NARRATE

Regenerative Resilient Smart Manufacturing Networks

D3.4 Automated Workflows and Production Process Orchestration (a)

2025/11/27

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D3.4 AUTOMATED WORKFLOWS AND PRODUCTION PROCESS ORCHESTRATION (A)

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Abstract	This deliverable presents methods and results for the modularised creation and orchestration of Digital Twins in Smart Manufacturing Networks. It details approaches for standards-based integration and transparent process mapping. The report demonstrates how Digital Twins enable flexible, scalable, and resilient production workflows, serving as a foundation for data-driven optimisation and sustainable operations in interconnected industrial environments.
Keywords	Manufacturing as a Service; Digital Twins; Process Orchestration; Smart Manufacturing Networks; Data Integration; Interoperability; Production Process Automation

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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.

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Abbreviations

AAS	Asset Administration Shell
AI	Artificial Intelligence
API	Application Programming Interface
AGV	Automated Guided Vehicle
BIM	Building Information Modelling
BMS	Blueprint Management System
CNC	Computer Numerical Control
CRM	Customer Relationship Management
DEC	Dissemination, Exploitation, Communication
DEM	Demonstrator (EU Deliverable Type)
DT/DTs	Digital Twin(s)
DTO	Data Transfer Object
DTPL	Digital Twin Processing Language
EC	European Commission
ERP	Enterprise Resource Planning
ETL	Extract, Transform, Load
FDIF	Federated Data Integration Framework
GIS	Geographic Information System
IEC	International Electrotechnical Commission
IoT	Internet of Things
IMC	Intelligent Manufacturing Custodian
ISO	International Standardisation for Organisation
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LCM	Life Cycle Management
MaaS	Manufacturing-as-a-Service
MES	Manufacturing Execution System
NSQA	Neuro-Symbolic Question Answering

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OPC UA	Open Platform Communications Unified Architecture
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
PU	Public (EU Deliverable Nature)
REST	Representational State Transfer (API)
RPA	Robotic Process Automation
SCM	Supply Chain Management
SMN	Smart Manufacturing Network

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EXECUTIVE SUMMARY

This deliverable explores how the adoption of Digital Twins can transform production networks and enable smarter manufacturing practices. It presents a comprehensive approach to modelling, synchronising, and managing manufacturing resources through digital representations, laying the groundwork for greater flexibility, transparency, and reliability in industrial operations.

By focusing on modular, structured approaches to representing real-world entities and processes, the report explores how manufacturing can become more agile and responsive to internal and external changes. The Digital Twin concept provides a unified view of physical assets, workflows, materials, and logistics, supporting continuous improvement and enabling more effective decision-making at all levels of production.

Throughout the deliverable, emphasis is placed on achieving consistency and quality throughout the entire lifecycle of products and manufacturing processes. The approach enables manufacturers to analyse their operations virtually, anticipate disruptions, and optimise process flows. This not only facilitates resource-efficient production and improves resilience but also supports broader sustainability and compliance goals relevant to modern industry.

Collaboration and integration across organisational boundaries are central components of the presented orchestration strategies. By leveraging standardised data exchange and shared models, different stakeholders and systems can work together seamlessly, fostering innovation and streamlining communication from initial product design to final delivery.

Looking ahead, the deliverable outlines how these foundations will be extended in future project stages, enabling even broader control and lifecycle management of innovative manufacturing environments. The findings contribute valuable conceptual, methodological, and practical insights for companies seeking to modernise their production systems, improve competitiveness, and move confidently toward sustainable, data-driven manufacturing.

This summary provides a high-level view of the deliverable's aims and contributions, focusing on the systemic benefits, conceptual advances, and implications for industry rather than technical or project-specific details.

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1. INTRODUCTION

Digital Twins are the foundation for enabling efficient, flexible, and resilient automated workflows throughout the entire value chain. A significant challenge lies not only in creating static digital representations of individual production stages, but in developing dynamic, modular, and continuously updated Digital Twins that can be directly applied to workflow automation and production process control.

