility as data at the boundary of open and closed data, where users need clarity on format, quality, and suitability before access or purchase.

controlled access. Both can contribute to interoperability, but they address different layers of the overall ecosystem.

Key Takeaways:

1. **Data interoperability as the central prerequisite:** Data interoperability is the core data-related prerequisite for Transnational Digital Twins, with semantic interoperability representing the greatest challenge. This requires common data models that describe reference objects, processes, and relationships in a consistent way. Without such shared models, existing local solutions cannot be meaningfully scaled, reused, or connected across borders.
2. **Need for robust metadata standards:** Metadata standards are a key prerequisite for improving interoperability, data discoverability, and reusability, but their current practical implementation often remains insufficient to effectively support Transnational Digital Twins. Even where formal standards exist, their uptake and implementation are often uneven, insufficiently harmonised across countries, and not adequately aligned with operational requirements.
3. **Limited data findability and access as a central barrier:** A major barrier to develop Transnational Digital Twins lies not in the absence of data, but rather in limited data findability, accessibility, and quality. In many cases, it is unclear which actors hold relevant data, the conditions under which it can be accessed, and whether it is usable for specific purposes. Legal, institutional, and commercial restrictions often further constrain effective access, while deficiencies in completeness, consistency, and documentation limit practical reuse. Mature metadata infrastructures and NAPs can provide an important foundation for improving Europe’s readiness for Transnational Digital Twin development.
4. **Open data as an important enabler, but not a sufficient basis:** Open data is an important enabler for Transnational Digital Twins, but most advanced Cross-Border Digital Twin use cases depend on mixed data ecosystems as many relevant datasets are sensitive, proprietary, operational, and security-critical. In practice, Transnational Digital Twin projects typically rely on a combination of open data, partner-provided internal data, and restricted datasets.
5. **Data spaces and toolboxes as complementary infrastructure pathways:** Data spaces and toolbox approaches represent two complementary infrastructure models for Transnational Digital Twins. Data spaces are considered a particularly promising backbone infrastructure because they combine interoperability, governance, and controlled access, thereby reducing data access and availability issues. Toolbox approaches support Transnational Digital Twins primarily through the reuse of shared software components, technical building blocks, and implementation patterns across local or national Digital Twin projects thus connecting them across borders.

5.5 Developing the technical infrastructure



A robust technical infrastructure is a central condition for implementing Transnational Digital Twins across national and sectoral boundaries. The interviewed experts describe this infrastructure as a layered architecture that enables federation, supports the reuse of open and interoperable components, and incorporates security and tiered data access by design.

Layered technical stack for Transnational Digital Twins

The interviewees commonly describe the technical infrastructure for Transnational Digital Twins as a layered and modular architecture composed of reusable building blocks. Rather than developing fully new solutions in each project or country, this approach emphasises the reuse of components across domains and jurisdictions. The expected benefit is reduced duplication, faster deployment, and gradual adoption because actors can implement selected modules first and expand later as needs and capacities increase. For instance, a project lead in railway infrastructure research and development emphasises that despite the apparent continuity of the rail network, European rail remains fragmented in practice due to persistent national differences in technical systems, signalling, and operational requirements (e. g. different voltages).[156]

This technical framing is closely linked to the current problem of fragmented legacy systems. Several interviewed experts describe a landscape of isolated, non-interoperable systems that were developed for local or sector-specific needs. In this context, Transnational Digital Twin infrastructure is presented as a response to fragmentation by promoting common technical standards, interoperable components, and architectures that can support cross-border use cases.

Transnational Digital Twins based on federated data exchange

[156] For visualisation of the diverse voltage system used in Europe, see Gallas, D., Stobnicki, P., Jakuszko, W., Urbański, P., & Kikut, J. (2023). Application of alternative drive systems in modern special-purpose rail vehicles. WUT Journal of Transportation Engineering, 136, pp. 23–33. Retrieved from https://www.doi.org/10.5604/01.3001.0016.3417 (Figure 5).

In the interviews, a recurring technical model is federated architectures. In this model, data remains with local actors or in local systems, while exchange is enabled through standardised interfaces, connectors, and interoperable protocols. This allows cross-border and cross-domain cooperation without requiring full centralisation of data.
Experts describe this federation layer as combining several technical functions: interoperable data exchange, identity-based access, and secure interaction between data providers and data users. In practice, this includes technical mechanisms for authentication, trusted exchange, and controlled access to data and services. Some interviewees also point to usage-control mechanisms that can define and enforce machine-readable access conditions (e. g. who can access which data under which constraints and for which purpose). This supports selective sharing in settings where full openness is not desirable.
In this sense, Transnational Digital Twins are not framed as single technical systems, but rather as a higher-level communication and federation layer connecting multiple Digital Twins and data systems across borders.

System integration via reusable and open components and reference architectures
Another recurring technical enabler is system integration through reusable components and reference architectures. They are described as interoperable sets of deployable components, APIs, and example implementations that can be adopted and combined by cities and other actors. This modular approach supports a differentiated uptake: organisations can implement one component, several components, or larger parts of the stack depending on their technical maturity, local requirements, and implementation capacity, e. g. LDTs. Project responsibles describe reference implementations and reference codes as being particularly important because they reduce integration effort, accelerate deployment, and promote interoperability by design when multiple actors build on the same technical foundations. At the same time, the interviewees note that uptake remains uneven. Smaller and medium-sized cities in particular often require technical support for deployment and integration. This means that the availability of modular components and reference architectures improves technical readiness, but does not automatically ensure uniform implementation.

Several interviewees also point to a non-proprietary and open technical orientation as an enabling condition for Cross-Border Digital Twin infrastructure. Open-source components, modular designs, and extensible system architectures are described as beneficial because they reduce vendor lock-in, increase adaptability, and support reuse across countries and projects. This is particularly relevant for transnational settings, where infrastructures must remain adaptable to different national systems, technical environments, and future integration requirements. Figure 8 shows the integration of federated Digital Twin instances, shared data and model infrastructures, and application services.

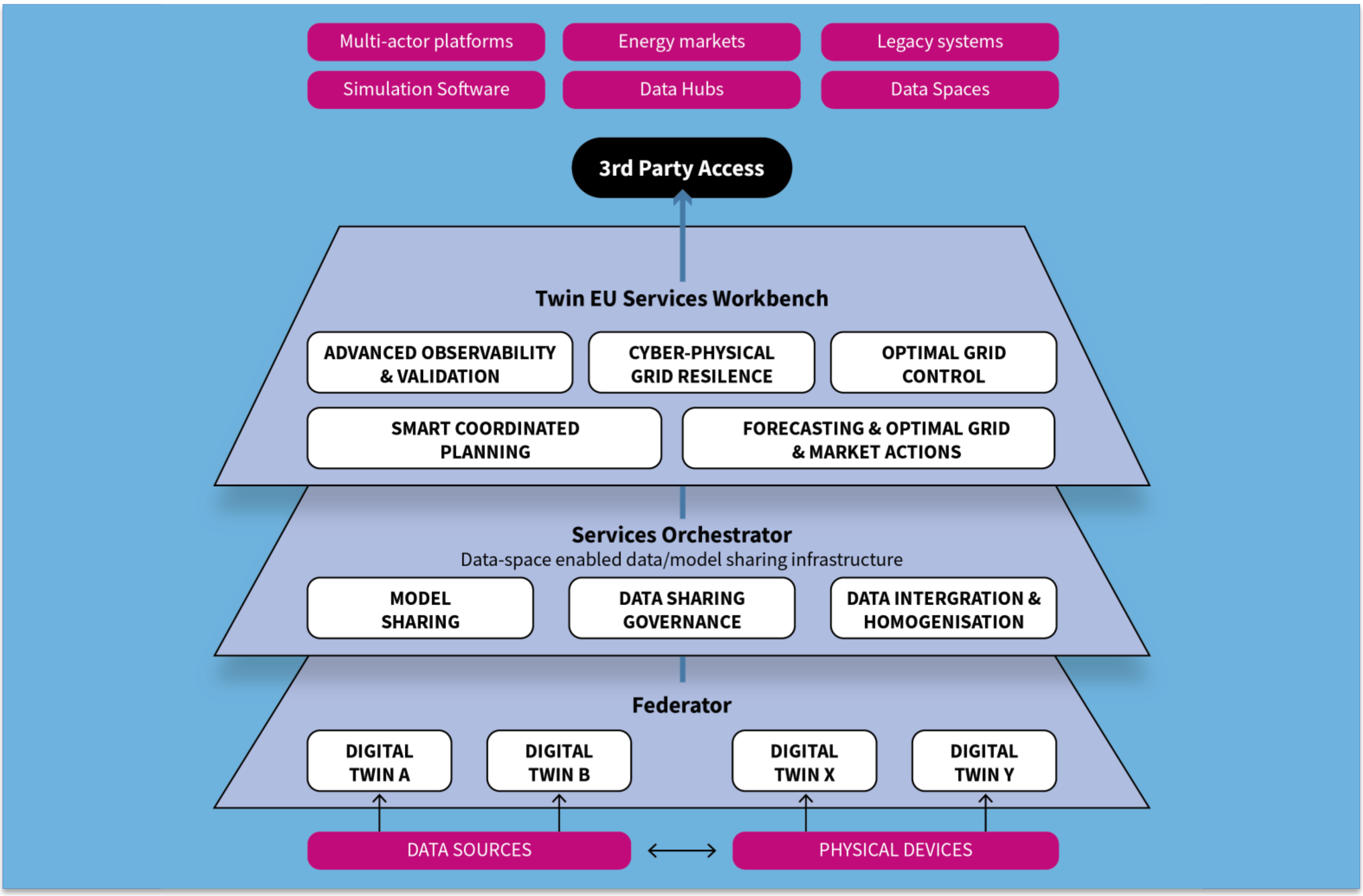


Figure 8: Exemplary architecture of a Transnational Digital Twin, showing the integration of federated Digital Twin instances, shared data and model infrastructures, and application services. Source: Own representation iRights.Lab based on TwinEU.

Security, identity, and controlled openness as core prerequisite

The experts describe security as a core technical condition for the adoption of Transnational Digital Twins. In cross-border settings, infrastructures must enable collaboration while ensuring that access to data and analytical results is restricted to authorised and trusted actors. This is especially important in domains linked to critical infrastructure, where unrestricted sharing is often not possible.

Accordingly, the interviewees emphasise the need for a technical security architecture that combines identity verification, authentication, and access control. This includes mechanisms such as identity hubs and stakeholder verification, as well as layered security designs that allow differentiated access and usage rights across users, organisations, and data types.

A recurring theme highlighted by project responsibles across domains is controlled data openness rather than full openness. The interviewees stress that transnational platforms should support graduated sharing models in which actors can collaborate securely with selected stakeholders without making all data or results available to the full community. This is presented as a key requirement for making platforms attractive to local and national actors, who need assurance that sensitive information remains protected. A technical coordinator of a European Digital Twin states:

> *We have to make sure to put in place a security platform with security layers and also to have the capability to restrict the produced data. [...] Because if we want to make the platform attractive for local, national levels and actors, we also need to make sure they are in a secure place if they want to work and share the data with their stakeholders and not the entire community. (Technical coordinator of a European Digital Twin)*

Several experts further note that security and access requirements vary by data type and level of granularity. More granular, operational, and security-relevant data typically involves stricter constraints and more complex handling requirements than aggregated or less sensitive data. In this sense, the complexity of secure transnational data sharing increases with the sensitivity and critical infrastructural relevance of the data.

