NARRATE

Regenerative Resilient Smart Manufacturing Networks

D1.4 Architectural requirements

2025/05/29

Grant Agreement No.: 101138094
Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01
Type of action: HORIZON-RIA

D1.4 ARCHITECTURAL REQUIREMENTS

Work package	WP 1
Task	T1.4
Due date	31/05/2025
Submission date	29/05/2025
Deliverable lead	SERVTECH
Version	1.0
Authors	Michael Papazoglou, Amal Elgammal, Bernd Kraemer (SERV)
Reviewers	Jesús Ávila (NUN) Jan Torka (FhG - IPK)
Abstract	This document outlines the reference architecture for the NARRATE project, integrating building blocks focused on Supply Chain Disruption Risk Detection and Strategic Resilience, Contextual Framework, Digital Twins, Knowledge Graph and Rules Engine, Real-Time Coordination & Complex Event Processing (CEP), and Large Language Model (LLM). This architecture empowers manufacturing networks with real-time risk visibility, intelligent reconfiguration, and resilience-by-design strategies — all orchestrated via the Intelligent Manufacturing Custodian (IMC) and enabled by a Smart Industrial IoT Platform.
Keywords	Reference Architecture, Digital Twin, Smart Manufacturing Network, Supply Chain Disruption Detection, Risk Assessment Tool, Complex Event Processing, IoT

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

Project co-funded by the European Commission in the H2020 Programme	
Type of the deliverable:	R
Nature of the deliverable:	PU

DOCUMENT REVISION HISTORY

Version	Date	Description of change	List of contributor(s)
0.1	2025/04/14	Definition of the Table of Contents	SERV
0.2	2025/04/22	Writing up of all the main section of the document	SERV
0.3	2025/04/25	Review of draft	Contributions from María José Núñez Ariño (AIDIMME), Jesús Ávila Molina(NUNSYS), Frank Werner (BlueBridge), Navid Sahebjamnia (BUL)
0.4	2025/05/15	Review of deliverable	Reviewers: Jesús Ávila Molina(NUNSYS), Jan Torka (FHG). Additional comments from María José Núñez Ariño (AIDIMME),
0.5	2025/05/19	Penultimate version	Final comments from B.J. Kraemer (SERV), check and removal of typos.
0.6	2025/05/28	Final version	Final version incorporating comments from various participants during the GA meeting in Lyon.
1.0	2025/05/29		Last revision by coordination

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

STATEMENT ON MAINSTREAMING GENDER

The NARRATE consortium is committed to including gender and intersectionality as a transversal aspect in the project's activities. In line with EU guidelines and objectives, all partners – including the authors of this deliverable – recognise the importance of advancing gender analysis and sex-disaggregated data collection in the development of scientific research. Therefore, we commit to paying particular attention to including, monitoring, and periodically evaluating the participation of different genders in all activities developed within the project, including workshops, webinars and events but also surveys, interviews and research, in general. While applying a non-binary approach to data collection and promoting the participation of all genders in the activities, the partners will periodically reflect and inform about the limitations of their approach. Through an iterative learning process, they commit to plan and implement strategies that maximise the inclusion of more intersectional perspectives in their activities.

DISCLAIMER

COPYRIGHT NOTICE

NARRATE(2025). D1.4 ARCHITECTURAL REQUIREMENTS

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

The NARRATE Consortium is the following:

Participant number	Participant organisation name	Short name	Country
1	INSTITUTO TECNOLOGICO METALMECANICO, MUEBLE, MADERA, EMBALAJE Y AFINES-AIDIMME	AID	ES
2	SCIENTIFIC ACADEMY FOR SERVICE TECHNOLOGY EV	SERV	DE
3	FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	FhG	DE
4	INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE LYON	INSA	FR
4.1	INSAVALOR SA	INSA-V	FR
5	SOFTWARE AG	SAG	DE
6	F6S NETWORK IRELAND LIMITED	F6S	IE
7	SYNESIS-SOCIETA CONSORTILE A RESPONSABILITA LIMITATA	SYN	IT
8	MICUNA SL	MIC	ES
9	DHL EXEL SUPPLY CHAIN SPAIN SL	DHL	ES
10	NUNSYS SA	NUN	ES
11	BUDATEC GMBH	BUD	DE
12	BRUNEL UNIVERSITY LONDON	BUL	UK
13	POLICY LAB OU	PL	EE
14	BLUEBRIDGE SOLUTIONS UG	BLU	DE
15	SANTER REPLY SPA	REP	IT

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

Table of Contents

List of figures

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

List of tables

Abbreviations

AI	Artificial Intelligence
BMS	Blueprint Management System
BOM	Bill of Materials
CA	Consortium Agreement
CEP	Complex Event Processing
CFX	Connected Factory Exchange
CNC	Computer Numerical Control

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

DL	Deliverable leader
DM	Data Manager
DT	Digital Twin
DoA	Document of Activities. It corresponds with the Annex I to the GA
DTPL	Digital Twin Processing Language
EC	European Commission
ERP	Enterprise Resource Planning
FDIF	Federated Data Integration Framework
HADEA	Health and Digital Executive Agency
HTL	Human in the Loop
IMC	Intelligent Manufacturing Custodian
IoT	Internet of Things
IIoT	Industrial Internet of Things
IIRA	Industrial Reference Architecture
KPI	Key Performance Indicator
MaaS	Manufacturing as a Service
LLM	Large Language Model
MBOM	Manufacturing Bill of Materials
MES	Manufacturing Execution System
MQTT	Message Queuing Telemetry Transport
MTO	Make-to-Order
Mx	Month x
NIST	National Institute of Standards and Technology
PCo	Project Coordinator
QM	Quality Manager
SCADA	Supervisory Control and Data Acquisition
SCST	Sustainability & Circularity Stress Testing
SMN	Smart Manufacturing Network
Tx.x	Task x.x
WP	Work Package

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

EXECUTIVE SUMMARY

The NARRATE Reference Architecture presents an innovative framework designed to transform traditional supply and manufacturing networks into resilient, intelligent ecosystems. At its core, the architecture integrates cutting-edge technologies—Artificial Intelligence (AI), Digital Twins, and Internet of Things (IoT)—to empower manufacturing organizations with real-time visibility, adaptive risk management, and proactive decision-making capabilities.

The centerpiece of the architecture is the **Intelligent Manufacturing Custodian (IMC).** Acting as a dynamic orchestrator, the IMC continuously aggregates, analyzes, and disseminates data across the Smart Manufacturing Network (SMN). It enables the early identification of risks, coordinates adaptive responses to disruptions, and evolves strategies through continuous feedback loops and learning mechanisms.

Key enablers of the NARRATE architecture include:

- **Supplier & SMN Risk Assessment Tool**: Provides critical insights into supplier and network vulnerabilities, enhancing risk sensitivity.
- **Risk Identification & Monitoring Tool**: Leverages Complex Event Processing (CEP) to detect potential disruptions and trigger real-time alerts.
- **Resilience Strategy Tool**: Delivers predefined and adaptive strategies to manage and recover from disruptions efficiently.
- **Blueprint Management System (BMS)**: Defines and governs the digital representation of manufacturing data, processes, supply chain structures, and adaptive workflows, ensuring a consistent foundation for orchestrating data and processes.
- **Large Language Model (LLM) Tool**: Utilizes Large Language Models to synthesize knowledge, assist human decision-making, generate recommendations, and dynamically adapt operational guidelines based on evolving scenarios and historical learning.
- **IMC**: Functions as a real-time digital intelligence hub that monitors, coordinates, and optimizes manufacturing and supply chain operations across distributed participants. It brings together data, digital twins, AI, and LLM systems to provide resilience, sustainability, and compliance capabilities.

Complementing its resilience focus, NARRATE also integrates a **Sustainability & Circularity Stress Testing (SCST) Tool**, ensuring that network operations not only withstand disruptions but also align with sustainable and circular economy principles.

In unifying these components, the NARRATE Reference Architecture establishes a **programmable, self-orchestrating Manufacturing-as-a-Service (MaaS)** environment. It offers manufacturing organizations a strategic scheme to achieve higher operational resilience, sustainability, agility, and competitive advantage in increasingly volatile global markets.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

1. INTRODUCTION

A reference architecture is a template solution that provides a standardized, high-level framework for designing and building systems within a particular domain. It defines the essential components, functions, relationships, and design principles necessary to guide the development of consistent, interoperable, and scalable solutions.

Below we provide an overview of what a reference architecture is, why it is important, and how it is associated with SMNs within the context of the NARRATE project.

1.1. DEFINITION IN SIMPLE TERMS

As networked manufacturing systems become increasingly interconnected, dynamic, and complex, the need for well-defined logical architectures to guide their design, integration, and evolution is more critical than ever [1], [2]. In this context, reference architectures play a pivotal role. They serve as high-level, abstract templates that offer a structured and standardized framework for organizing and aligning the various components, interactions, and design principles of such systems.

Rather than prescribing a one-size-fits-all solution, a reference architecture provides a common master plan for system design, ensuring consistency across projects. It outlines the essential building blocks of a system—such as its functional modules, data flows, and communication interfaces—and illustrates how these elements should interoperate within the overall ecosystem. By doing so, it provides guidance on system characteristics, design choices, integration strategies, and compliance with relevant standards and reduces effort and time for architectural decisions.

Reference architectures also promote consistency and reusability by offering best practices and validated design patterns that can be adapted to different use cases or implementation scenarios. This structured approach reduces complexity, accelerates development, and enhances interoperability across heterogeneous systems and stakeholders. Ultimately, reference architectures are vital tools for enabling scalable, resilient, and future-proof manufacturing system designs in an increasingly digital and distributed industrial landscape.

1.2. CORE ELEMENTS OF A REFERENCE ARCHITECTURE

The typical core elements of a reference architecture are the following.

1. Structure: Finalizing the overall framework and arrangement of architectural elements using building blocks. Building Blocks are functional components that represent key capabilities (e.g., data collection, processing, security).
2. Operation: Defining how each building block interacts and functions with other building blocks and within the broader architecture.
3. Interfaces & Data Flows: How the components communicate with each other and exchange data.
4. Technology Agnostic Foundation: It focuses on what needs to be done, not how to do it, so that the architecture and its building blocks remains adaptable across different technologies and platforms.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

1.3. WHY REFERENCE ARCHITECTURES ARE USEFUL

Reference architectures are useful because they:

Accelerate development: By reusing proven patterns and structures.

Ensure consistency: Across teams, systems, and projects.

Promote interoperability: Especially in ecosystems with multiple vendors or collaborators.

Guide innovation: Provides a clear structure for integrating emerging technologies.

Support compliance: Helps meet industry standards and regulatory requirements.

In a Smart Manufacturing context, a reference architecture would:

Define how sensors, machines, software systems, and humans interact.

Clarify how data flows from production to cloud to decision-makers.

Ensure security, resilience, and flexibility are built into the system from the start.

Provide a foundation for integrating AI, Digital Twins, IoT, LLM and cloud platforms.

Overall, a reference architecture is a strategic design tool—it helps organizations build complex systems more efficiently, with fewer risks and more clarity, by offering a shared, structured vision of how all the parts fit together.

1.4. PURPOSE OF A REFERENCE ARCHITECTURE FOR SMART MANUFACTURING NETWORKS

A reference architecture is an important element that influences the design, integration, and evolution Smart Manufacturing Networks. As such it supports:

1. Standardization and Interoperability: The reference architecture ensures all stakeholders—suppliers, manufacturers, technology providers—work from a common framework, using harmonized interfaces and data models, reducing integration complexity.

2. Scalability and Modularity: The reference architecture supports growth by defining reusable, composable modules (building blocks) that can be scaled or replaced independently.

3. Technology Alignment: It aligns industry with emerging technologies such as Industrial IoT, AI, Digital Twins, and LLM, ensuring solutions are forward-compatible and innovation-friendly.

4. Design & Implementation Guide: The reference architecture acts as a roadmap for developers, system architects, and factory planners to build compliant and future-proof manufacturing networks.

5. Governance and Compliance: Facilitates traceability, accountability, security, and sustainability by clearly specifying the roles and functions of each part of the system.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

1.5. WHY IT IS IMPORTANT FOR THE NARRATE PROJECT

The NARRATE project aims to build resilient, intelligent, and adaptable supply and production ecosystems, powered by AI, Digital Twins, LLM and Smart Manufacturing concepts. The reference architecture is crucial for NARRATE because:

1. It structures innovation: The architecture ensures that novel elements like the Intelligent Manufacturing Custodian (IMC), Digital twins and Digital twin Processing Language, Sustainability & Circularity Stress Testing (SCST), Risk Detection Tools, etc are logically integrated into a broader system.
2. It enables orchestration: NARRATE envisions a Smart Manufacturing Network (SMN) that self-orchestrates. The architecture defines where orchestration happens, how systems communicate, and how disruptions are handled in real-time.
3. It supports resilience-by-design: By embedding Disruption Risk Tools and Digital Twins into the architecture, NARRATE ensures predictive monitoring and reconfiguration are not just add-ons but foundational capabilities.
4. It facilitates collaboration: Across use cases, sectors, and partners, the architecture serves as a common language for discussing requirements, components, data flows, and capabilities.

1.6. THIS DELIVERABLE

Deliverable D1.4 defines a reference architecture rooted in agile principles, aimed at enhancing the resilience, adaptability, and user-centricity of modern supply chain operations. The architecture embraces a modular and flexible design approach that facilitates rapid iteration, continuous improvement, and the seamless integration of new capabilities as user needs evolve.

Crucially, this reference architecture serves as the structural backbone of the NARRATE ecosystem, weaving together all technical deliverables, functional components, and pilot-specific requirements into a cohesive and interoperable framework. In doing so, it ensures that innovation across the project—from AI-driven decision support to digital twins and sustainability stress testing—is fully aligned, interoperable, and responsive to real-world operational demands.

In keeping with principles of openness and interoperability, the architecture will encourage the use of platform-independent solutions, open-source software, and non-proprietary technologies. This approach not only reduces vendor lock-in but also facilitates broad adoption, seamless integration across diverse systems, and collaborative innovation within the supply chain ecosystem.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

2 OVERVIEW OF REFERENCE MODELS FOR SMART MANUFACTURING

2.1 INDUSTRY STANDARDS

ISA-95 (also known as IEC 62264) is an international standard that defines a structured framework for integrating enterprise systems (like ERP) with control systems (like SCADA, MES) in manufacturing defining a functional hierarchy for manufacturing systems, ranging from physical processes (Level 0) to enterprise systems (Level 4). It establishes a consistent set of models and terminology to support communication across different system levels. The goal is to improve interoperability, reduce integration costs, and enhance production efficiency. While the ISA-95 standard envisions a strict vertical integration of manufacturing and enterprise systems, the two main paradigms outlined aim to achieve a horizontal integration by developing decentralised connected information systems

RAMI 4.0 [3] offers a standardized reference architecture for Industry 4.0, presenting a three-dimensional model that captures key system aspects. The left horizontal axis represents the product and asset life cycle, based on IEC 62890. The right horizontal axis, derived from the IEC 62264 hierarchy, maps functional levels within factories—extended to include elements like "Product," "Field & Control Devices," "Enterprise," and the "Connected World" to reflect IoT integration. The vertical axis defines six IT layers, from business processes down to physical devices, outlining how Industry 4.0 features are digitally represented and integrated.

RAMI 4.0 bridges physical assets and digital models, enabling interoperability and modular system design. Its advantages include:

Standardized, structured approach aligned with IEC standards (62890, 62264).

Supports modularization and lifecycle tracking of assets.

Promotes interoperability across diverse systems.

Limitations include:

Conceptually complex and abstract—challenging for practical implementation.

Strong alignment with diverse industry standards may limit global applicability.

The Industrial Internet Reference Architecture (IIRA) [4] provides an open, non-prescriptive framework for building secure, resilient, and interoperable Industrial Internet Systems. While not a standard itself, it aligns with ISO/IEC/IEEE 42010:2011 for architectural descriptions, using viewpoints to structure design around stakeholder concerns. IIRA defines four key viewpoints: Business (strategic goals and stakeholders), Usage (operational scenarios), Functional (system components and their interactions), and Implementation (technology realization) to address stakeholder concerns and system design. It addresses core concerns such as integration, composability, connectivity, data management, and analytics. Its advantages include:

Broad applicability across sectors beyond manufacturing (e.g., energy, healthcare).

Emphasizes security, resilience, and scalability.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

- Aligns with global architectural standards (ISO/IEC/IEEE 42010).

Limitations include:

- High-level and conceptual—less guidance on implementation details.
- May require significant adaptation for domain-specific applications like discrete manufacturing.

ISA-95 provides the operational and functional scaffolding, especially in traditional manufacturing, upon which broader architectures like RAMI 4.0 and IIRA build. RAMI integrates them explicitly, while IIRA references them contextually.

2.2 OTHER NOTABLE ARCHITECTURES

2.2.1 4+1 View Model

A software architecture framework that organizes system design using five interrelated views: Logical, Development, Process, Physical, and a central Scenarios (Use Case) view [5]. Focuses on capturing different stakeholder perspectives (e.g., developers, integrators, users) to ensure system completeness, consistency, and scalability. Commonly used in complex, software-intensive systems, including those in manufacturing contexts.

2.2.2 NIST SMS Architecture

A reference architecture developed by NIST to support smart manufacturing systems through interoperability, standardization, and modularity [6]. Provides a layered structure focusing on system integration across manufacturing functions, from equipment control to enterprise-level planning and supply chain. Emphasizes composability, digital thread integration, and support for measurement science and data models.

Together, they can be complementary: the 4+1 model helps design the software components within an SMS, while the NIST architecture provides the domain context and interoperability framework.

2.2.3 Open Platform Communications Unified Architecture

OPC UA (Open Platform Communications Unified Architecture) is an open, platform-independent, and service-oriented communication standard widely used in industrial automation and smart manufacturing [7]. OPC is a completely independent platform that allows data to move seamlessly between multiple devices from different vendors. It scales from sensor to cloud.

Key Features include:

- Platform Independence: Works across operating systems, hardware platforms, and network types.
- Interoperability: Enables seamless data exchange between devices, machines, and software systems from different vendors.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

Information Modelling: Supports rich, hierarchical data models—allowing machines to not only share values but also describe their structure, status, and behaviour.

Scalability: Suitable for everything from embedded devices on the factory floor to cloud-based enterprise systems.

Security: Built-in support for encryption, authentication, and access control.

Extensibility: Supports vendor-specific and domain-specific extensions without breaking interoperability.

OPC UA has several appealing properties:

Acts as a universal translator between heterogeneous systems—critical for Industry 4.0, Digital Twins, and IIoT (Industrial Internet of Things).

Serves as the data backbone for reference architectures like RAMI 4.0, which formally recognizes OPC UA as the standard for communication between layers.

Helps unify real-time machine data, configuration information, and historical trends into a single, consistent interface.

2.3 COMPARATIVE ANALYSIS

The NARRATE reference architecture builds upon the solid foundations laid by RAMI 4.0, IIRA, and NIST SMS by introducing intelligence, dynamic orchestration, and resilience tooling tailored to modern manufacturing networks. It adopts critical elements like hierarchical structuring (RAMI), system viewpoints (IIRA), and standard-compliant interoperability (NIST SMS, OPC UA), while going further with real-time AI-driven coordination and sustainability focus. The relation of the NARRATE reference architecture to RAMI 4.0, IIRA, OPC UA and NIST SMS is shown in Figure-1 and explained in Table-1.

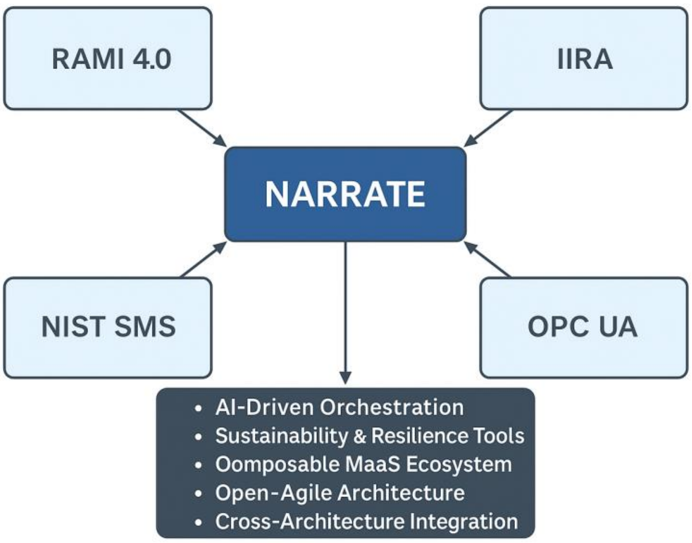

FIGURE 1 Relation of the NARRATE reference architecture to RAMI 4.0, IIRA, OPC UA and NIST SMS.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

Table 1 Comparative analysis of popular reference architectures with NARRATE.