Transnational Digital Twins as shared computing infrastructure

Project representatives from large-scale Transnational Digital Twin projects describe advances in computing infrastructure as an important enabler for widening access to computationally intensive models and simulations. They emphasise that high-performance simulation and analysis, which was previously limited to institutions with direct access to High Performance Computers (HPCs) resources, can increasingly be made available to a broader set of users through shared digital infrastructures such as Transnational Digital Twins.

In this model, resource-intensive computation is performed by institutionally strong and central Transnational Digital Twins, which provide results, services, and interactive access to a wider community of stakeholders. The interviewees describe this as a more resource-efficient arrangement as it reduces duplication of computing infrastructure and enables a broader use of advanced modelling capacities beyond the core research organisations.

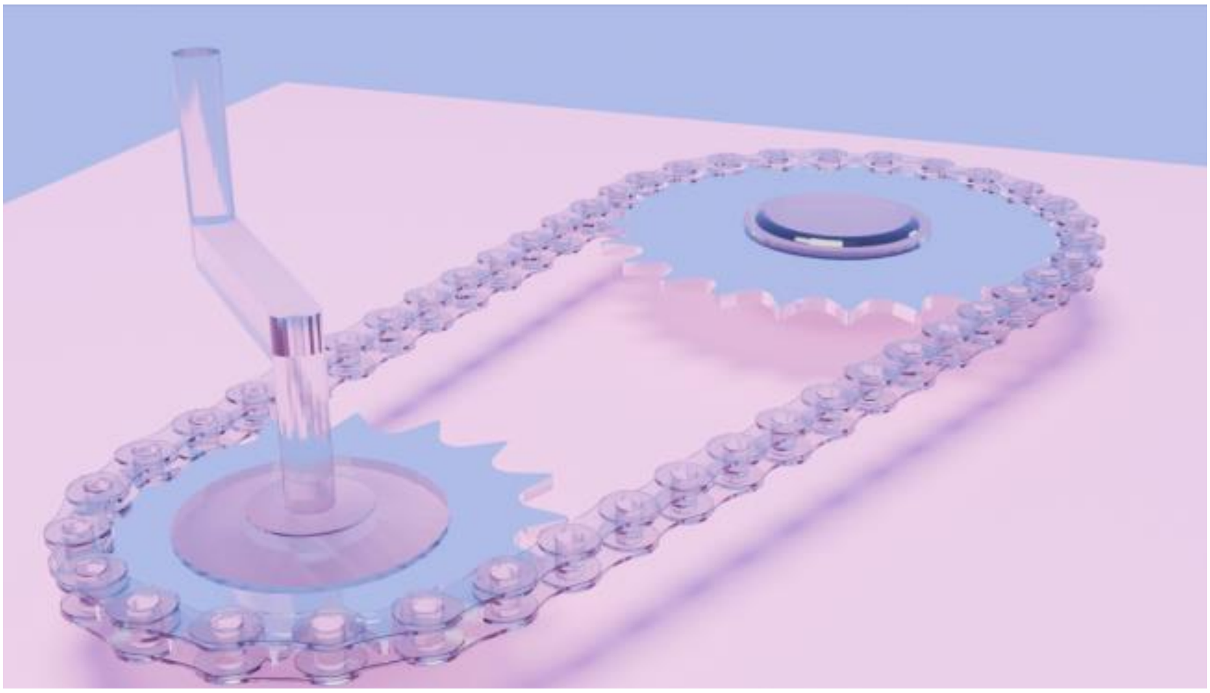
Key Takeaways:

1. **Layered and federated technical architecture as a core prerequisite:** Transnational Digital Twins require a layered, modular, and reusable technical architecture. In this model, Cross-Border Digital Twins function less as centralised applications and more as a higher-level communication and federation layer that connects local or national Digital Twins, data systems, and services across borders. Reusable components, shared interfaces, and reference architectures are central to reducing duplication, accelerating deployment, and enabling gradual scaling across different national and sectoral contexts.
2. **Federation, reuse, and openness as key design principles for cross-border interoperability:** A technically viable Transnational Digital Twin infrastructure depends on federated data exchange, interoperable protocols, and reusable components that allow local systems to remain in place while still supporting cross-border cooperation.
3. **Security and controlled access are essential enabling conditions for transnational adoption:** Transnational Digital Twin infrastructures must combine collaboration with secure and differentiated access to data, services, and analytical results. This requires

robust technical security architectures, including identity management, authentication, and access control. Controlled openness, rather than full openness, is therefore a main condition for making Transnational Digital Twin platforms viable and attractive for local and national (implementing) actors who need assurance that sensitive and operationally relevant data remains protected.

4. **Transnational Digital Twin infrastructures can widen access to advanced simulation and analysis capacities:** Transnational Digital Twins can broaden access to resource-intensive modelling, simulation, and analytical services. By concentrating high-performance computation in shared infrastructures and making results and services accessible to a wider group of actors, Transnational Digital Twins can reduce duplication of computational resources and extend the use of advanced modelling capacities beyond a small number of highly equipped institutions.

5.6 Challenges of the regulatory framework



Developing and implementing Transnational Digital Twins is intrinsically linked to the European legal regime and data regime because Transnational Digital Twin architectures require a structured, an interoperable, and a legally compliant data exchange. In recent years, European legislators have created an increasingly coherent set of rules for this purpose. At the same time, interviews with project managers and experts show that the practical implementation of these requirements continues to cause considerable tension. Regulation thus acts both as an enabling and a limiting framework for Transnational Digital Twin projects.

Data access and provision vs. legal uncertainty

The European legal framework provides the normative basis for the access, provision, and interoperability of data, thereby creating key prerequisites for the realisation of Transnational Digital Twins. With the Data Governance Act (Regulation (EU) 2022/868)[157]; the Data Act (Regulation (EU) 2023/2854)[158]; the INSPIRE Directive (Infrastructure for Spatial Information in Europe) (Directive (EU) 2007/2/EC)[159]; Free Flow of Non-Personal Data Regulation (Regulation (EU) 2018/1807); Environmental Information Directive (Directive 2003/4/EC); EU Space Programme, which regulates access to EU satellite and Earth observation data (Regulation (EU) 2021/696); and the Open Data Directive (Directive (EU) 2019/1024,[160] the EU aims to make access to data structured, trust-based, and usable across borders. For a detailed explanation of the aforementioned legal bases, see Table 2 below.

Of particular importance here are the Data Act, Open Data Directive, and INSPIRE Directive. The Data Act establishes access rights to data from networked products, e. g. vehicles, for the first time, while the INSPIRE Directive promotes the Europe-wide standardisation of geodata. Finally, the Open Data Directive (Directive (EU) 2019/1024) on open data and the reuse of public-sector information specifies the free, machine-readable provision of high-value datasets via APIs and bulk downloads, including geospatial, mobility, and environmental data. These regulatory initiatives create key prerequisites for Transnational Digital Twins, as they promote the availability, standardisation, and interoperability of data.

In practice, however, as underlined by the interviews with the experts and this analysis, considerable uncertainties remain with regard to the integration of sensitive data such as mobility, infrastructure, and energy data; the consideration of data protection; liability issues; and, especially when private actors are involved, intellectual property rights as the head of operations of a pan-European project in energy and mobility states.

Furthermore, from a data protection perspective, project responsibles face two key challenges for the development of Transnational Digital Twins: assessing whether (infrastructure) data can be linked to individuals and uncertainties regarding the provision, exchange, and processing of certain geographic, mobility, and infrastructure data, such as location data from car-sharing vehicles and energy consumption data. Often, the personal nature of the data is unclear and as a result, so is the question of whether it is subject to comprehensive data protection regulations.

Even though the GDPR (Regulation (EU) 2016/679)[161] does not fundamentally prevent data-driven applications, according to experts interviewed, uncertainty in interpretation often leads to

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[157] See the European Commission. Data Governance Act: https://digital-strategy.ec.europa.eu/de/policies/data-governance-act

[158] See the EU Rules on Fair Access to and Use of Data: Data Act (2023) at https://eur-lex.europa.eu/EN/legal-content/summary/rules-on-fair-access-to-and-use-of-data-data-act.html

[159] See the Federal Ministry for the Interior: INSIPIRE Directive at https://www.bmi.bund.de/SharedDocs/downloads/DE/gesetzestexte/richtlinie/inspire-richtlinie.html

[160] See the Open Data and the Reuse of Public-Sector Information (2019) at https://eur-lex.europa.eu/EN/legal-content/summary/open-data-and-the-reuse-of-public-sector-information.html

[161] See the European Parliament and Council of the European Union (2016). Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of

reluctance in providing such data. In addition, a Digital Twin data infrastructure manager points to uncertainties regarding trust, security architecture, and political sensitivity in connection with the openness of transnational data platforms. The experts emphasise that local and national regional actors need to be able to trust that sensitive data is not automatically accessible to all stakeholder groups and the entire community, but rather is shared with their specific target group and stakeholders in a controlled and context-dependent manner.

The analysis shows that although European data regulation establishes a structural framework for openness, standardisation, and cross-border data use, its practical impact depends largely on trust, a clear allocation of responsibility, and legal certainty of their interpretation. For Transnational Digital Twins, the formal availability of data is therefore not sufficient. However robust governance and security architectures that enable differentiated access levels and take national protection interests into account without undermining interoperability are needed. The tension between data openness and legal uncertainty thus becomes a central design issue for Transnational Digital Twin systems (for the technical dimension of this tension, see sections 5.4 and 5.5).

European harmonisation vs. national fragmentation

With the ITS Directive (Directive 2010/40/EU),[162] its delegated regulations, and the obligation to set up National Access Points (NAPs), the EU is pursuing the goal of a harmonised mobility data infrastructure, and initiatives such as NAPCORE[163] are intended to provide operational support for data harmonisation by aligning metadata standards, harvesting mechanisms, and minimum requirements.

In addition, the interviewees consider the following four delegated regulations to be particularly important for the implementation of Transnational Digital Twins in the mobility sector: Delegated Regulation (EU) 2017/1926 on multimodal travel information services[164]; Delegated Regulation (EU) 2022/670 on real-time traffic information services[165]; Delegated Regulation (EU) 886/2013 on road safety information; and Delegated Regulation (EU) 885/2013 on secure truck parking information.[166] As directly applicable EU law, these delegated regulations require member states to establish NAPs, which must make the relevant mobility data from public and private actors, depending on the area of application, available to the public. In doing so, they effectively create a harmonised data governance structure across Europe as a central infrastructural prerequisite for interoperable, Cross-Border Digital Twins in the mobility sector.

personal data and on the free movement of such data, and repealing Directive 95/46/EC: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679; https://gdpr-info.eu/

[162] See the European Parliament and Council of the EU on the framework for the deployment of Intelligent Transport Systems Directive (2010): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0040-20231220

[163] See NAPCORE at https://napcore.eu/

[164] See the Commission Delegated Regulation (EU) 2017/1926 (2017) on Multimodal Travel Information Services (2017) at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R1926

[165] See the Commission Delegated Regulation (EU) 2022/670 on Real-Time Traffic Information Services (2022) at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022R0670

[166] See the Commission Delegated Regulation (EU) No 886/2013 on Road Safety-Related Minimum Universal Traffic Information (2013) at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32013R0886

Despite this formal harmonisation, practical access to data remains heterogeneous, as implementing actors stress. Differences in administrative structures, national interpretations, technical architectures, and market logic significantly complicate cross-border integration (see section 5.2). In the interviews, representatives of transnational projects point out that fragmented legal frameworks and diverging data-sharing rules significantly increase the complexity of Cross-Border Digital Twin applications.

As the head of operations of a pan-European project in energy and mobility emphasises, one of the main challenges in implementing complex cross-border cooperations is not about technology, but rather the differing regulatory developments in national markets, which determine whether data-based business models and innovative developments are feasible and therefore can be a hindering factor and challenge for implementing cross-border activities across Europe.

This demonstrates a structural tension between harmonisation efforts at the European level and the existing national fragmentation of regulatory frameworks. Although European regulation creates a binding framework for data access, standardisation, and interoperability, its practical effectiveness remains largely dependent on consistent national implementation, administrative capacity, and the regulatory design of individual markets. For Transnational Digital Twins, interoperability cannot be guaranteed by EU law alone; it requires the actual harmonisation of technical infrastructures, a coherent interpretation of regulatory requirements, and functioning coordination mechanisms in the multi-level European system.

Market regulation, sectoral logic, and critical infrastructure

Finally, further tension arises from the fact that regulatory challenges vary considerably depending on the sector. For example, project managers of cross-border projects in the energy sector perceive strong market regulation and the multitude of legal requirements as major challenges that determine whether flexible markets with data-based services will emerge:

> *I think when it comes to innovative solutions, the one that is actually limiting you is always a regulation, especially in the electricity sector, which is at the core of the energy transition and heavily regulated. Meaning that the regulation is kind of at the centre of everything. If you want to provide flexibility services, it is the regulation that tells you whether a market is open or not, meaning whether there is a business case behind it or not. I would say that here it is more the regulation that drives the markets and not the other way around. (Head of operations of a pan-European project in energy and mobility)*

Beyond this market regulatory dimension, regulatory and security complexity increases the closer a Digital Twin comes to modelling critical infrastructure. In such cases, data exchange and cross-border integration are increasingly being assessed with regard to security policy concerns, which can lead to further restrictions and significantly slow down the implementation of transnational architectures.

In the mobility sector, on the other hand, experts state that the challenge is less the heavily regulated market, as in the energy sector and more the fragmentation of responsibilities, the lack of enforcement and sanction mechanisms, and heterogeneous technical implementation. Barriers to the implementation of transnational data projects are therefore caused by institutional, organisational, and political conditions at the national and regional levels, as well as by varying national regulations.

Evidently, regulatory challenges of Transnational Digital Twins vary across sectors and differ in terms of their structure. The closer they are to critical infrastructure as in the transport and energy sectors, the greater the security and sovereignty concerns implementing actors have to face, which further limits cross-border data integration. Institutional fragmentation, lack of enforcement, and administrative capacity constraints further hinder the implementation of Transnational Digital Twin projects. Thus, the central challenge lies not in regulation as such, but in the lack of a cross-border and consistent implementation of these regulatory requirements. Table 2 shows an overview of the most relevant EU regulations on data access and data use.

Legal Act	Category	Key content	Eligible beneficiary/ Obligated parties	Typical data
Data Act Regulation (EU) 2023/2854	Horizontal data access act	Regulates the use, access, and sharing of data from connected products (Internet of Things (IoT)) and associated services	**Eligible beneficiary:** Users, designated third parties, and public authorities in exceptional cases **Obligated parties:** Providers of connected products and associated services	IoT, machine, vehicle, and sensor data
Data Governance Act Regulation (EU) 2022/868	Data governance framework	Establishes the framework for data brokerage services, data altruism, and the controlled reuse of protected public data	**Eligible beneficiary:** Businesses, research institutions, and public bodies **Obligated parties:** Data brokerage services, and public bodies when reusing protected data	Administrative, research, industrial, and other protected data
Open Data Directive Directive (EU) 2019/1024	Public data sharing	Regulates the reuse of public-sector information and mandates greater openness, particularly for high-value datasets	**Eligible beneficiary:** Any natural or legal person **Obligated parties:** Public bodies and other data-holding entities covered by the directive	Administrative, spatial, statistics, environmental, mobility, and business data
INSPIRE Directive Directive 2007/2/EC	Geodata and interoperability	Establishes a framework for spatial data, metadata, web services, and interoperable data schemas	**Eligible beneficiary:** Public authorities **Obligated parties:** All public authorities that hold spatial reference data or environmental spatial data	Spatial reference data and environmental spatial data

Free Flow of Non-Personal Data Regulation Regulation (EU) 2018/1807	Data mobility and cloud	Prohibits unjustified data localisation and facilitates cross-border storage, processing, and cloud migration	**Eligible beneficiary:** Businesses, public authorities / **Obligated parties:** Member states	Non-personal operational data, platform, and process data (e. g. machine data in the factory (log files), data bases for inventory management, and anonymised sales statistics)
ITS Directive Directive 2010/40/EU	Traffic data framework	Establishes the framework for the deployment of intelligent transport systems (ITSs) in road traffic and at interfaces with other modes of transport	**Eligible beneficiary:** Service providers and indirect users **Obligated parties:** Member states	Static data (speed limits and parking spaces) and dynamic data (traffic jams, construction sites, and availability of charging stations)
MMTIS Commission Delegated Regulation (EU) 2017/1926	Implementing act on travel data	Specifies the provision of EU-wide multimodal travel information services via national access points	**Eligible beneficiary:** Travel information service providers **Obligated parties:** Transport companies (private & public), infrastructure operators, and mobility service providers	**Static data:** Schedules, stop locations, and fare structures **Dynamic data:** Real-time departure times, delays, and availability of rental bikes/e-scooters

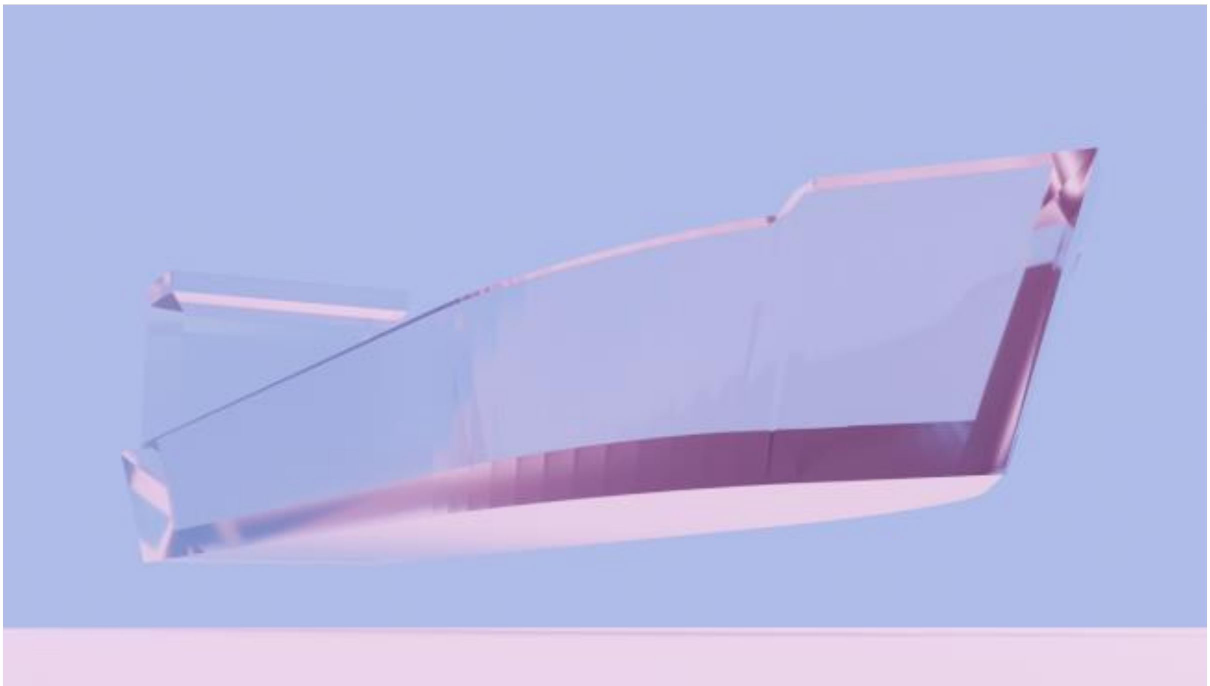
RTTI — Real-Time Traffic Information Commission Delegated Regulation (EU) 2022/670	Traffic data-specific implementing act	Regulates the provision of EU-wide, real-time traffic information via national access points	**Eligible beneficiary:** Providers of traffic information services **Obligated parties:** Road operators and traffic authorities	**Dynamic data:** Current traffic flow, travel times, and end of congestion **Event data:** Short-term roadworks, accidents, wrong-way drivers, closures, and weather-related hazards
Environmental Information Directive Directive 2003/4/EC	Access to environmental information	Grants a right of access to environmental information held by public authorities	**Eligible beneficiary:** Any natural or legal person **Obligated parties:** Public authorities and private entities to the extent that they perform public environmental management functions	Information on air, soil, water, noise, emissions, as well as plans and measures that affect the environment
EU Space Programme Regulation (EU) 2021/696	Space and Earth observation framework	Regulates open access to EU satellite and Earth observation data in the areas of climate protection, agriculture, and disaster management	**Eligible beneficiary:** The public and data-processing entities **Obligated parties:** The European Commission and competent implementing bodies	Satellite data, monitoring of the atmosphere, seabed, land use, and climate change

Table 2: Overview of EU regulations on data access and data use. Source: Own representation iRights.Lab.

Key Takeaways:

1. **European regulation as a necessary but insufficient condition:** The European legal framework is increasingly creating a coherent basis for data access, standardisation, and interoperability. However, actual data access remains heterogeneous due to different national implementation practices, administrative structures, and diverging data-sharing rules. For transnational applications, it is therefore crucial to have a European regulation that is coherently interpreted and consistently implemented in the member states. This requires functioning coordination mechanisms in the multi-level European system.
2. **Legal uncertainty and trust issues**: Despite formal data access rights, implementing actors and project responsibles face considerable uncertainties in practice regarding data protection, liability, and the handling of sensitive infrastructure and mobility data. National and regional actors must be able to trust that sensitive data is not automatically accessible, but is shared in accordance with context-dependent release and usage rules. To successfully develop Transnational Digital Twin applications, the legal obligation to provide data alone is therefore not sufficient. Resilient governance and security architectures with tiered access models are required that take national protection interests into account while enabling interoperable data exchange.
3. **Sectoral differences:** Regulatory challenges vary considerably among sectors and increase with proximity to critical infrastructure, particularly in the energy sector, where security and sovereignty policy requirements lead to additional restrictions on cross-border data exchanges. One possible solution lies in tiered data access and governance models that take sector-specific requirements into account, protect sensitive information, and at the same time, enable controlled, interoperable data exchanges among actors.