Architecture	Core Focus	Relation to NARRATE	Distinctive Differences	Features Adopted in NARRATE
RAMI 4.0	Layered model for Industry 4.0 (life cycle, IT levels, hierarchy)	Aligns with RAMI's structuring of assets, hierarchy levels, and life cycle dimensions	RAMI is descriptive and static; NARRATE adds real-time orchestration and AI-driven resilience	- Hierarchy levels - Asset life cycle - Digital Twin model - OPC UA support
IIRA	Viewpoint-driven IIoT architecture for safe, secure, interoperable systems	Incorporates viewpoint modelling and alignment with concerns (business, usage, functional, implementation)	IIRA is general-purpose; NARRATE targets manufacturing-specific, proactive orchestration and sustainability	- Stakeholder viewpoints - Interoperability concerns - Resilience as a key concern
NIST SMS Architecture	Modular, standards-based integration of factory and enterprise systems	Supports layered integration and data interoperability with standards-based interfaces	NARRATE builds on this by embedding intelligent control (IMC) and dynamic adaptation tools (SCST)	- Functional layering - Standards like ISA-95 - Modular interoperability
OPC UA	Industrial communication standard for data exchange and modeling	Used by NARRATE for secure, interoperable connectivity across distributed manufacturing nodes	OPC UA is a protocol that standardizes the simple data exchange with machines and systems; NARRATE is a system-level reference architecture built on top of such protocols	- Information modelling - Secure communication - Plug-and-play device integration
4+1 View Model	Software architecture framework based on 5 interrelated stakeholder views	Applied to define software components within NARRATE (e.g., IMC)	4+1 is software-centric; NARRATE is a domain-specific system architecture for smart manufacturing	- Scenario-driven design - Logical & process views - Modular component modelling

The summary of key advantages of the NARRATE reference architecture with respect to the above-mentioned reference architectures are summarized in Table-2.

Table 2 Key advantages of the NARRATE reference architecture.

NARRATE Features	Differentiation
AI-Driven Orchestration (IMC)	Enables dynamic, intelligent coordination of supply and production systems
Sustainability & Resilience Tools (SCST)	Built-in tools to evaluate and adapt to disruptions and environmental impact
Programmable Digital Twin Framework with a Domain-Specific Language	Simulates, and orchestrates SMNs with a domain-specific language that enables real-time data integration, rule-based logic, and coordination of distributed manufacturing assets
Composable MaaS Ecosystem	Supports distributed, programmable Manufacturing-as-a-Service
Open, Agile Architecture	Promotes platform independence, open standards, and adaptability

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

Cross-Architecture Integration	Synthesizes strengths of RAMI, IIRA, NIST SMS, OPC UA, and 4+1 into a unified model

3 BUILDING BLOCKS IN THE NARRATE REFERENCE ARCHITECTURE

Figure 2 presents the conceptual structure of a Smart Manufacturing Network comprising a lead manufacturer and a distributed set of suppliers. This figure illustrates how users and the Intelligent Manufacturing Custodian interact with the network through the Digital Twin Processing Language (DTPL) — as specified in Deliverable D3.2 — to access, query, and process heterogeneous data streams originating from the suppliers' digital ecosystems. These ecosystems typically include enterprise systems such as ERP, MES, and other domain-specific tools. Overall, Figure 2 encapsulates the foundational mechanisms that NARRATE employs to support data-driven, AI-enhanced, and resilient manufacturing ecosystems, where information from diverse sources is abstracted, harmonized, and leveraged for real-time decision-making and adaptive control across complex supply and production chains.

In this figure, the Digital Twins act as proxies for real-world supplier assets and processes, offering a programmable interface for dynamic analysis, decision support, and orchestration within the SMN.

The DTPL enables semantic querying and computational reasoning over Digital Twins, represented as blueprint frames that abstract and synchronize the status, capabilities, and constraints of each supplier's infrastructure and operational processes.

Building blocks in NARRATE are the composable modular functional components of the architecture that can be integrated naturally. Each represents a distinct capability necessary for running an intelligent and resilient SMN. The building blocks of the NARRATE architecture—including data ingestion pipelines, semantic interoperability layers, context-aware reasoning engines, and adaptive orchestration components—are integral to the realization of this vision. They collectively support the creation, evolution, and reconfiguration of SMNs in response to operational goals and external disruptions. Their purpose is based on sound software-engineering principles and Includes:

- *Functional Encapsulation*: Each block performs a specific task (e.g., risk detection, orchestration, analytics).
- *Loose Coupling, High Cohesion*: Building blocks can operate independently but also work together seamlessly.
- *Technology Neutrality*: They describe what must be done, not how, allowing flexibility in technology choices.
- *Ease of Evolution*: New capabilities (e.g., LLMs or Knowledge Graphs) can be added without rearchitecting the entire system.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

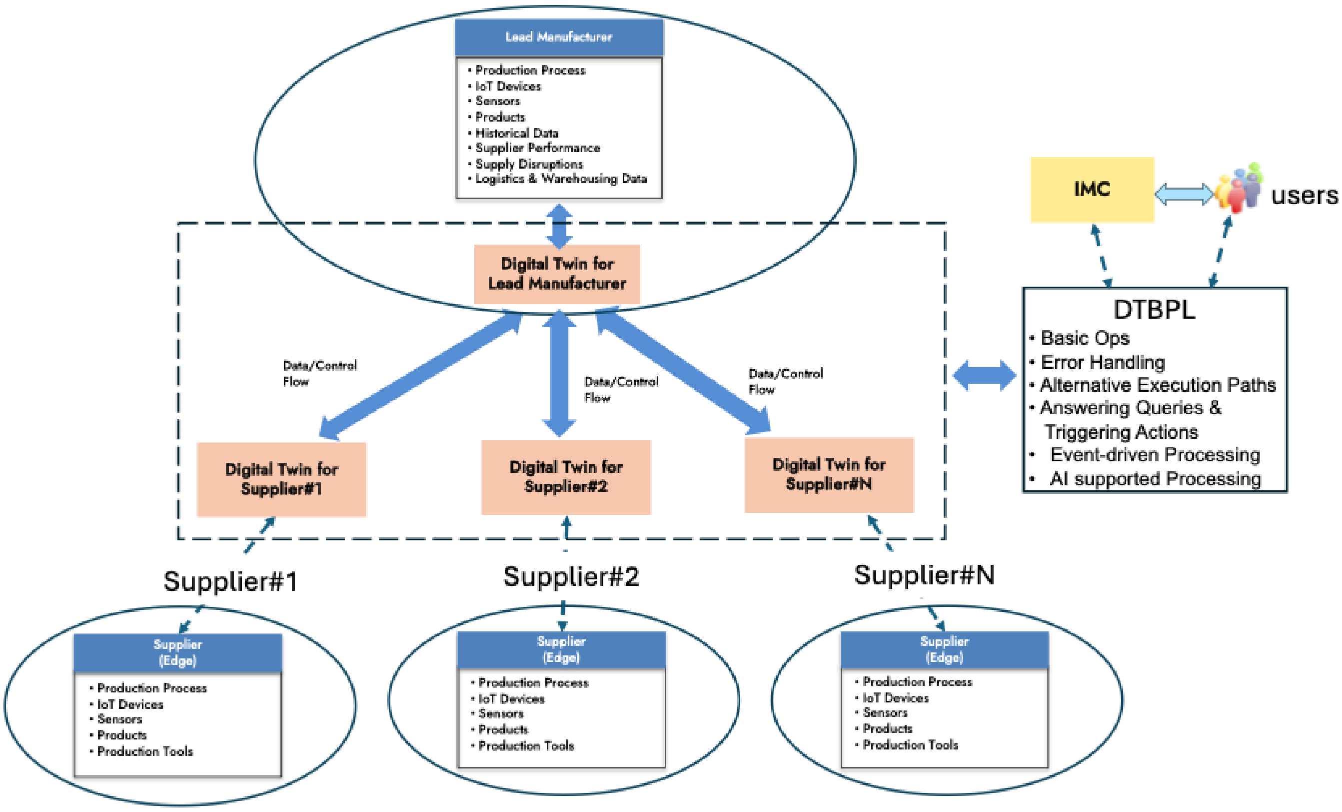

Figure 2 High-level view of a Smart Manufacturing Network.

The NARRATE architecture's modular building blocks—including but not limited to semantic middleware, AI-based reasoning engines, interoperability frameworks, and orchestration layers—enable the creation, operation, and dynamic reconfiguration of the SMN. These components work in concert to realize key project ambitions, including:

Supply Chain Resilience: Continuous monitoring through Digital Twins empowers the IMC to identify potential disruptions early and respond proactively through scenario analysis, resource substitution, or production reallocation.

Reconfigurability: The architecture supports the dynamic reconfiguration of the SMN in response to internal or external events, allowing new partners to be integrated rapidly and workflows to be adapted with minimal downtime.

Programmable MaaS (Manufacturing-as-a-Service): DTPL allows the encapsulation and orchestration of distributed manufacturing capabilities as services, enabling flexible and on-demand execution of production tasks across the SMN.

End-to-End Visibility and Decision Support: By federating data from across the SMN, the IMC can generate holistic insights into system performance, sustainability metrics, and supply chain dependencies.

The three essential characteristics of a building block are typically:

Well-Defined Functionality: Each building block encapsulates a specific function or service (e.g., data aggregation, orchestration, security) and is responsible for delivering that capability in a consistent and predictable manner.