5.7 Funding structures, knowledge transfer, scalability, and overarching challenges



Long-term (re)use and scaling of local or national Digital Twins, along with the associated funding structures, represent not only a decisive practical challenge for developing Cross-Border Digital Twins but also an overarching prerequisite. Currently, the planning and implementation of Transnational Digital Twin projects is characterised by demanding infrastructural and political requirements and by a significant investment in needed resources. Consequently, existing cross-border projects or pilots are largely enabled by EU funding programmes such as Horizon, Interreg, and thematic Directorates-General (see section 2.2) and national funding.[167]

Transferability of flagship projects

Similar to the implementation of Digital Twins at the national level, Transnational Digital Twins are currently predominantly flagship projects, pilots, or demonstrators in early maturity levels (see chapter 4). In the previous sections, fundamental structural characteristics of Transnational Digital Twins are identified with regard to their system architectures; technical and data requirements; organisational, operational, and legal challenges; and respective enabling factors in practice (see sections 5.1 to 5.6). However, these findings are only to a limited extent transferable to smaller project consortia or cities, where human, financial, and technical resources are often too scarce to invest to fulfil the necessary infrastructural, governance-related, and organisational requirements for planning and implementing such complex cross-border applications. According to experts and implementing actors, this project- and funding-driven logic considerably challenges long-term planning, scalability of existing use cases, and knowledge transfer beyond a concrete project scope. This is because conceptualisation prior to the implementation of initial pilots or demonstrators, e. g. as in the case of the cross-border EU-funded project Begonia, are often not pursued further after the rather short funding periods end, as a project representative states. Furthermore, in

[167] For an overview of national funding programmes for Digital Twins in Germany, see Blüml et al. (2025), pp. 75–79.

practice, similar to funding requirements on a national level, such EU initiatives require considerable time and financial resources on reporting activities. Although these are necessary for documentation and accountability, they effectively reduce the capacity for technical and organisational implementation work as a European standardisation expert in transport and mobility states.

In this context, similar to national Digital Twin applications, experts also point to the challenge that new projects often address similar topics without systematically building on existing results. At the same time, experts observe a significant convergence between European cities, particularly with regard to Urban Digital Twins and in terms of needs, requirements for technical and data infrastructures, and use cases for Digital Twins as tools for solving overarching, shared challenges like climate adaptation, traffic control, sustainable mobility, and urban planning (see chapter 3). Consequently, promoting replicability and reusing existing knowledge and infrastructures is more and more reflected as a strategic aim within the EU's funding programmes, as the head of operation of a pan-European project in energy and mobility states:

> *I think that this was one of the very interesting parts of our project, because we were tasked not to invent anything. The point was exactly to build on something that already exists, build on the, maybe even data space initiatives that already exist to create something bigger. And I think this is very important because whatever we do, even if we develop a nationwide Digital Twin, which would be a fantastic achievement, the key question is how it can be integrated into a functioning ODP [Operational Digital Platform] and then scaled up. How can such a solution be integrated into what already exists and then scaled to a neighbouring country first and subsequently to multiple countries in a cascading way? This is absolutely crucial. (Head of operations of a pan-European project in energy and mobility)*

According to the interviewees, the durability of funding and the significance of reuse of lessons learned are also crucial to establish mature data infrastructures and data governance processes as well as to foster standardisation. These core requirements for developing Cross-Border Digital Twins, but are continuous and time-consuming tasks and processes that cannot be promoted within limited time frames. Furthermore, standardisation processes themselves could be one building block to improve knowledge transfer and reuse, as a Digital Twin data infrastructure manager emphasises, *"If people use standards, then it's already an investment, and if we apply these standards, then others can easily exchange and understand."* However, as implementing actors at national and European levels point out, reuse and standardisation of technical infrastructures and project governance as well as forming a community of Cross-Border Digital Twins is still a *"work in progress"*, particularly due to its early implementation stage. Progress requires a broader application of use cases across sectors as well as the establishment of the concept and stronger strategic promotion of Transnational Digital Twins by project responsibles and decision makers on national and European levels.

Political dimension of funding mechanisms

The political dimension is crucial for the sustainability of Transnational Digital Twin projects, as the discussions with experts show. EU initiatives such as the European Mobility Data Space aim to make mobility data findable, accessible, and reusable across Europe. Although the EU is creating central guidelines for harmonisation and standardisation, which are important infrastructural foundations for data-driven projects such as Transnational Digital Twins as shown above, member states have considerable freedom in their implementation. For example, the design of National Access Points differs considerably across Europe due to the EU's governance structures and the EU Commission's limited enforcement possibilities and need for support from member states, as a team lead for mobility data at a public-sector innovation organisation highlights: *"The Commission can't just say, 'I want this now, and the member states have to do it.' So, if there is no agreement, they can't push it through".* In the case of NAPs, this leads to different implementation models ranging from simple data catalogues to data warehouses or commercial data marketplaces. A long-term strategy for creating standardised conditions for data availability and establishing Transnational Digital Twins must therefore be politically coordinated across Europe and clearly highlight the benefits for member states, as they usually have to make considerable investments in the relevant structures. Strategies such as those envisaged for a European Data Union should therefore aim to create permanent infrastructures and coordinated processes to enable Transnational Digital Twins.

Knowledge transfer, reuse, and replicability

Replicating and connecting existing knowledge on local, regional, and national Digital Twins across domains, topics, and borders is not only a main overarching challenge for project responsibles but also a central added value and incentive for developing Transnational Digital Twins or scaling local and national use cases (see chapter 3). Implementing actors, such as infrastructure operators and representatives of municipalities can save considerable resources by avoiding parallel or double structures or investments in different local entities simultaneously, despite the often-shared requirements and challenges they face. Therefore, a promising good practice, particularly stemming from municipalities and urban spaces, is to develop and apply "blueprints" or transferable reference architectures or frameworks to simplify knowledge transfer between cities, across sectors, and between nation states.

One concrete example to enable long-term reuse despite limited funding periods is the development of the jointly agreed framework architecture EDIC, which is to be implemented in practice in the coming months and years.[168] Such reference frameworks aim at promoting the development of local or national Digital Twins with the help of modular service catalogues and governance structure, among others (see section 4.1.3). The goal is ultimately to build a transnational European network of connected LDTs, based on the different levels of maturity of the cities, as an expert and deputy chair in several European initiatives on (Urban) Digital Twins points out:

> *[The idea] is to be able to cover the necessities independently of your city dimensions. By having a Local and Regional Digital Maturity Assessment tool (LORDIMAS) and other tools that are inside of this ecosystem, we will build this catalogue of services in order to help cities avoid repetitions and take advantage of what already exists. (Leading expert and deputy chair in several European initiatives on (Urban) Digital Twins)*

While EDIC represents the overarching European infrastructural framework, the LDT Toolbox (see section 4.1.3) is an instrument that more specifically addresses and operationalises scalability,

[168] See the European Commission. European Digital Infrastructure Consortium (EDIC) at https://digital-strategy.ec.europa.eu/de/policies/edic

particularly with a maturity matrix that adjusts applications to different organisational and technical contexts in cities and attempts to improve organisational interoperability among municipalities, regions, and urban units. At the same time, data spaces and interoperability mechanisms are being tested. The aim of the toolbox is also to help integrate gained experience and knowledge from local and regional projects into cross-border architectures or cooperations to be made more transferable.

A representative of the LDT Toolbox initiative points to the trend to consolidate past projects and successes and to set up new projects that try to combine past knowledge and achievements and that the first challenge is really increasing the maturity level of the cities, not only the technical capabilities but also the value that the local Digital Twin and data spaces can bring to them concretely. Regardless of the specific area of application and the scope of the project, interviewees across domains emphasise the great need for mutual learning and the exchange of solutions. According to experts on smart cities and local Digital Twins, the greatest added value by far is peer-to-peer exchange, e. g. in *“open round tables”* between cities or border regions with their specific challenges. Overall, it is evident that replicability is not just a downstream effect, but an explicit objective in the pilot architecture itself, as a technical manager of a European energy project illustrates:

> *The main idea here is something that is pan-European. We only try to see that it is well-functioning and good practices can be replicated in the sense of other cross-pilot activities or cross-country activities. And we will try to do that through different implementations of validation cases among countries.* (T*echnical manager of an European energy project)*

In this project, knowledge transfer is organised, for example, through targeted networking events such as webinars with experts, funding bodies, political actors, technical partners, researchers, and intermediaries to make content-related, technical, procedural, and strategic findings available for reuse after the funding period. This enables the long-term collection of European good practices and success stories if strategic levers for the further utilisation of project results are already integrated into the funding programmes.

From a more general perspective, a technical coordinator of a European Digital Twin project emphasises that project elements can often be reused. For example, as the expert describes, Urban Digital Twins can be adapted to the context of large European cities such as Paris, Amsterdam, and Rome. While there are national specifics, such as disaster information and country-specific regulations, many components, such as the modelling of movement patterns based on mobile phone data, could be reused in other countries. Without exchange and open-source accessibility, these solutions would have to be redeveloped over and over again, wasting time and resources (see section 5.5). Thus, from the standpoint of implementation, it is no longer effective to perform projects in isolation at the national level; instead, knowledge should be shared across borders, as practitioners request. The interviewee also pointed out the importance of standards for interoperability. If concepts and technical solutions are based on common standards, they can be more easily applied, understood, and passed on, which would reduce effort and costs in the long term. Despite the overarching challenge of reuse and replication of gained knowledge across projects and domains, existing use cases and cross-border initiatives illustrate that a variety of enabling methods and mechanisms to foster knowledge transfer and reduce parallel work structures and resources consumption are already being developed or implemented.

Key Takeaways:

1. **Funding-driven flagship projects dominate but transferability is limited:** The implementation of Transnational Digital Twin projects is currently predominantly project- and funding-driven, supported by comprehensive EU or national subsidies. Flagship projects within large EU programmes provide valuable insights into system architectures, technical requirements, organisational challenges, and good practices. However, due to their size, resource allocation, and infrastructural requirements, they are only transferable to a limited extent to smaller municipalities, regions, and project consortia.
2. **Long-term financing and standardisation as prerequisites for reuse:** Since funding structures are usually limited to project durations, they rarely promote the long-term operation of pilot applications and demonstrators. However, complex digitisation projects such as Transnational Digital Twins require permanent financial resources. Standardisation and interoperable data structures can promote long-term reuse by securing investments in existing solutions and facilitating exchange between projects. It is therefore promising to establish systematic reuse of technical and organisational structures and, in the future, to build a user community for Transnational Digital Twins.
3. **Political coordination of fragmented funding landscape:** The sustainability of Transnational Digital Twin initiatives depends systematically on political coordination and European governance structures. Although EU initiatives create guidelines for harmonisation and standardisation, different national implementations lead to heterogeneous data infrastructures. At the same time, the highly fragmented project and funding landscape makes it difficult to establish, sustain, and reuse initiatives in the long term. In the future, it will be important to establish a Europe-wide coordinated strategy for data availability and transnational applications.
4. **Replicability, scaling, and knowledge transfer as strategic value of Transnational Digital Twins** A key potential of Transnational Digital Twin initiatives lies in the possibility of reusing existing solutions from local or national Digital Twins and enabling knowledge transfer between cities, sectors, and topics via transferable frameworks or “blueprints”. Initiatives such as the EDIC pursue the approach of making local Digital Twins reusable in the long term through the development of modular service catalogues, governance structures, and common framework architectures, establishing peer-to-peer exchange and open knowledge networks, and, in the long term, building a transnational European network of connected Digital Twins.

6. Conclusion: Future Potential of Transnational Digital Twins

This report examines the current state, main application areas, data foundations, and implementation conditions of Transnational Digital Twins in the fields of mobility, infrastructure, and cities, with particular attention given to the role of open data in their development and implementation. The analysis shows that the status quo of Transnational Digital Twins is shaped by a diverse but nascent project landscape, with initial applications and use cases emerging particularly in mobility and traffic management as well as in urban development. Overall, Transnational Digital Twins are at an early stage of development and testing and currently show a low level of maturity, meaning existing projects and applications are often still conceptual or limited to initial demonstrators, while fully operational and integrated cross-border applications remain rare, with only a few prominent exceptions such as Destination Earth. Among the different fields of application, mobility is currently the most advanced, especially in rail infrastructure and road transport, as these already require cross-border coordination and data exchange while border regions, in particular, function as important testbeds for transnational applications.