Standardized Interfaces: Building blocks expose clearly defined interfaces (APIs, protocols, or data formats) that enable them to interact with other components within the architecture, ensuring interoperability and loose coupling.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

Reusability and Composability: A building block can be reused across multiple systems or use cases and composed with other blocks to form more complex services or workflows. This modularity supports flexibility, scalability, and faster system evolution.

In the following we outline the key building blocks in the NARRATE architecture.

3.1. KEY BUILDING BLOCKS IN THE NARRATE REFERENCE ARCHITECTURE & THEIR CHARACTERISTICS

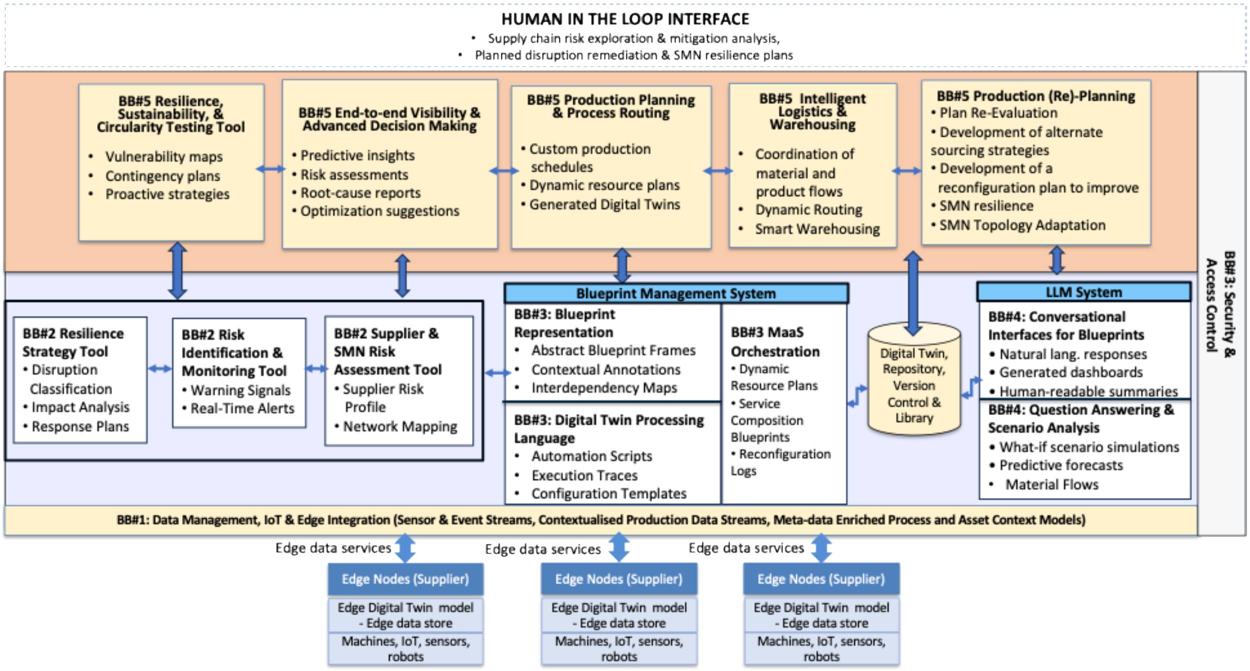

Figure 3 Logical NARRATE architecture.

Figure 3 illustrates a modular, next-generation architecture for digital supply chain management, fully aligned with the principles and components of the NARRATE project. At its core, the architecture leverages edge data integration, secure multi-party communication, and advanced AI-driven analysis and planning modules to deliver end-to-end supply chain intelligence. These capabilities are coordinated by the Intelligent Manufacturing Custodian —NARRATE's central command and control unit— which orchestrates data flows, digital twins, and decision-making across the network. By integrating Digital Twin technology, real-time sensor data, and LLM-powered decision support, this architecture enables the IMC to maintain a high degree of agility, visibility, and resilience. It fosters an adaptive supply chain capable of responding to disruptions, sustainability constraints, and evolving regulations—exactly the type of intelligent, modular ecosystem envisioned by the NARRATE project.

The architecture is composed of five interconnected modular building blocks (BB#1 to BB#5), each of which aligns with specific functional roles within NARRATE. These building blocks are described in what follows.

3.1.1 Data Management, IoT & Edge Integration

The Data Management, IoT & Edge Integration building block (BB#1) in Figure-3 enables Smart Manufacturing Networks to seamlessly connect the physical and digital realms by

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094 Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

combining data contextualisation with real-time responsiveness. It unifies the **Federated Data Integration Framework (FDIF)** -- in deliverable D3.1 -- with an integrated **IoT & Edge Framework**, delivering a scalable architecture that ensures contextualized, actionable data across distributed production systems.

The core objective is to represent and manage production data and operational events from multiple sources using open standards, structured metadata, and edge-enabled responsiveness. This approach empowers manufacturers to make informed decisions based on rich, real-time data without relying on centralized infrastructures.

Key Capabilities and Components of BB#1

1. Federated Data Integration Framework (FDIF)

The FDIF offers a structured, federated approach to data management across heterogeneous manufacturing systems. It supports decentralized data ownership while enabling unified access through semantic and metadata-driven techniques. The FDF supports the following:

- **(1) Standardised Ontologies and Metadata Models (WP3)**
  Ensures all data and context models are semantically harmonised, using shared vocabularies for interoperability and reusability across systems. Provides the foundation for discoverability and reasoning. Metadata aligned to ontologies (e.g., CDIF) provides a shared vocabulary for describing data assets, enabling FAIR (Findable, Accessible, Interoperable, Reusable) principles in practice.
  Key Data Outputs
  - Semantic Data Catalogues
  - Process and Asset Context Models
  - Metadata-Enriched API Payloads
  - Blueprint Frames provide the structured format for organizing and conveying both meta-data and remote data payloads.
- **(2) Metadata-Aware APIs for Interoperability (WP3)**
  Facilitates secure and meaningful exchange of data between distributed manufacturing systems, preserving context, access control, and lineage in each payload. Lightweight, secure APIs support data exchange across network partners. These interfaces preserve metadata and contextual annotations, ensuring that data retains its meaning and lineage as it flows across systems.
  Key Data Outputs
  - Federated Data Mesh Registry Entries
  - Data Provenance and Audit Trails
- **(3) Contextualised Aggregation and Semantic Enrichment (WP3)**
  Enriches raw data with metadata and semantic tags at collection or ingestion points. Supports analytics, traceability, and structured reporting. Data is enriched at the point of collection, embedding context such as source, timestamp, process state, and quality indicators. This ensures that analytics and decision-support systems work with high-quality, semantically consistent data.
  Key Data Outputs
  - Contextualised Production Data Streams
  - Semantic Data Catalogues
  - Data Provenance and Audit Trails
  - Time-Series Records: Structured historical data for trend analysis, AI-training, or Digital Twin simulations.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

2. IoT & Edge Integration Framework
Working in tandem with the FDIF, the IoT & Edge Integration Framework bridges the gap between physical assets and digital intelligence, enabling low-latency responsiveness and local optimisation.

- **(4) Edge Devices for Real-Time Data Acquisition (WP2, WP3)**
  Captures data directly from supplier (edge) machines and sensors at the shop floor level. Provides foundational input for real-time monitoring and diagnostics. Deployed across machinery and environments (e.g., CNC machines, sensors), edge devices continuously capture production data at the source with minimal latency.
  Key Data Outputs
    - Contextualised Production Data Streams
    - Edge Event Logs and Local Diagnostics
- **(5) Local Control Loops (WP2)**
  Enables immediate reactions to process deviations or failures, generating event logs and local process outcomes. Edge computing nodes enable fast, closed-loop reactions for latency-sensitive processes (e.g., machine stop conditions, safety triggers) without requiring cloud or central system involvement.
  Key Data Outputs
    - Edge Event Logs and Local Diagnostics
    - Key Performance and Health Indicators

Data Flow Example in Practice:

A temperature sensor on a CNC machine sends a data stream via an Edge Device (4). Local processing at a supplier's site - edge detects overheating and triggers a shutdown via a Local Control Loop (5). The event is logged and enriched with metadata (3), transmitted via a Metadata-Aware API (2), and stored in a Semantic Catalogue (1) linked to the affected asset's Context Model (1). The whole sequence is recorded in the Provenance and Audit Trail (2,3) for traceability.

Figure-4 illustrates a flowchart representing the flows of the Data Management, IoT & Edge Integration building block.

Impact and Value

By tightly integrating data management, semantic context, and edge computing, this building block creates a robust foundation for decentralized, real-time, and interoperable smart manufacturing. Manufacturers benefit from:

- **Improved responsiveness** through localised intelligence.
- **Enhanced data quality and usability** via semantic metadata and standardised ontologies.
- **Resilience and scalability** through federated architectures and distributed edge processing.
- **Actionable insights** enabled by combining contextual metadata with near real-time operational data.

This building block transforms fragmented data into a coherent, intelligent asset—supporting adaptive decision-making, cross-site coordination, and the evolution of self-orchestrated Smart Manufacturing Networks.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

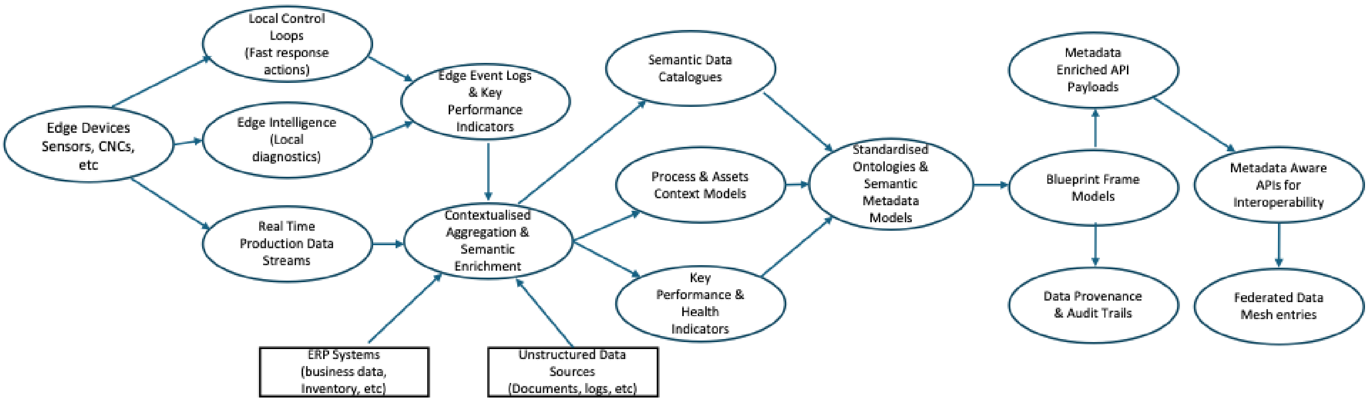

Figure 4 Flowchart of the data management and IOT and edge integration building block.

3.1.2 Supply Chain Disruption Risk Detection & Diagnostic Framework

The Supply Chain Disruption Risk Detection & Diagnostic Framework (BB#2) in Figure-3 represents a crucial backbone for smart, resilient, and adaptive Smart Manufacturing Networks (SMNs), especially in complex, multi-participant ecosystems like those envisioned in the NARRATE project. The building block comprises three interrelated tools, each playing a distinct role, yet intricately connected in terms of data flow, decision support, and proactive intervention. These are shown in Figure-5 and outlined below.

1. Resilience Strategy Tool (WP-2)

Purpose:

This tool develops the principal strategic framework to ensure continuity and resilience within SMNs. It does so by codifying:

- A taxonomy of disruptions, such as supplier failures, construction defects, extreme weather, or cost spikes.
- Impact analysis to assess operational and financial consequences of different disruption types.
- A library of conventional response strategies (e.g., alternative sourcing, rerouting logistics, inventory buffers).
- Structured plans for resilience-building actions, stored and made available for use by the Intelligent Manufacturing Custodian.

Key Data Outputs:

- Disruption classification rules
- Historical impact assessments
- Response plan templates

These outputs are stored in the IMC's Platform Library, providing a strategic knowledge base for responding to real-time risk signals detected by other tools.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

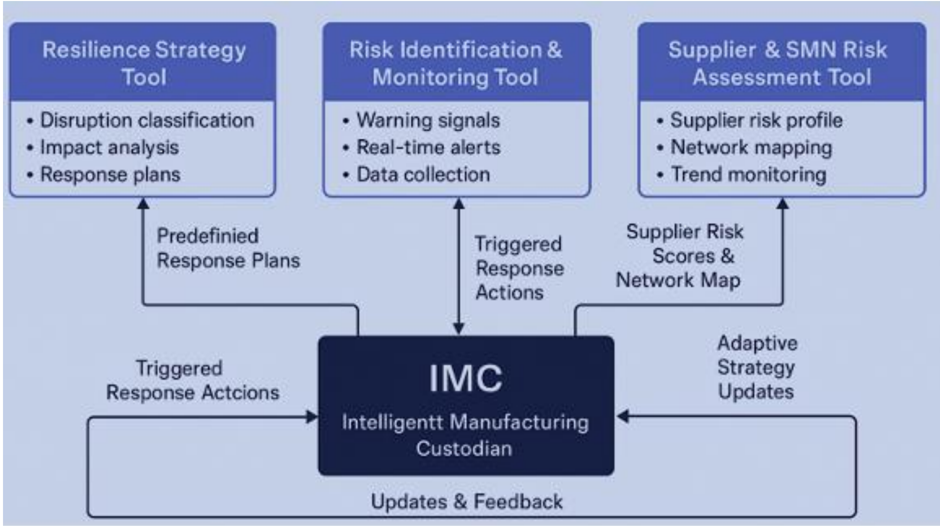

Figure 5 Supply chain disruption risk detection and diagnostic framework.

2. Risk Identification & Monitoring Tool (WP-2)

Purpose:
This tool enables proactive, real-time detection of disruptive signals from a multitude of external and internal sources, functioning as the SMN's early warning system. It relies on:

- **Complex Event Processing (CEP)**: Detects patterns across real-time feeds to flag potential disruptions.
- **News and social media feeds**: For geopolitical, financial, or operational events.
- **IoT-based sensing**: For quality control, location tracking, and environmental monitoring in the physical supply chain.
- **Dashboards and alerting mechanisms**: Providing visibility for SMN analysts and feeding structured alerts into the IMC.

Key Data Outputs:
- Real-time risk alerts
- Event metadata (type, time, location, severity)
- Trigger conditions matched (e.g., missed deliveries)

Data Flow:

This tool activates the knowledge base of the resilience strategy tool by trying to match live data with known disruption patterns. When a disruption pattern is recognized (e.g., repeated supplier delay or environmental hazard), the CEP engine triggers an alert which it forwards to the IMC triggering adaptive responses.

3. Supplier & SMN Risk Assessment Tool (WP-2)

Purpose:
This tool performs comprehensive assessments of suppliers and the broader SMN to uncover vulnerabilities and predict weak points. It supports longer-term risk mitigation via the following features:

- **Supplier Risk Profiling**: Evaluates the impact and likelihood of risks associated with suppliers and other entities within the SMN, including transportation and warehousing companies.
- **Network Mapping via Digital Twins**: Identifies critical nodes, transportation routes, and single points of failure.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094 Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

- **Trend Monitoring**: Analyses historical data to project trends regarding the impact and likelihood of risks affecting suppliers and other actors in the SMN.

Key Data Outputs:

- Supplier risk scores
- SMN structural risk maps
- Trend-based risk flags

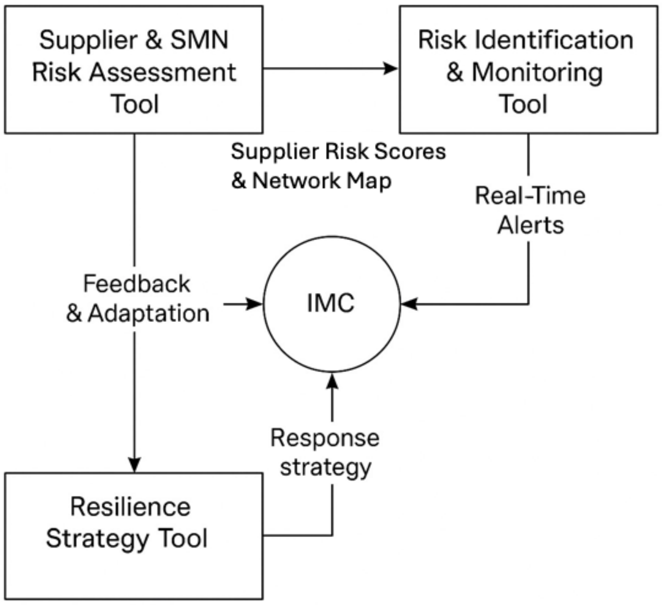

Figure 6 Flow chart of supply chain disruption risk detection and diagnostic framework.

Data Flow:

Outputs from this tool feed into the CEP engine in the Risk Identification & Monitoring Tool to enrich its understanding of context and criticality. For example, if a risk alert is generated from a supplier, Supplier & SMN Risk Assessment Tool helps determine whether this supplier is a critical node in the SMN and if alternative routes or sources are viable. The tool also refines the classification and response plans held in the Resilience Strategy Tool based on evolving supplier profiles.

Data Flow & Tool Interdependency

Below is a labelled version of this building block's flowchart in plain text Mermaid syntax how data flows between the tools and how they collaborate. This is also illustrated in Figure-6.

Entities and Data Flows:

- Supplier & SMN Risk Assessment Tool
  → (provides) → Risk Identification & Monitoring Tool
  (supplies insights to CEP engine for risk sensitivity)
- Risk Identification & Monitoring Tool
  → (generates) → Real-Time Alerts
- Real-Time Alerts
  → (sent to) → IMC (Intelligent Manufacturing Custodian)
  (alerts trigger adaptive responses)
- Resilience Strategy Tool
  → (provides) → IMC
  (provides strategies and impact assessments when disruptions are confirmed)

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

- IMC
  ↔ (bidirectional flow with) ↔ All Tools (Supplier & SMN Risk Assessment Tool, Risk Identification & Monitoring Tool, Resilience Strategy Tool)
  (IMC orchestrates communication, feedback loops, and adapts strategies)

3.1.3 Blueprint Management System (BMS)

The Blueprint Management System (BMS, BB#3) in Figure-3 serves as the digital intelligence core of the NARRATE architecture, enabling the modelling, orchestration, and adaptive control of Smart Manufacturing Networks. At its heart lies the concept of Blueprint Frames—semantic representations of Digital Twins that abstract manufacturing entities, capabilities, and constraints across the supply chain. These blueprints serve as the programmable, query-able, and reconfigurable interface between real-world operations and the Intelligent Manufacturing Custodian.

Blueprint Representation (WP-3)
Key Data Outputs:
- **Blueprint Frames:** Structured, modular representations of supplier capabilities, configurations, and dependencies.
- **Contextual Annotations:** Metadata that maps operational context to parts of the blueprint (e.g., capacity limits, preferred suppliers).
- **Access-Filtered Views:** Role-specific blueprint extracts for different stakeholders.
- **Configuration Snapshots:** Instance-based data reflecting the current or target manufacturing state showing how components and suppliers relate within the SMN.

The Digital Twin Processing Language (DTPL) is tightly woven into the BMS. It provides a formalized, domain-specific means of querying, composing, and orchestrating Blueprint Frames, enabling automation, optimization, and dynamic reconfiguration of SMNs. The key data outputs of the Blueprint representation and the Digital Twin Processing Language are as follows.

Digital Twin Processing Language (WP-3)
Key Data Outputs:
- **Executable Logic Scripts:** Machine-readable orchestration and control flows derived from blueprints.
- **Adaptation Rules:** Runtime logic for dynamic reconfiguration based on triggers.
- **Intervention Alerts:** Notifications for human or automated interventions when logic conditions are met.
- **Configuration Templates:** Parameterized blueprints that can be reused to instantiate twins or orchestrations under different scenarios.

In addition to the Blueprint representation Layer and the Digital Twin Processing Language, the Blueprint Management System is composed of the following interconnected sub-building blocks:

1. **Digital Twin Repository & Version Control (WP-3)**
   - Function: Stores, manages, and tracks versions of Digital Twin models, ensuring traceability and support for iterative evolution.
   - Blueprint Integration: Enables the historical and real-time refinement of Blueprint Frames, capturing changes in supply chain performance, configurations, or partner capabilities.