In addition to these early Transnational Digital Twin applications, important foundations for their future implementation are already being established. European data spaces, National Access Points, and complementary efforts in data harmonisation and standardisation are creating key technical and governance conditions for Transnational Digital Twins. They improve the availability, accessibility, and interoperability of data across national and organisational contexts and can therefore provide an important basis for connecting distributed data sources within future applications. At the same time, Urban Digital Twin initiatives are also acting as important drivers to foster the development of Transnational Digital Twins. Many cities across Europe are already developing or implementing local (Urban) Digital Twins. Building on this, initiatives such as the Local Digital Twin Toolbox promote interoperable, reusable, and transferable solutions. These efforts can help to connect existing Local Digital Twins, improve technical compatibility, and create important preconditions for more integrated and potentially Transnational Digital Twin applications in the future.

Overall, the current landscape shows that Transnational Digital Twins are not yet a mature field of application, but rather a strategically important enabler to further develop key technical, organisational, and institutional components. The status quo therefore points less to broad operational deployment than to a formative phase in which the foundations for future scalable and interoperable Transnational Digital Twin applications are gradually being established across Europe.

Added value and implementation potential of Transnational Digital Twins

Transnational Digital Twins offer added value especially where infrastructures, services, and governance structures are inherently cross-border. As digital representations of physical objects, systems, and processes, they can support shared data infrastructures, interoperable standards, and integrated analytical capacities across jurisdictions and sectors. This is particularly relevant in mobility and infrastructure, where national infrastructure operator planning, operation, and governance already depends on cross-border coordination. By connecting heterogeneous data from, e. g. transport, geospatial systems, demographics, energy, and environmental monitoring, Transnational Digital Twins can further improve data sharing and interoperability across domains, borders, and institutions. This enables more consistent and system-level analyses, including visualisation, simulation, forecasting, and evidence-based decision making. Particularly important potential lies in the integration of applications that are still largely organised in sectoral silos. While many existing Digital Twin projects focus on individual fields such as mobility, energy, and urban planning, their combination can enable cross-domain analyses of complex infrastructure interdependencies. In areas such as mobility, energy, and climate adaptation, Transnational Digital Twins can therefore support a more comprehensive understanding of how planning decisions in one sector affect other systems and territories. This creates significant potential for more coordinated governance; evidence-based, data-driven policy decisions; and integrated approaches to infrastructure transformation across Europe for different target groups, such as public authorities, infrastructure operators, businesses, researchers, and the general public.

Overall, the potential of Transnational Digital Twins is especially high where they help assess interdependencies between sectors, improve resource efficiency and sustainability, and reduce fragmentation in complex infrastructure systems. Their strategic value therefore lies not only in improving single sectors and domains but also in enabling more coordinated, interoperable, and system-oriented governance of cross-border infrastructures and public services.

Summary of Added Value:

- **Improved cross-border planning, coordination, and governance:** Transnational Digital Twins can represent interconnected transport, energy, and infrastructure systems across borders and sectors, thereby supporting more coordinated planning, investment, and decision making between countries and institutions. By creating shared analytical frameworks for complex systems, they also enable integrated assessments of interdependencies beyond isolated sectoral silos and help reduce fragmentation in governance across legal, administrative, and technical contexts.
- **Higher resilience and crisis preparedness:** Continuous monitoring, simulation, and systemic impact assessment can help identify vulnerabilities, anticipate cascading effects, and support coordinated cross-border responses to disruptions in critical infrastructures.
- **Higher efficiency, sustainability, and lifecycle optimisation:** Through integrated data environments and simulation-based optimisation, Transnational Digital Twins can support more efficient use of infrastructure and resources across planning, construction, maintenance, and operation, while improving predictive maintenance of transnational infrastructure and the assessment of emissions, energy consumption, and wider sustainability impacts across jurisdictions.
- **Reuse, scalability, and integration across governance levels:** Transnational Digital Twins can help avoid duplication of work and support the reuse of modular and interoperable architectures across cities, regions, and infrastructure contexts. In the longer term, they can also function as a connecting layer between local Digital Twins thereby supporting more integrated digital infrastructures across Europe.

- **Stronger data sharing and interoperability:** By linking heterogeneous datasets across domains, borders, and systems, Transnational Digital Twins can improve data availability, consistency, harmonisation, and integration across Europe.

Key Challenges, enabling factors, and future development of Transnational Digital Twins

This analysis shows that the implementation of Digital Twins across borders is shaped by closely connected barriers and enabling conditions. These do not lie in the technical domain alone, but instead extend across organisational, governance-related, political–regulatory, and legal dimensions of interoperability. Progress therefore depends less on isolated technological solutions and more on the ability to build coordinated frameworks for cooperation, data use, long-term operation, and institutional learning across borders. The main challenges and enabling factors can be summarised along three dimensions.

1. **Organisation and governance**

Organisational and governance-related conditions are particularly important for implementing Transnational Digital Twins and are often assessed by interview partners as being even more decisive and challenging than technical factors. This is because Transnational Digital Twin projects typically involve large transnational consortia, often bringing together public, private, and academic actors and therefore requiring governance structures that enable the coordination of different institutional logics, legal frameworks, technical systems, and organisational cultures across borders. The main organisational and governance challenges and enabling factors to foster the development of Transnational Digital Twins include the following:

- Developing projects around a shared and conceptually clear vision that links local needs, concrete problems, and clear benefits for participating actors and translates these into targeted, user-oriented use cases and credible success stories to demonstrate practical relevance and strengthen political and funding support.
- Organising complex multi-stakeholder consortia through clear coordination structures, defined roles, and a combination of vertical use cases and horizontal work strands such as governance, technical architecture, and long-term institutionalisation.
- Addressing unequal starting conditions across countries, cities, and institutions, as differences in data infrastructures, resources, governance arrangements, and institutional capacities can significantly hinder collaboration and require targeted mechanisms for alignment and support.
- Supporting implementation through precise and prioritised requirement management, clearly defined and adaptable target groups, iterative roadmap-based planning, and continuous impact monitoring with measurable indicators in order to strengthen efficiency, scalability, and long-term steering.

2. **Technical and data infrastructures**

Technical and data-related conditions are a core prerequisite for Transnational Digital Twins, because cross-border applications can only function if data can be exchanged, understood, and used consistently across systems, organisations, and countries. For Transnational Digital Twins to work in practice, data must be interoperable, findable, accessible, reusable, and secure, while also taking into account sector-specific sensitivities, critical infrastructures, and differing legal and regulatory contexts. The main technical and data-related hurdles and good practices include the following:

- Develop common technical standards, harmonised data models, interoperable interfaces, and shared metadata in order to ensure syntactically and especially semantic interoperability and improve the findability, accessibility, and usability of data across domains, systems, and countries.
- Use open data as an important enabler and starting point for Transnational Digital Twin development, particularly for testing, while recognising that Transnational Digital Twins cannot rely on open data alone. In practice, they require a mixed data base that combines open data with partner-provided, operational, sensitive, proprietary, and other privately held datasets.
- Build layered and federated architectures, for example, through data spaces as enabling infrastructures that allow data to remain within existing legal and organisational structures while still supporting cross-border integration through interoperability, governance, and controlled access.
- Combine technical collaboration with differentiated and secure access regimes, especially for critical infrastructure and operational data. This requires robust security architectures, including identity management, authentication, and access control. Controlled openness is therefore essential to make Transnational Digital Twins both viable and trustworthy.

3. **Political and regulatory frameworks**

Political and regulatory conditions are essential because Transnational Digital Twins are still in an early phase and require both initial and sustained support to move beyond pilot projects. At the same time, coherent regulatory and political frameworks are necessary to improve data access, enable harmonisation across countries, and create the stable conditions needed for long-term data-driven Transnational Digital Twin implementation. The main political and regulatory conditions for Transnational Digital Twin implementation include the following:

- Move beyond short-term pilot logic by establishing long-term European coordination, durable infrastructures, clear responsibilities for operation and maintenance, and sustained support for flagship projects so that Transnational Digital Twin initiatives can generate lasting rather than temporary effects.
- Strengthen shared political commitment across member states and align national and European strategies more closely in order to improve data access and reduce legal and practical uncertainties related to data use, data sharing, liability, and privacy.
- Address the fact that regulatory barriers differ across sectors; e. g. in energy, market regulation is often the main constraint, while in the mobility sector, fragmentation of responsibilities, weak enforcement, and heterogeneous implementation are the main barriers. Across areas of application, structural tension remains between formal European harmonisation and continued national fragmentation due to local needs and prerequisites. For Transnational Digital Twins, this means that interoperability cannot be achieved through EU regulation alone, but instead requires more consistent national

implementation, aligned technical infrastructures, coherent interpretation of regulatory requirements, and effective coordination across the multi-level European system.
- Recognise that proximity to critical infrastructure increases security, sovereignty, and regulatory concerns and may significantly slow cross-border integration.

Overall, these findings suggest that the main challenges for Transnational Digital Twins are currently less technical and more organisational, political, institutional, and legal. Their successful implementation therefore depends on the joint development of interoperable data infrastructures, reusable governance models, long-term political and financial support, and stronger capacities for cross-border cooperation.

The future of Transnational Digital Twins will depend on if Europe can move from fragmented pilot activity towards durable, coordinated, and scalable implementation structures. The successful development of Transnational Digital Twins is unlikely to result from a single technological breakthrough, but rather from a gradual process of integrating existing initiatives. In this process, national and Local Digital Twins, data spaces, and sectoral platforms can become increasingly interconnected and, over time, form a shared European data and analysis base enabling Transnational Digital Twins.

Appendix I. Project Overview of Use Cases

Below is a list of current and completed projects in the field of (Transnational) Digital Twins and similar initiatives in the mobility and transport sector, infrastructure, and cities. This list is not exhaustive. All of the links were last accessed on 29 April 2026.

Project Title	Brief Description and Link	Area of Application	Type of Application	Status	Region and Scope of Project
EMob-Twin — A Digital Twin for Electromobility Flexibility Forecast	An electromobility Digital Twin project that combines urban mobility patterns, vehicle battery state, and charging infrastructure data to simulate electric vehicle energy demand in time and space. Supports charging planning, grid flexibility analysis, renewable integration, and decision making for more efficient and scalable electric mobility systems. (https://cordis.europa.eu/project/id/101112783/de)	Energy	Digital Twin	Research project	EU
CITWIN — A generic Digital Twin framework to foster sustainable mobility in the 15mC	A sustainable mobility Digital Twin project that develops a generic framework to model, simulate, and evaluate changes in active transport infrastructure. It combines mobility, urban infrastructure, and human-centric data to assess how walking, cycling, and shared mobility systems can support safer, more inclusive, and more accessible neighbourhoods. Supports infrastructure planning, stakeholder engagement,	Urban areas	Digital Twin	Research project	EU

	living lab experimentation, and decision making for sustainable and scalable 15-minute city mobility systems. (https://www.citwin.uliege.be/)				
ACUMEN — AI-aided deCision tool for seamless mUltiModal nEtwork and traffic managemeNt	A multimodal mobility Digital Twin project that develops AI-aided decision support for seamless network and traffic management across urban transport systems. Integrates decentralised real-time data sharing, advanced monitoring and forecasting, mobility modelling, and visualisation to improve safety, reduce congestion, support decarbonisation, and optimise operations across intersections, networks, and fleets. (https://acumen-project.eu/about-acumen/the-project/)	Urban areas (mobility)	Digital Twin	Implementation phase	EU
Aveiro Tech City Living Lab (Portugal)	Aveiro Tech City Living Lab (Portugal) is a grid-like IoT Digital Twin with 44 mmWave/WiFi/5G/ITS nodes. (https://new.aveiro-living-lab.it.pt/realtime)	Mobility, environment, focus on data collection using IoT and other sensors	Digital Twin	Operational (research project)	Aveiro (Portugal)

RailData — Rail data and wagon tracking in real time	A shared European rail data platform that enables real-time wagon tracking and standardised data exchange across railway operators. Integrates operational, consignment, and train movement data to create a cross-border logistics Digital Twin for monitoring, coordinating, and optimising freight transport flows. (https://www.raildata.coop/)	Rail operation	Data platform	Operational	EU
Barcelona — "15-Minute City" Digital Twin	Barcelona — "15-Minute City" Digital Twin for real-time monitoring of traffic, parking, and public transportation. AI-optimised traffic signals and traffic flow management (https://bsc.es/news/bsc-news/barcelona-tests-digital-twin-developed-bsc-if-it-15-minute-city)	Urban areas (mobility, urban development, energy, environment, citizen participation)	Digital Twin	Operational	Barcelona
Begonia	The Begonia project develops operational digital platforms (ODPs) that transcend national boundaries. It identifies, studies, and prepares the development of ODPs across EU countries, starting from the identification of cross-border use cases in the energy and transport sectors. Then, it will develop early case studies to prepare for future works project(s). https://www.begonia-project.eu/	Energy and transportation	Operational digital platform	Implementation phase	EU

BIPED — Building Intelligent Positive Energy Districts	A European positive energy district Digital Twin project that integrates heterogeneous urban data to model and optimise energy, mobility, environment, and social factors at district scale. Uses interoperable standards, AI-based optimisation, and cross-domain simulations to support decarbonisation, local energy management, and policy-ready urban planning, with Aarhus as its main demonstrator. (https://www.bi-ped.eu/)	Urban areas (energy)	Digital Twin	Research project	EU
X4ITS — Central European cross-border cooperation for ITS	A Central European transport data and traffic management initiative that strengthens cross border intelligent transport systems across the Trans European Transport Network. Connects road, rail, public transport, and mobility data across countries to improve interoperability, corridor coordination, and traffic information services for more efficient and connected transport operations. (https://x4its.eu/)	Road infrastructure	Digitalisation	Implementation phase	EU
CitiVERSE	A European Digital Infrastructure Consortium that builds an EU ecosystem of AI-powered local Digital Twins, data spaces, and augmented and virtual reality tools to help cities share solutions, improve urban planning, strengthen citizen participation, and support more sustainable public services.	Urban areas (urban planning, citizen participation, public services, community engagement)	Collaboration digital space including digital tools	Implementation phase	Urban areas (EU)

	(https://digital-strategy.ec.europa.eu/en/factpages/citiverse)				
Connected Urban Twins	A cross-city, Urban Digital Twin initiative led by Hamburg, Leipzig, and Munich that develops shared standards and interoperable Digital Twin tools for integrated urban development. Combines 3D city models, geospatial and planning data, simulation, and immersive visualisation to support scenario analysis, participatory planning, housing and mobility decisions, and more transparent communication between city administrations and citizens. (https://digital.hamburg.de/digitale-stadt/urbanes-leben/connected-urban-twins-mit-digitalen-zwillingen-die-zukunft-der-staedte-gestalten-644020)	Urban areas	Digital Twin	Implementation phase	Germany
Destination Earth (DestinE)	Flagship initiative of the European Commission to develop a highly accurate digital model (twin) of the Earth to model, monitor, and simulate natural phenomena, hazards, and related human activities. The European Centre for Medium-Range Weather Forecasts is working on two DestinE Digital Twins: the Climate Change Adaptation Digital Twin and the	Climate	Transnational Digital Twin	Operational	Worldwide

	Weather-induced Extremes Digital Twin produce global high-resolution simulations of extreme weather events, climate projections, and 'what-if' climate scenarios. They provide insights into sectors most impacted by climate change and extreme weather. (https://destination-earth.eu/)				
DIDYMOS-XR	A European Digital Twin project that develops dynamic and responsible twins for extended reality applications in cities and industry. Integrates heterogeneous sensor data, AI-based data fusion, scene understanding, and real-time synchronisation to create large-scale digital representations for urban planning, smart mobility, and industrial collaboration with autonomous robots, with privacy-aware design. (https://cordis.europa.eu/project/id/101092875)	Urban areas	Digital Twin tools	Research project	EU
DIGEST — Digital Twin of the Road Transport System"	A road transport Digital Twin project led by the German Aerospace Center that creates a realistic virtual representation of roads, traffic situations, and environmental influences to support connected and automated mobility. Combines real and virtual test field data to validate traffic management measures, improve traffic flow, and support infrastructure planning for vehicle communication across European road networks.	Road infrastructure	Digital Twin	Research project	Germany

	(https://www.dlr.de/de/ts/forschung-und-transfer/projekte/digest)				
Digital Twin Aachen (Germany)	Project-based Digital Twin: combines above-ground and underground data (roads, sewers, and trees), enabling traffic modelling and asset management. (https://www.aachen.de/in-aachen-leben/mobilitaet-verkehr/mobilitaetskonzepte/digitalisierung-in-der-mobilitaet/)	Urban areas (mobility, urban development, energy, environment, citizen participation)	Digital Twin	Operational	Local (Aachen)
Digital Twin Academy	An innovation- and capacity-building initiative by the EU funding programme Interreg that develops Digital Twin skills, training, and applied test cases across the Euregio Meuse-Rhine region. Connects academic partners, industry, and societal actors to build Digital Twin expertise, strengthen workforce capabilities, and validate Digital Twin applications in real business environments. (https://digital-twin-academy.eu/)	Cross-sectoral, knowledge transfer building up Digital Twin expert community	Digital Twin	Implementation phase	EU

Digital Twin Ocean	A European Digital Twin platform of the ocean that creates a high-resolution, multi-dimensional, and near-real-time virtual representation of marine environments. Integrates ocean observations, satellite data, AI, and advanced modelling to support scenario analysis, biodiversity monitoring, climate adaptation, disaster risk management, and science-based decision making for ocean governance and sustainable blue economy activities. (https://digitaltwinocean.mercator-ocean.eu/)	Oceans, climate	Digital Twin	Implementation phase	International
Digital Twin of Public Mobility Vehicles	This develops AI-based, 3D Digital Twins of public transport vehicles from images to track vehicle history, support traffic and parking planning, and improve monitoring and public mobility services. (https://www.ifabfoundation.org/project/digital-twin-of-public-mobility-vehicles/)	Public transportation, fleet management, sustainability, emissions reduction, predictive maintenance	Digital Twin	Operational	Objects
Digital twin of the London Piccadilly line	This is in collaboration with Transport for London and Spinview. Incorporates tunnel, environmental, and infrastructure data to optimise maintenance and energy-saving measures. (https://erp.today/going-underground-the-digital-twin-tech-turning-the-piccadilly-line-green/)	Asset management for the London Underground, including digital monitoring of	Digital Twin	Operational	London Public Transport

		tracks and tunnels, as well as data on noise, heat, and carbon emissions.			
Digital Twin Zürich	The city government created a high-resolution, 3D twin (terrain, building structures, and roofs) using light detection and ranging and photogrammetry. It visualises infrastructure and the surrounding environment to support, among other things, administrative tasks, climate simulations, and public engagement. (https://www.stadt-zuerich.ch/artikel/de/klick/digitaler-zwilling.html)	Urban areas (mobility, urban development)	Digital Twin	Operational	Local (Zürich)
Digital Twin Digitale Schiene Deutschland	Digitaler Zwilling für Störfallsimulation in der Schiene is a rail infrastructure Digital Twin project by Digitale Schiene Deutschland that creates a photorealistic, one-to-one, virtual representation of railway tracks, stations, and the surrounding environment to simulate rare disruption scenarios and generate training data for automated train operation. Integrates high-resolution rail maps, 3D models, sensor models, and simulated data to improve object detection, AI training, operational robustness, and the reliability of future	Rail infrastructure	Digital Twin	Implementation phase	Germany

	autonomous rail systems. (https://digitale-schiene-deutschland.de/de/projekte/Digitaler-Zwilling)				
EDIC — European Digital Infrastructure Consortium	A European legal and governance framework that enables member states to jointly build and operate cross-border digital infrastructures and services. Supports interoperable data spaces, local Digital Twins, public-sector platforms, and other multi-country digital projects by providing a common structure for governance, funding, and implementation across Europe. (https://digital-strategy.ec.europa.eu/de/policies/edic)	Digital infrastructure	Legal framework	Implementation phase	EU
deployEMDS — European Mobility Data Space	deployEMDS aims at building the common European Mobility Data Space. The goal is to cultivate a broad European ecosystem of data providers and users, facilitating the adoption of common building blocks. Sixteen use cases from nine EU countries will contribute to the development of innovative services and applications. (https://deployemds.eu /, https://transport.ec.europa.eu/transport-	Mobility	Data space	Implementation phase	EU

	themes/smart-mobility/creating-common-european-mobility-data-space_en)				
EnergyDataSpace	A European energy data space project that develops a reference implementation for interoperable and intelligence-enabled data sharing across the energy value chain. Connects heterogeneous energy data sources, supports Digital Twin applications for network operators, and enables data-driven optimisation, prosumer participation, and more efficient and decarbonised energy system management. (https://energydataspaces.eu/)	Energy	Data space	Implementation phase	EU
EU DTLF & SESAR Programme	European initiatives focusing on harmonising air traffic data and air traffic management across Europe. These initiatives enable interoperable data spaces, standardised interfaces, and Digital Twin capabilities to improve capacity, efficiency, and sustainability of the European airspace. (https://www.dfs.de/homepage/de/flugsicherung/rechtlicher-rahmen/sesar/	Air traffic	Instrument for digitalisation of airspace	Operational	EU

DS4SSCC — European Data Space for Smart Communities	A European data space initiative that enables interoperable, cross-sectoral data sharing for smart communities to improve public services, support sustainability goals, and help governments deploy data spaces across Europe. (https://www.ds4sscc.eu/)	Urban areas (data sharing)	Data space	Implementation phase	Urban areas (EU)
European Digital Twin Ocean	The European Digital Twin Ocean offers tools to develop Digital Twins, support science-based decision making, and ensure maximum impact for research and innovation across the key objectives of the EU Mission Ocean & Waters, which are to protect biodiversity, restrict marine pollution, and support a sustainable blue economy. (https://www.edito.eu/)	Oceans, climate	Transnational Digital Twin	Operational	Worldwide
European Local Digital Twin Toolbox (LDT Toolbox)	This EU initiative aims to advance the digital maturity of EU cities, particularly focusing on those less prepared for digital transformation. It supports the creation of a European local Digital Twin (LDT) Toolbox to foster the adoption of Digital Twins across rural and urban areas, ensuring technology is accessible for all. (https://interoperable-europe.ec.europa.eu/collection/ldttoolbox)	Urban areas (mobility, urban development, energy, environment, citizen participation)	Software for building Digital Twins	Implementation phase	European cities