Funded by the European Union
Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions
UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

- DTPL Role: Supports versioned scripting and parametric configurations of Digital Twins, allowing reproducible scenarios and programmable lifecycle management.

Key Data Outputs:

- **Versioned Digital Twin Models:** Captures successive iterations of Digital Twins, supporting historical tracking and configuration rollback.
- **Change Logs & Metadata:** Logs detailing updates, timestamps, and authorship for each modification to Blueprint Frames.
- **Scenario Snapshots:** Saved states of the SMN for use in simulation, validation, and reproducibility.

2. **Manufacturing-as-a-Service (MaaS) Orchestration (WP-3)**
    - Function: Provides programmable orchestration across distributed manufacturing resources, enabling flexible, on-demand service composition.
    - Blueprint Integration: Operates over Blueprint Frames to dynamically reconfigure SMNs, adapting workflows to changing operational contexts or disruptions.
    - DTPL Role: Employs DTPL scripts to declaratively define and automate resource allocation, production task delegation, and workflow orchestration, allowing seamless adaptation with minimal latency.

    Key Data Outputs:

    - **Dynamic Resource Allocation Plans:** Real-time mappings of tasks to available manufacturing assets across the SMN.
    - **Service Composition Blueprints:** Structured definitions of orchestrated production and resource workflows using Blueprints.
    - **Reconfiguration Logs:** Records of adaptation actions triggered in response to disruptions or demand shifts.

3. **Data Management & IoT Integration (WP-3)**
    - Function: Continuously collects, normalizes, and streams real-time data from suppliers, factory floor sensors, production lines, logistics systems, and edge devices.
    - Blueprint Integration: Ensures that Blueprint Frames are synchronized with live operational data, preserving fidelity between the physical and digital layers.
    - DTPL Role: Exposes data as a programmable interface, enabling DTPL expressions to reason over time-series inputs, trigger adaptive responses, or activate predictive alerts in the IMC.

    Key Data Outputs:

    - **Sensor Data Streams:** Live operational metrics such as temperature, speed, utilization, etc.
    - **Event Streams:** Time-series data from equipment, logistics systems, and environmental sensors.
    - **Alerts & Anomalies:** Automatically generated notifications when thresholds are breached or patterns deviate from expected norms (KPIs).

4. **Security & Access Control Framework (WP-3)**
    - Function: Provides granular authentication, authorization, and audit mechanisms to secure data flows and user interactions.
    - Blueprint Integration: Implements role-based access policies on Blueprint Frames, enabling collaborative yet controlled manipulation and orchestration across partners.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

- DTPL Role: Enforces secure script execution, validating compliance with access permissions and regulatory constraints during runtime.

Key Data Outputs:

- **Access Control Policies:** Configurable role-based rules governing who can view or modify specific Blueprint components.
- **Audit Trails:** Records of all interactions with digital twins, blueprints, and orchestration commands.
- **Validation Reports:** Outputs confirming that DTPL scripts or automation processes comply with access permissions and industry standards.

Data Flow & Tool Interdependency

Figure-7 depicts the data flows and interactions within the Blueprint Management System, focusing specifically on the interconnections between key tools in Building Block #3 (BB#3). This figure highlights how these tools shape the creation, evolution, and operational use of Blueprint Frames related to risk monitoring, disruption modelling, and resilience management.

Each tool in BB#3 contributes to the semantically rich construction of blueprints, embedding contextual information such as supplier dependencies, real-time risk indicators, and critical thresholds for disruption scenarios. These enriched blueprints are not static artifacts—they evolve dynamically as new data is ingested, simulations are executed, and risk conditions change.

The data flows and interactions within the BMS are summarised briefly below.

Contextualized Blueprints for Archival: Newly created or updated Blueprint Frames—including their contextual annotations and interdependencies—are sent to the repository for storage, version control, traceability, and future reuse.

Access Policies: The Blueprint Layer uses security policies to restrict or allow modifications and visibility per stakeholder roles. Depending on user roles, tailored or masked versions of blueprint data are retrieved for secure manipulation.

Retrieved Blueprint Frames & Historical Model Instances: Validated stored or historical blueprint versions are retrieved from the repository to the Blueprint Representation Layer, either to instantiate a previous configuration, compare against current states, simulate changes, or reapply validated production setups. DTPL scripts tied to specific blueprint versions are saved for traceability and scenario reproducibility.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

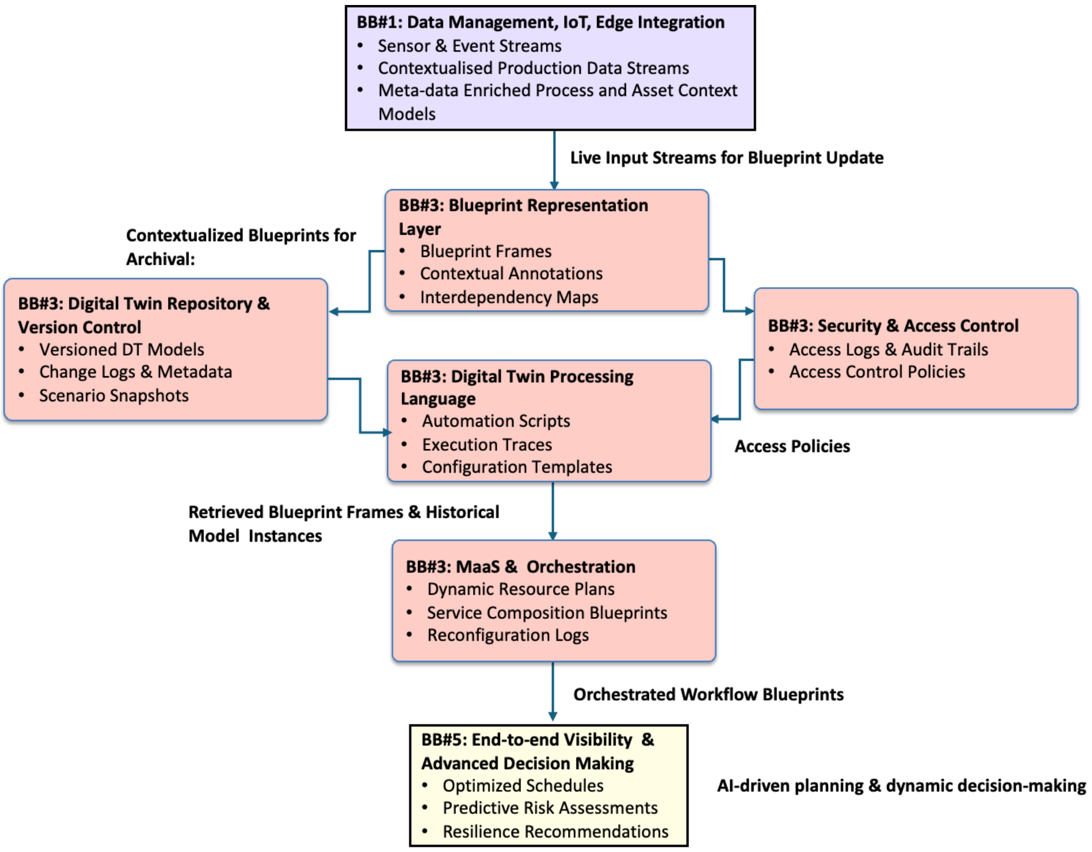

Figure 7 Blueprint management system data flows

Orchestrated Blueprints: The orchestration tool consumes Blueprint Frames to identify capabilities, resources, and dependencies for dynamic task assignment it provides updated compositions or resource allocations.

AI-driven planning & advanced decision-making: The orchestration layer provides data on active workflows and resource usage to support and guide AI-supported visibility and advanced decision making.

Importantly, as outlined above, the outputs and updated blueprint states from BB#3 feed directly into the AI-powered modules in BB#5, particularly those supporting supply chain visibility and advanced decision-making. The integration enables the Intelligent Manufacturing Custodian to reason over up-to-date, context-aware digital representations of the supply chain and to generate timely, explainable, and resilient responses.

This seamless connection between BB#3 and BB#5 ensures that strategic risk intelligence directly informs operational AI tools, enabling the NARRATE architecture to support transparent, agile, and resilient control of complex manufacturing and logistics networks.

3.1.4 Large Language Models System

A Large Language Model (LLM, BB#4) in Figure-3 is an advanced artificial intelligence system trained on vast amounts of text data to understand and generate human language. Using deep learning, LLMs can analyse, synthesize, and respond to textual information across domains. Today's most advanced language models are built on a technology called the *transformer*, introduced in 2017. This design allows the model to understand the relationships and context between words across an entire passage.

Funded by the European Union
Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions
UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

These models are trained by reading vast amounts of text from books, websites, and other sources, learning to guess the next word in a sentence. Over time, they pick up on grammar, meaning, and context, allowing them to perform tasks like answering questions, summarizing information, translating languages, and even writing code—all without being explicitly programmed for each one. They excel in tasks such as natural language understanding, text generation, summarization, and answering complex queries by recognizing patterns and relationships in data. Key limitations of LLMs include bias propagation (amplifying societal biases in training data), hallucination (producing confident but false or fabricated information), and limited reasoning (struggling with tasks requiring consistent logic, multi-step inference, or common sense).

In Figure-8 the LLM System is shown to comprise the two following modules:

1. **Conversational Interface for Blueprint Frames (WP3)**
   - Enables natural language interaction with stakeholders (e.g., factory operators, planners, quality managers) using the human-in-the-loop interface in section 3.1.6 for accessing complex data stored in Blueprint Frames. A simple example follows.
     - Example: A manager could ask, "What is the current productivity rate for line A?" or "What is the expected impact of supplier delay on production volumes?"

Key Data Outputs:

- Natural language responses to user queries.
- Acts as a bridge between human users and the Intelligent Manufacturing Custodian (IMC) for both operational control and scenario exploration.
- Could generate dashboards or visual summaries (on-demand).