ExPEDite	A Digital Twin project for positive energy districts that enables real-time monitoring, visualisation, and management of district-level energy flows to support planning, optimisation, and sustainable urban energy decisions. (https://expedite-project.eu/)	Energy	Digital Twin	Implementation phase	Urban districts
Fehmarnbelt Tunnel – Sund & Bælt	A transport infrastructure Digital Twin initiative that creates real-time, 3D representations of bridges, motorways, and rail corridors to support condition monitoring and future maintenance. Integrates sensor data, images, asset information, and operating history to improve inspection planning, reduce errors, extend asset life, and make infrastructure operations more efficient and sustainable. (https://sundogbaelt.dk/en/digitisation/we-build-digital-twins-of-reality/sund-baelt-deploys-digital-twins-for-future-maintenance/)	Rail infrastructure	Digital Twin	Implementation phase	Denmark & Germany
FinEst Twins	FinEst Centre for Smart Cities. This is a smart city innovation platform that develops and pilots multiple Digital Twin applications for urban resilience, energy, underground infrastructure, and green planning. Connects city challenges, research, and real-world experimentation to create Digital Twin solutions for disaster response, urban underground asset management, dynamic	Urban areas	Research centre	Research project	Estonia & Finland

	vegetation modelling, and AI-supported energy intelligence and decision making. (https://finestcentre.eu/)				
Flagship Project 3 IAM4RAil	A European rail asset management Digital Twin project that combines advanced condition monitoring, AI, and decision support tools to improve the maintenance of fixed and rolling stock assets. Integrates asset condition data with traffic management systems through an interoperable and a cross-border approach to reduce life cycle costs, extend asset lifetime, and improve reliability, availability, and safety across the rail system. (https://rail-research.europa.eu/rail-projects/fp3-iam4rail/)	Rail infrastructure	Digital Twin	Implementation phase	EU
Flightradar24	A real-time, global, flight-tracking platform that creates real-time digital representations of aircraft movements to support monitoring, visualisation, and analysis of air traffic worldwide. (https://www.flightradar24.com/)	Air traffic	Digital Twin	Operational	Worldwide

Florenz — Snap4City	Digital Twin solutions for setting up sustainable decision support systems and business intelligence. An open-source platform that integrates data updated every 5 minutes on traffic, air quality, and energy. Real-time simulations with AI-powered forecasting. (https://www.snap4city.org/drupal/node/997)	Digital Twin tool, including mobility, tourism, environment, construction, energy	Digital Twin software	Operational	Urban areas
Hamburg's Digital Twin	Hamburg's Digital Twin is a real-time, urban model that combines geospatial, mobility, and environmental data to visualise traffic flows, support planning decisions, simulate urban processes, and improve climate adaptation and infrastructure management. (https://www.hamburg.de/politik-und-verwaltung/behoerden/behoerde-fuer-stadtentwicklung-und-wohnen/themen/stadtentwicklung/stadtwerkstatt/forschung-und-entwicklung/connected-urban-twins-187056)	Urban areas (mobility, urban development)	Digital Twin	Operational	Local/urban (Hamburg)
Hangzhou City Brain	Digital model that combines mobility, camera, emergency, and historical data into a traffic Digital Twin with traffic congestion analysis and incident management. (https://atlasofurbantech.org/cases/chn-hangzhou/)	Public transportation management (e. g. smart routing)	Digital Twin	Operational	Urban areas (worldwide)

Helsinki 3D+	Helsinki 3D+ (Finland) is an interactive 3D Digital Twin of the capital featuring infrastructure, population, and environmental data. Visualisation of underground networks (e. g. utility lines) for effective coordination. (https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d)	Urban areas (mobility, urban development)	Digital Twin	Operational	Local (Helsinki)
HyProTwin	HyProTwin develops software for the simplified, automated creation of Digital Twins for transport infrastructure. Using waterway assets such as locks, weirs, and culverts, it links current and historical data through a hybrid approach that combines symbolic and sub-symbolic AI to analyse, connect, and provide heterogeneous asset information in a usable Digital Twin. (https://daten.plus/projekte/hy-pro-twin)	Mobility infrastructure (waterways as pilot)	Software for automated generation of Digital Twins for infrastructure	Implementation phase	Local (Germany)
Inland waters in the Digital Twin ocean (IDEATION)	IDEATION is an EU-funded project focused on preparing the development of the Digital Twin of inland waters (rivers, lakes, reservoirs, wetlands, snow, and ice) that is interoperable with the Digital Twin Ocean. It offers valuable insights for scientists, researchers, and policymakers to make informed decisions about freshwater health and management. (https://ideation-euproject.eu/the-project/)	Inland waterways	Transnational Digital Twin	Implementation phase	EU

KISA — AI-based creation of a Digital Twin of traffic control systems on highways	AI-based highway traffic management Digital Twin project that reconstructs the control algorithms of motorway traffic control systems from traffic and switching data. Uses machine learning, neural networks, and traffic flow simulation to create realistic virtual representations of roadside control logic and to support more accurate traffic simulations, optimisation of traffic management, and improved motorway operations. (https://www.ifv.kit.edu/forschungsprojekte_2345.php)	Road infrastructure	Digital Twin	Research project	Germany
LDT4SSC — Local Digital Twins for Smart and Sustainable Communities	Local Digital Twins for Smart and Sustainable Communities aim to create a robust, interconnected ecosystem of local Digital Twins (LDTs) that scales across sectors, regions, and borders, driving the adoption of LDT services. A key goal is to connect (existing) LDTs into a European "federation" through a common interoperability blueprint, consolidating work from DSSC, DS4SSCC, GAIA-X, and SIMPL. (https://ldt4ssc.eu/)	Urban areas	Transnational Digital Twin	Implementation phase	EU
LEAD	A Digital Twin project for urban logistics networks that supports experimentation and decision making for on-demand logistics in public and private city environments. Integrates adaptive modelling, agent-based simulation, and stakeholder-specific operational data to test	Urban areas (logistics)	Digital Twin	Implementation phase	EU

	shared, connected, and low-emission logistics solutions across six European cities and improve urban freight planning. (https://civitas.eu/projects/lead)				
Liveable City Digital Twin	Sydney (Australia) — Integrated Urban Digital Twin for sustainability analysis. Combines weather, emissions, traffic, and crime data and uses machine learning for forecasting and crash risk analysis. (https://www.unsw.edu.au/arts-design-architecture/our-schools/built-environment/our-research/clusters-groups/grid/projects/liveable-city-digital-twin)	Urban areas (mobility, urban development, energy, environment, citizen participation)	Digital Twin	Operational	Local (Sydney)
LIFE — Local Inclusive Future Energy City Platform	Amsterdam — LIFE City Platform. This is a district-scale energy management platform that integrates local stakeholder needs to optimise urban energy systems and address grid constraints. (https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/intelligent-electrical-power-grids-iepg-group/projects/current-projects/life)	Energy	Digital Twin	Operational (research project)	Amsterdam district

MetaCities Excellence Hub in southeastern Europe	A European Urban Digital Twin and data space initiative that supports cities in developing interoperable local Digital Twins for planning, simulation, and decision support. Connects urban data, governance tools, and stakeholder collaboration to help cities design scalable digital services, improve policy making, and accelerate sustainable urban transformation. (https://metacities-hub.com/)	Urban areas	Digital Twin and data space	Implementation phase	Southeastern Europe
Mobilithek	A national mobility data platform in Germany that provides standardised access to open and regulated transport data for public authorities, infrastructure operators, mobility providers, and information services. Enables interoperable exchange of timetable, real-time traffic and infrastructure data to support journey planning, traffic management, digital mobility services, and data-driven transport innovation. (https://mobilithek.info/)	Mobility	Data platform	Operational	Germany
Mobility Data Space	A mobility data-sharing ecosystem that connects companies, public authorities, and service providers to exchange and use mobility-related data for innovative transport solutions. Enables interoperable and trusted data sharing across sectors to support new digital services, improve operational efficiency, and strengthen data-driven	Mobility	Data space	Implementation phase	Germany

	mobility applications within the Gaia-X context. (https://mobility-dataspace.eu/)				
MOTIONAL — MObility managemenT multImodal envirOnment aNd digitAl enabLers	FP1 MOTIONAL is a European rail traffic management and mobility coordination project that develops interoperable and resilient planning and operational management for rail services in a multimodal environment. Integrates digital enablers such as Digital Twins, rail data spaces, and advanced traffic management functions to improve capacity, operational adaptability, cross-service coordination, and the role of rail within seamless door-to-door transport. (https://rail-research.europa.eu/rail-projects/fp1-motional/)	Rail - infrastructure	Digital Twin and data platform	Implementation phase	EU
MOVE21	This is a European smart mobility and logistics initiative that transforms cities and surrounding regions into zero-emission multimodal hubs. Integrates urban transport, freight, and infrastructure innovations across living labs and replicator cities to reduce transport-related emissions and improve the efficiency, connectivity, and the sustainability of the flow of passengers and goods. (https://move21.eu/)	Urban areas	Digital Twin and data platform	Research project	EU

NAPCORE	A European mobility data coordination platform that harmonises more than 30 national access points for transport and mobility data across Europe. It supports interoperable data exchange, common standards, aligned access interfaces, and improved data availability to strengthen travel information services, cross-border mobility applications, and the European mobility data ecosystem. (https://napcore.eu/)	Mobility	Data platform	Implementation phase	EU
North.io	A maritime data platform and marine Digital Twin application provider that enables the management, processing, analysis, and visualisation of complex underwater sensor data and geodata. Supports offshore wind, surveying, defence, security, and public-sector use cases by integrating marine data workflows, scalable analytics, and interoperable geospatial services for faster insight, risk reduction, and more efficient subsea infrastructure and ocean planning decisions. (https://north.io/)	Maritime and ocean	Digital Twin and data platform	Operational	Baltic Sea
OBSERVER	This aims at developing Copernicus-based solutions for the provision of a Digital Twin of the external borders, enabling the virtual representation of specific areas and associated processes. The Digital Twin is expected to support the European border and coast guard community in scenario simulations, for operational exercises, and	Border control, migration	Digital Twin	Conception phase	EU external borders

	with technical equipment deployment planning. (https://www.copernicus.eu/en/news/news/observer-driving-innovation-border-surveillance-copernicus-digital-twins)				
Digital Twin Munich: Public engagement using the 3D city model	A city Digital Twin application for public participation that uses interactive 3D scenes, web applications, video animations, and virtual reality to communicate urban and transport planning scenarios more clearly. Integrates current city conditions with proposed planning concepts to support citizen engagement, reduce misunderstandings in infrastructure projects, and improve acceptance of mobility and public space transformations. (https://muenchen.digital/projekte/digitaler-zwilling/01_oeffentlichkeitsbeteiligung-de.html)	Urban areas	Digital Twin	Implementation phase	Germany
Offshore For Sure (O4S)	A cross-border, offshore energy innovation initiative that applies Digital Twins to wind, tidal, and energy storage systems to improve predictive maintenance, real-time monitoring, system design, and immersive operational support. Combines simulation models, supervisory control and data acquisition and operational data, machine learning, and XR-based visualisation to make offshore	Energy	Digital Twin	Implementation phase	EU

	renewable energy systems safer, more reliable, and more efficient. (https://interregvlaned.eu/en/nieuws/mastering-digital-twins-real-world-cases-from-offshore-experts)				
Omega-X	A federated energy data space that uses open, Gaia-X-ready standards to enable a sovereign and an interoperable exchange of multi-vector energy data across actors and systems. (https://omega-x.eu/)	Energy	Data space	Implementation phase	EU
Ports & Waterways Digitalization Lab	This is a research and innovation lab at TU Delft that develops Digital Twin applications for ports and inland waterways. Creates virtual replicas of complex maritime systems and networks to support real-time monitoring, predictive analysis, and data-driven decision making for port operations, infrastructure management, and waterborne transport systems. (https://www.tudelft.nl/citg/over-faculteit/afdelingen/hydraulic-engineering/sections/rivers-and-ports/research/ports-waterways-digitalization-lab)	Ports and waterways	Digital Twin	Implementation phase	Netherlands

Providentia ++	A real-time, highway Digital Twin project for connected and automated mobility that extends traffic sensing from motorways into rural roads and urban intersections. It combines large-scale sensor networks, AI-based object detection, data fusion, and real-time processing to create precise digital representations of traffic flows for congestion forecasting, driver assistance, and traffic management. (https://www.bmv.de/SharedDocs/DE/Artikel/StV/AVF-projekte/providentia-plusplus.html?editorSupport=true%3FresourceId%3D452902)	Road infrastructure	Digital Twin	Research project	Germany
Rail Baltica	A cross-border rail infrastructure and mobility project that develops a high-speed and an interoperable railway corridor connecting the Baltic States with the wider European rail network. It Integrates transport infrastructure planning, passenger and freight connectivity, and multimodal logistics to improve regional accessibility, strengthen European transport integration, and support more sustainable long-distance mobility and supply chains. (https://www.railbaltica.org/)	Rail infrastructure	Digital Twin	Implementation phase	Baltic States

Rail4Future	Rail4Future is an Austrian R&D project that is developing a Digital Twin of rail infrastructure by linking measurement data, simulation models, and AI to improve resilience, reliability, predictive maintenance, and lifecycle-based infrastructure management. (https://www.rail4future.com/)	Predictive maintenance, asset monitoring, load analysis, infrastructure planning	Digital Twin	Research project	Austria
Resi.Form	A municipal resilience platform and urban Digital Twin application for Guben and Gubin that integrates spatial data across administrative and institutional boundaries to support resilient urban development. Combines data aggregation, planning, analysis, and simulation modules to improve cross-border coordination, embed evidence-based decision support in administrative processes, and strengthen climate adaptation and disaster preparedness. (https://www.smart-city-dialog.de/wissen/massnahmen/resiform-resilienz-plattform-guben-0)	Urban areas	Digital Twin	Implementation phase	Germany & Poland
Rhine-Alpine Corridor	The Rhine–Alpine Corridor is a European transport corridor project that connects major North Sea and Mediterranean hubs to improve cross-border freight transport, strengthen multimodal infrastructure, and shift traffic towards more efficient rail-based logistics across five countries. (https://www.corridor-rhine-alpine.eu/home.html)	Rail operation	Harmonisation project	Implementation phase	European railway

Shanghai-Yangpu Bridge Twin	Shanghai–Yangpu Bridge Twin monitors traffic and emergencies in real time, serving as a "smart brain" for a faster response. (https://service.shanghai.gov.cn/sheninfo/specialdetail.aspx?Id=6530e08a-9de4-4667-8580-17b9007d23a3)	Maintenance, compliance regarding regulations such as maximum truck weight limits	Digital Twin	Operational	Shanghai Bridge
SIMON — Sichere Mobilität und Navigation durch voraus-schauendes Risikomanage-ment mittels Schwarm-Intelligenz und V2X-Kommunikation	A traffic Digital Twin project for safe and predictive mobility that uses AI-based risk management and vehicle-to-everything communication to analyse real-time traffic context and identify safety-critical situations. Integrates vehicle, bicycle, infrastructure, and simulation data into a dynamic traffic context model to support coordinated recommendations for road users, improve traffic flow, and strengthen safety and environmental efficiency in multimodal transport. (https://www.bmv.de/SharedDocs/DE/Artikel/mFUND/Projekte/simon.html)	Mobility	Digital Twin	Research project	Germany
Siemens Gridscale X	A grid management software suite that includes Digital Twin capabilities to create and maintain accurate models of power grids, combine real-time and asset data, and support grid monitoring, planning, capacity optimisation, and more autonomous operations.	Energy grid	Digital Twin, software	Operational	Grid operators

	(https://www.siemens.com/en-us/products/gridscale-x/)				
Singapore’s Digital Urban Climate Twin (DUCT)	Cooling Singapore — A multidisciplinary urban climate Digital Twin initiative led by Singapore-ETH Centre. Develops the Digital Urban Climate Twin (DUCT) by integrating environmental, traffic, building, and energy models to simulate urban heat dynamics and test mitigation strategies such as green infrastructure and urban design at city and district scale. Supports scenario analysis and decision making for climate-resilient urban planning and policy. (https://sec.ethz.ch/research/)	Urban areas	Digital Twin	Research project	Local (Singapore)
Straße der Zukunft	A road infrastructure, monitoring, and maintenance project that equips roads with sensor-based and functional surface technologies to detect traffic loads, environmental conditions, and structural changes in real time. Supports predictive maintenance, improved road safety, and more efficient infrastructure management through continuous data collection and intelligent road system integration.	Road infrastructure	Digital Twin	Research project	Germany

	(https://www.igb.fraunhofer.de/de/referenzprojekte/strasse-der-zukunft.html)				
The Civic Digital Twin	Bologna (Italy) — The Civic Digital Twin is a citizen-centred system that links mobility and urban development with social behaviour and civic engagement. (https://interoperable-europe.ec.europa.eu/collection/public-sector-tech-watch/bolognas-digital-twin-enhancing-decisions-and-citizen-engagement)	Urban areas (mobility, urban development, energy, environment, citizen participation)	Digital Twin	Operational	Local (Bologna)
EONA-X — The Tourism Mobility & Logistics Data Space	A non-profit, European, data-sharing ecosystem for logistics, mobility, and tourism that connects public and private actors through a trusted, sovereign, and interoperable infrastructure to discover, exchange, and use data products across sectors. (https://eona-x.eu/)	Mobility, tourism	Data space	Implementation phase	EU
TRANS4M-R	FP5 TRANS4M R is a European rail freight digital transformation project that develops interoperable and seamless digital freight operations across borders and transport modes. Combines digital automatic coupling, software-defined systems, and digital rail services to improve capacity, throughput, coordination, and network	Rail infrastructure	Data platform	Implementation phase	EU

	management, with the aim of establishing rail freight as the backbone of a low-emission and resilient European logistics chain. (https://rail-research.europa.eu/rail-projects/fp5-trans4m-r/)				
TriRegio Data Space	A cross-border, urban, data space initiative that creates a shared digital infrastructure for Basel, Freiburg, and Mulhouse. Enables a trusted and sovereign data exchange across national boundaries to support climate resilience, mobility, energy, health, urban planning, and crisis preparedness, while providing a foundation for AI applications, federated learning, and evidence-based regional decision making. (https://www.bs.ch/pd/kantons-und-stadtentwicklung/triregio-data-space)	Urban areas	Data space	Implementation phase	Germany, France, Switzerland
TrilaWatt	The Digital Hydromorphological Twin of the Trilateral Wadden Sea has been funded by the Federal Ministry of Digital and Transport (now the Federal Ministry of Transport) for a period of three years starting 1 January 2022 and is being developed by the Federal Institute for Hydraulic Engineering and several partners. TrilaWatt is developing innovative digital geodata and an analysis infrastructure for the entire Trilateral	Maritime transport	Transnational Digital Twin	Completed research project	Germany, Netherlands, Denmark

	Wadden Sea (the Netherlands, Germany, and Denmark). TrilaWatt thus supports the planning and maintenance of transportation infrastructure with harmonised, quality-assured data on geomorphology, sedimentology, and hydrodynamics. Geodata, analysis, and documentation methods are linked via web portals and services to form an assistance system within an interactive web viewer. (https://trilawatt.eu/)				
TWIN4DEM	This is a European social and political Digital Twin project that uses computational social science, agent-based modelling, and real-time political and social data analysis to study democratic backsliding and strengthen democratic resilience. Supports scenario simulation, policy testing, and stakeholder collaboration to identify risks to rule of law institutions and provide actionable evidence for policymakers and civil society. (https://twin4dem.eu/)	Democracy	Digital Twin	Implementation phase	EU
Twin4Resilience (T4R)	A Local Digital Twin initiative that helps cities and regions use Digital Twins for more resilient, inclusive, and sustainable territorial planning. Supports public authorities in visualising data, testing scenarios, and improving decision making through pilot actions, training, and shared frameworks for the responsible deployment of local	Urban areas	Digital Twin	Implementation phase	EU

	Digital Twins across Northwestern Europe. (https://t4r.nweurope.eu/)				
TwinERGY	This is a European energy Digital Twin project that places citizens at the centre of the energy market. Integrates energy data, automation, and demand response services through an interoperable platform to help households and communities adapt consumption to market conditions, improve flexibility, and support more efficient and collaborative energy management across pilot sites. (https://www.twinergy.eu/)	Urban areas (energy)	Digital twin	Research project	EU
TwinEU	TwinEU is creating a concept of a pan-European Digital Twin of the electricity system based on the federation of local Digital Twins. (https://twineu.net/)	Energy	Transnational Digital Twin	Implementation phase	EU

Virtual Singapore	Virtual Singapore is a city-scale Digital Twin that integrates 3D urban data, sensor information, and simulation tools to support planning, policy testing, infrastructure management, and more informed decision making across the city. (https://oecd-opsi.org/innovations/virtual-twin-singapore/)	Urban areas (mobility, urban development)	Digital Twin	Operational	Local (Singapore)
YVR Digital Twin	YVR's IT organisation is leveraging twins across all aspects of the airport ecosystem, enabling a complete, real-time view of activities. The Digital Twins will not only transform operations but also help the airport to connect with its community and build new revenue streams. (https://www.yvr.ca/en/business/work-with-yvr/yvr-digital-twin)	Airport operations	Digital Twin	Operational	Local (Vancouver Airport)

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Appendix III. List of Abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
AIS	Automatic Identification System
API	Application Programming Interface
BIM	Building Information Modelling
BIPED	Building Intelligent Positive Energy Districts
BMDV	Federal Ministry for Digital and Transport
BMV	Federal Ministry of Transport
C-ITS	Cooperative Intelligent Transport System
CCAM	Cooperative, Connected and Automated Mobility
CEF	Connecting Europe Facility
CO_2	Carbon dioxide
DCAT	Data Catalog Vocabulary
DCAT-AP	Data Catalog Vocabulary Application Profile
DestinE	Destination Earth
DT	Digital Twin
DIN	German Institute for Standardization
EDITO	European Digital Twin Ocean

EDIC	European Digital Infrastructure Consortium
EIB	European Investment Bank
EMDS	European Mobility Data Space
EU	European Union
FDT	Federated Digital Twin
GDPR	General Data Protection Regulation
GIS	Geographical Information System
GTFS	General Transit Feed Specification
HPC	High Performance Computing
IDSA	International Data Spaces Association
IDS	International Data Spaces
IEC	International Electrotechnical Commission
IMs	Interoperability Mechanisms
INSPIRE	Infrastructure for Spatial Information in Europe
IoT	Internet of Things
ISO	International Organization for Standardization
ITSs	Intelligent Transport Systems
KER	Key Exploitable Result
KPIs	Key Performance Indicators

KRITIS	Critical Infrastructure
LDT	Local Digital Twin
LDT4SSC	Local Digital Twins for Smart and Sustainable Cities
MDS	Mobility Data Space
MIMs	Minimal Interoperability Mechanisms
MMTS	Multinational and Multimodal Transportation System
NAP	National Access Point
NAPCORE	National Access Point Coordination Organisation for Europe
NeTEx	Network Timetable Exchange
OASC	Open and Agile Smart Cities & Communities
ODP	Operational Digital Platform
SERA	Single European Railway Area
TDT	Transnational Digital Twin

Appendix IV. List of Figures

Appendix V. List of Tables

Imprint

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