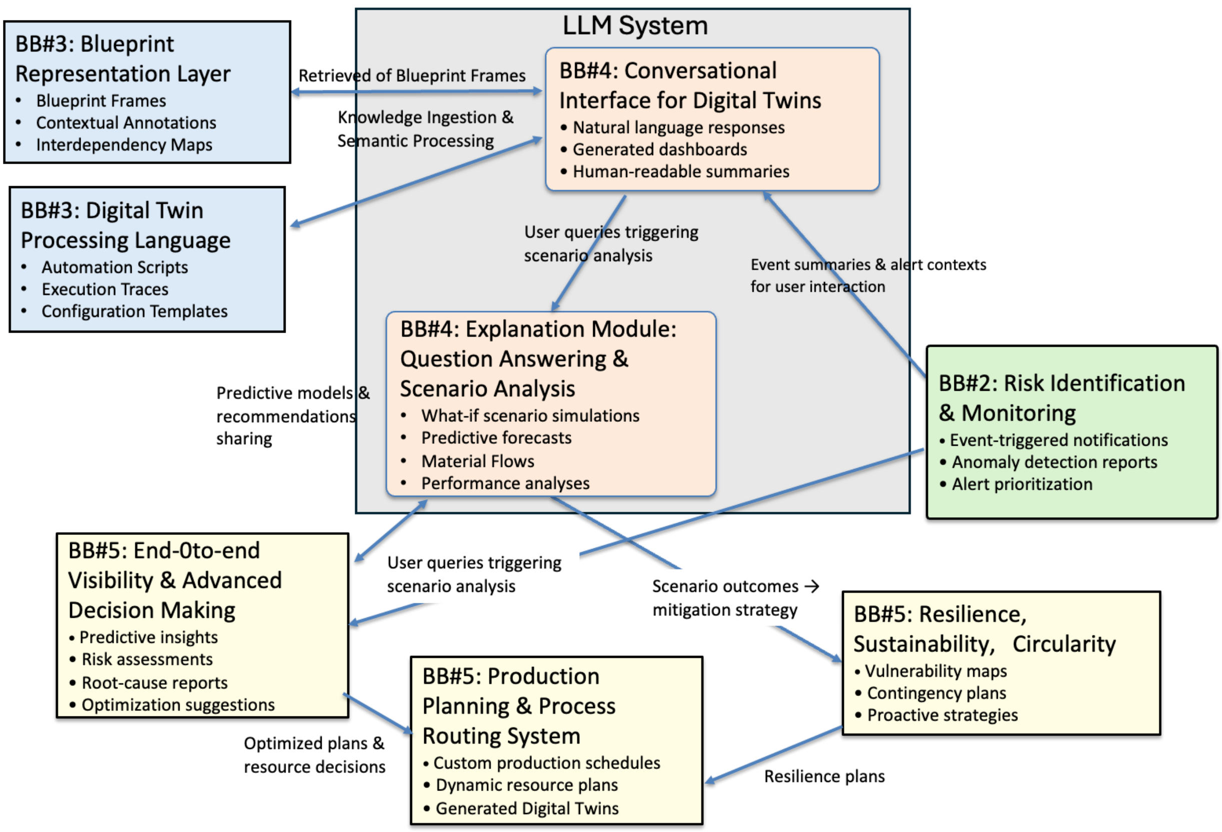

Figure 8 Conceptual architecture of the LLM system.

Funded by the European Union
Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions
UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

2. **Explanation Module: Question Answering & Scenario Analysis (WP3)**
   - Provides traceable, explainable outputs to support decision-making and regulatory compliance.
   - Acts as a bridge between human users and the Intelligent Manufacturing Custodian for both operational control and scenario exploration.
   - Generates justifications for IMC recommendations or alerts (e.g., disruption warnings, sustainability risks).
   - Can simulate and analyse "what-if" scenarios using digital twin data to support proactive planning. A simple example follows.
     - Example: Predicting the impact of a 10% reduction in raw materials on overall production and suggesting mitigations.

Key Data Outputs:

- Simulated outcomes for "what-if" scenarios
- Predictive forecasts (e.g., delivery delays, capacity shortages)
- Comparative analysis between different scenarios

Pairing LLMs with Digital Twins in a Smart Manufacturing Network

Digital twins (Blueprint Frames) in an SMN represent physical assets, processes, and operations. When these digital twins include and structure rich descriptive data—such as product information, production deadlines, supplier data, logistics, and supply chain operations—LLMs can serve as a powerful tool to analyze, contextualize, and optimize operations. Key Data Outputs for Blueprint Frames are as follows.

Key Data Outputs:

- Unified knowledge graphs linking entities (e.g., product-spec → supplier → production schedule)
- Semantic tags/classifications for unstructured content
- Extracted entities and relationships (e.g., material → supplier → capacity)

The previous discussion points out that in NARRATE the LLM system is tightly integrated with:

- The IMC, acting as a cognitive engine for interpreting data patterns, user intents, and system responses.
- The Digital Twin (Blueprint) Infrastructure, for translating simulations and real-time sensor data inputs into narratives and insights.
- The BMS, ensuring alignment between the LLM's language understanding and the structured frame-based modelling of the SMN.

Table 3 shows the broader functions of the LLM System within the NARRATE architecture.

Table 3 Function of the LLM system in the NARRATE architecture

LLM Function	Primary Roile	Inputs	Outputs	Integration Points
1. Knowledge Ingestion & Semantic Processing	Transforms diverse data into semantically interpretable forms	Structured data (BMS frames, IMC logs), unstructured data (documents, emails, manuals)	Semantic vectors, contextual embeddings, enriched ontology-linked data	- BMS (Blueprint Frames) - IMC (data lake and control

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

				plane) - SCST Tool
2. Conversational & Query Interface	Enables natural interaction with system via NL queries or instructions	User input (typed or spoken queries), context state	Machine-interpretable queries, user-oriented visual/textual responses	- Human interface layer (dashboard, mobile apps) - IMC command interface - Real-time data dashboards
3. Explanation & Justification Module	Generates traceable, interpretable explanations	Decisions, predictions, and alerts from IMC, SCST, or BMS	Explanations in natural language, visual aids, rationale trees	- IMC decision engine - Regulatory Compliance Frame - User Alert Systems
4. Predictive Reasoning & Disruption Support	Aids in interpreting simulations and identifying emerging risks	Sensor streams, historical patterns, Digital Twin simulations, SCST scenarios	Risk forecasts, potential mitigation narratives, disruption impact summaries	- Digital Twin Engine - SCST Tool - IMC decision support modules

The functions of the LLM system in Table-3 are assisted by the following systems and BBs in the NARRATE architecture.

1. **Visibility model & Advanced Decision Making (WP3&WP4)**
   - The LLM can analyse digital twin data in real-time to suggest actions or predict disruptions.
     - Example: Recommending supplier adjustments based on a delay in raw material delivery or aligning production schedules to meet logistics constraints.

Key Data Outputs:

- Predictive insights (e.g., likelihood of production delay)
- Risk assessment reports
- Root-cause correlations (e.g., material shortage linked to supplier backlog)

2. **Risk Identification, Monitoring & Alerts (WP2&WP3)**
   - The LLM can monitor digital twin data streams and generate alerts and issue explanations when deviations occur.
     - Example: Detecting lower-than-expected production volumes and generating a report with root cause analysis.

Key Data Outputs:

- Event-triggered notifications (e.g., performance threshold breached)
- Anomaly detection notifications
- Alert prioritization with suggested actions

3. **Production Planning & Process Routing System (WP4)**
   - Programming the SMN to offer customizable, on-demand manufacturing services (viz. MaaS) requires dynamic data interpretation. LLMs can interpret customer requirements and translate them into actionable production schedules and processes.
     - Example: Configuring a production line to meet a custom order based on available resources and deadlines.

Funded by the European Union
Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions
UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

Key Data Outputs:

- Custom production schedules
- Dynamic routing and resource allocation plans

3.1.5 Intelligent Manufacturing Custodian (IMC)

A detailed breakdown of the five core components of the Intelligent Manufacturing Custodian -Building Block#5, within the NARRATE architecture in Figure-3, including their key activities and interrelations is shown in Figure-9 and is described below.

1. Resilience, Sustainability & Circularity Stress Testing Tool (SCST)-WP4

Purpose:

Enables proactive evaluation of manufacturing and supply chain configurations against potential disruptions and environmental criteria.

Key Activities:

- **Stress Testing:** Simulates various disruptive scenarios (e.g., supplier failure, logistic bottlenecks, climate impacts) across the Smart Manufacturing Network.
- **Sustainability Assessment:** Assesses carbon footprint, resource use, and circularity metrics for different configurations.
- **Circularity Metrics Monitoring:** Evaluates reusability, and recyclability.
- **Scenario Comparison:** Ranks supply chain options and process configurations by risk resilience and environmental impact.

Key Data Outputs:

- Stress test results (resilience under disruption scenarios)
- Sustainability KPIs (e.g., energy usage, waste reduction scores)
- Circularity reports (reuse/recycle rates, material lifecycle data)
- Scenario-based recovery strategies
- Environmental impact assessments

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094 Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

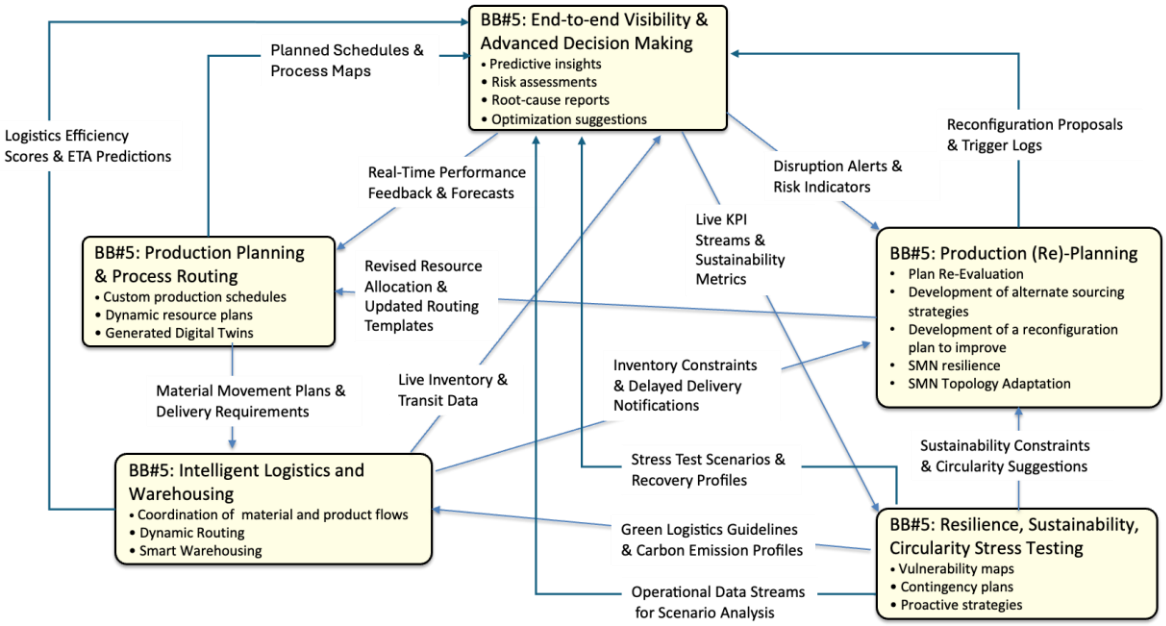

Figure 9 Conceptual architecture of IMC building block.

2. End-to-End AI-driven Visibility & Advanced Decision Making (WP4)

Purpose:

Provides a unified, real-time view of the entire production and supply network, and supports intelligent decision-making using AI.

Key Activities:

- **Data Fusion:** Integrates real-time data from IoT devices, digital twins, ERP/MES systems, and external partners.
- **AI-based Insight Generation:** Detects patterns, trends, and anomalies using machine learning algorithms.
- **Dynamic Dashboards & KPIs:** Visualizes status, bottlenecks, and forecasted metrics across the SMN.
- **Decision Support:** Recommends operational actions (e.g., rerouting, schedule adjustments) based on predictive analytics and optimization.

Key Data Outputs:

- End-to-end supply chain snapshots
- KPI dashboards (e.g., throughput, lead time, delivery adherence)
- Decision recommendations (e.g., production shifts, supplier substitutions)
- Anomaly detection alerts
- Root cause analyses and traceability logs

3. Production Planning & Process Routing System (WP4)

Purpose:

Plans and optimizes production sequences and workflows across the SMN and distributed manufacturing assets.

Key Activities:

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

- **Workflow Orchestration:** Allocates and schedules tasks across suppliers and production cells.
- **Process Optimization:** Selects optimal routes and processing steps considering costs, availability, and performance targets.
- **Real-Time Adaptation:** Recalculates workflows in response to disruptions or demand changes.
- **Constraint Management:** Handles machine availability, supplier limitations, lead times, and quality constraints.

Key Data Outputs:

- Optimized production schedules
- Resource capacity plans
- Task-machine-operator assignments
- Process routing maps (with alternatives)
- Bottleneck and latency indicators

4. Intelligent Logistics and Warehousing (WP4)

Purpose:

Manages the efficient flow and storage of materials and finished goods across the network strictly on the basis of relevant data produced in the METWOOD and BUDATEC pilots.

Key Activities:

- **Real-Time Inventory Management:** Tracks material availability and movements using IoT and barcode/RFID systems.
- **Smart Warehousing:** Uses AI for slotting optimization, picking strategies, and resource planning.
- **Dynamic Routing:** Adapts delivery routes in real time based on traffic, priority, and inventory needs.

Key Data Outputs:

- Inventory levels and reorder alerts
- Delivery route optimizations
- Logistics tracking data (ETA, status updates)
- Logistics risk assessments and contingency plans

5. Production (Re-)Planning (WP4)

Purpose:

Supports dynamic reconfiguration of the SMN in response to changes in demand, disruptions, or optimization opportunities.

Key Activities:

- **Plan Re-Evaluation:** Continuously monitors execution versus plan and triggers replanning if deviations occur.
- **SMN Topology Adaptation:** Reorganizes manufacturing and supplier networks based on performance, risk, and cost.
- **Automation via Digital Twins:** Uses programmable twins and LLMs to simulate and reconfigure production plans.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

- **Recommendation of proactive measures**: Develops a list of recommended changes and a reconfiguration plan to improve SMN resilience and make the necessary adjustments regarding demand related events (e.g., supplier changes) and resource related events (e.g., machine breakdowns, route blockages, as well as regular uncertainties and sourced for delays in logistics processes).

Key Data Outputs:

- Reconfiguration plans (e.g., supplier switch, task reallocation)
- Real-time re-planning logs
- System state snapshots before/after reconfiguration
- Adaptive workflow blueprints
- Feedback loops for continuous improvement

Table 4 presents an overview of key tool interrelations within the Intelligent Manufacturing, highlighting how various components within the NARRATE architecture collaborate to enable coordinated decision-making, planning, and adaptive control. These interrelations are not merely technical linkages—they represent the operational logic that underpins the IMC's role as a real-time command and coordination hub for the Smart Manufacturing Network.

The table outlines how core IMC subsystems—such as the SCST Tool, Planning and Routing, Replanning and DDS modules—interact to support functions like risk assessment, sustainability evaluation, supply chain visibility, and regulatory compliance. It also illustrates how outputs from one module (e.g., stress test results from the SCST Tool) feed into others (e.g., decision-support interfaces in BB#5), ensuring that insights are propagated throughout the network for proactive, informed action.

By clarifying these interdependencies, Table 4 underscores the IMC's integrative intelligence and its ability to unify real-time data, predictive analytics, and semantic knowledge across the manufacturing and supply chain ecosystem.

Table 4 IMC tool interrelations at a glance.

From Component	Flows To	Interaction
SCST Tool	Advanced DSS	Provides risk/sustainability feedback to inform AI predictions.
Advanced DSS	Planning & Routing	Informs with real-time data and analytics to enable optimal routing.
Planning & Routing	Replanning Module	Feeds baseline workflows in an SMN; adapts under new constraints & changing conditions.
Replanning	Planning & Routing, Logistics	Adjusts SMN structure, delivery schedules and routing based on updated plans.
Advanced DSS	All AI-Modules in IMC	Coordinates insights across all IMC components.

3.1.6 Human-in-the-Loop Interface

The **Human-in-the-Loop (HITL) Interface** in the NARRATE architecture in Figure-3 plays a critical enabling role by embedding human judgment, oversight, and decision-making into the intelligent automation ecosystem. While the broader NARRATE system leverages advanced technologies like Digital Twins, Large Language Models (LLMs), the Intelligent Manufacturing Custodian (IMC), and the Blueprint Management System (BMS), the HITL Interface ensures that *human expertise remains a central part of the operational decision loop*, particularly where ambiguity, choice or unstructured information is involved.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.

Role of the Human-in-the-Loop Interface in NARRATE

The HITL Interface acts as a *bidirectional gateway* between users (e.g., planners, operators, engineers, decision-makers) and the NARRATE system's automated intelligence components. It provides:

- **Context-aware feedback mechanisms**, enabling users to validate or override automated decisions.
- **Natural language and visual interfaces** to explore Digital Twin states, production analytics, resilience plans, and more.
- **Manual curation tools** to refine blueprints, production plans, or risk mitigation strategies based on human insight.

Table 5 The functions of the HITL in the NARRATE architecture.

Function	Description
1. Natural Language Interaction	Uses LLM-powered conversational agents to let users query and control the system using human language (e.g., "What are the active disruptions in supplier cluster B?").
2. Validation & Override of Automated Actions	Allows operators to review and approve or reject suggestions made by the IMC, such as supply chain reconfigurations or production plan adaptations.
3. Scenario Exploration & Simulation Control	Interfaces with the Blueprint Management System and Blueprint Frames to let users simulate "what-if" scenarios, adjust parameters, and visualize outcomes.
4. Dashboard Customization & Alerts Review	Provides customizable interfaces for reviewing KPIs, alerts, predictive forecasts, and stress test results from the IMC and DSS modules.
5. Blueprint & DTPL Oversight	Enables the update of Blueprint Frames after interaction with the user to support adaptive configuration in exceptional or novel circumstances.
6. Decision Traceability & Audit Trail Visualization	Offers historical logs of human decisions, interactions, overrides, and validations for compliance, accountability, and trust-building.

Table 5 provides an overview of key tool-user interaction patterns within the NARRATE architecture, emphasizing how different system components engage with users through a Human-in-the-Loop (HITL) interface. It illustrates the critical role of human oversight, °, NARRATE ensures that automated intelligence is always subject to human review, configuration, and contextual override. This tight coupling between human reasoning and AI automation enables an AI-based system that is not only powerful and predictive, but also transparent, accountable, and adaptable in the face of unforeseen circumstances.

4 REFERENCES

[1] Papazoglou, M.P., Heuvel, W.J.V.D., Mascolo, J.E., 2015. A reference architecture and knowledge-based structures for smart manufacturing networks. IEEE Software, 32 (3), May-June 2015, pp. 61–69.

[2] Pedone, G., Mezgár, I., 2018. Model similarity evidence and interoperability affinity in cloud-ready industry 4.0 technologies. Computers in Industry. vol. 100, September 2018, pp. 278–286.

[3] IEC PAS 63088: 2017. Smart Manufacturing–Reference Architecture Model Industry 4.0 (RAMI4. 0), International Electrotechnical Commission - IEC, Geneva, 2017

[4] Industrial Internet Reference Architecture, https://www.iiconsortium.org/iira/.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORIZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation
UK Research and Innovation, Horizon Europe Guarantee.

[5] Kruchten, P. (1995). Architectural blueprints—The "4+1" view model of software architecture. IEEE Software, 12(6), November 1995, pp. 42–50.

[6] Lu, Y., Morris, K. C., & Frechette, S. (2016). Current standards landscape for smart manufacturing systems (NISTIR 8107). National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/ir/2016/NIST.IR.8107.pdf.

[7] https://opcfoundation.org/

[8] Vaswani, A. et. al. (December 2017). "Attention is All you Need". In I. Guyon and U. Von Luxburg and S. Bengio and H. Wallach and R. Fergus and S. Vishwanathan and R. Garnett (ed.). 31st Conference on Neural Information Processing Systems (NIPS). Advances in Neural Information Processing Systems. Vol. 30.

Funded by the European Union

Funded by the European Union under GA No 101138094. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. • Grant Agreement No.: 101138094
Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

UK Research and Innovation

UK Research and Innovation, Horizon Europe Guarantee.