Several issues characterise the path toward practical use of Digital Twins in process automation: On one hand, interoperability and visibility are often lacking because Digital Twins are typically created in proprietary formats and cannot be directly integrated with other IT systems in value networks. On the other hand, companies require the ability to programmatically describe, simulate, and orchestrate production resources and scenarios, a capability that traditional digital models still struggle to deliver effectively.

The NARRATE project, with its blueprint framework as developed in D3.2a [1]. It takes a novel approach: it structures and standardises Digital Twins for products, processes, logistics chains, and machines based on the principles of modularisation and separation of concerns. Each blueprint represents a clearly defined, reusable component of the overall digital model. In combination with the Digital Twin Processing Language (DTPL), a flexible and programmable environment is created, which allows modelling of production flows in real time, integration of shopfloor and external partner data, and automation of adaptive, AI-supported decision processes

A key focus of Deliverable D3.4a is the lifecycle management of Digital Twins within Smart Manufacturing Networks. While the orchestration and automation of workflows will be addressed in the subsequent Deliverable D3.4b, D3.4a prioritises setting up the foundational mechanisms to reliably manage Digital Twins as the basic building blocks for later automation. Since manual creation of Digital Twins is often error-prone and inconsistent, D3.4a will also introduce a tool to automate the Digital Twin generation process. This tool aims to ensure standardised, accurate, and efficient creation of Digital Twins, reducing the risks and inefficiencies associated with manual efforts and paving the way for robust and resilient workflow automation in the following project stage.

1.1. PURPOSE OF THE DOCUMENT

The purpose of this document is to present, analyse, and contextualise the results and methodologies developed for modular Digital Twin creation and process orchestration within Smart Manufacturing Networks. By outlining the project's objectives, approaches, and key findings, this document facilitates understanding and implementation of Digital Twin strategies to improve coordination, lifecycle management, and sustainable operations across diverse manufacturing environments.

1.2. DOCUMENT STRUCTURE

The document is organised to guide through the conceptual foundations, technical approaches, and application of Digital Twins for orchestration in Smart Manufacturing Networks. It begins with an introduction outlining the document's objectives and overall context. The technical and conceptual background chapter provides a review of key terms, state-of-the-art developments, and major requirements for production process orchestration. This is followed by detailed sections on the integration of the proposed

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concepts into the broader architecture of Smart Manufacturing Networks, including descriptions of the underlying frameworks and interfaces.

Subsequent chapters explain the methodological approaches for creating Digital Twins, managing their lifecycles, and orchestrating workflows, supplemented by use case descriptions and requirements analysis. An implementation section presents real-world validation, including system architecture, solutions for data extraction and validation, and the integration of dashboards for process transparency. Finally, the document concludes with a comprehensive discussion of findings, a summary of main results, and an outlook for future research and practical applications.

1.3. OBJECTIVES

The objective "O3.4: Create automated workflows for production from the confirmation of the order up to the delivery of the product that foster resilience and environmental sustainability" is addressed in this deliverable by defining, modelling, and validating digital-based production processes that span the entire lifecycle from order acceptance to product shipment. Throughout the report, Digital Twins are used as dynamic representations of products, resources, and workflows, enabling seamless orchestration, automated monitoring, and data-driven optimisation. The deliverable documents how these digital workflows contribute to resilient process execution, improved anticipation and management of disruptions, and enhanced resource efficiency. Environmental sustainability is supported via ongoing transparency into energy and material flows, allowing the identification and reduction of waste and emissions. By making production systems more adaptable and transparent, the deliverable demonstrates how NARRATE advances the goal of future-proof, sustainable manufacturing practices in real-world scenarios.

2. TECHNICAL AND CONCEPTUAL BACKGROUND

Chapter 2 introduces the technical and conceptual background of the deliverable. It begins by clarifying the terminology and relevant theoretical foundations for Digital Twins and process orchestration. The following sections provide a synthesis of the current state of the art, including a review of literature and best practices in both research and industry. The chapter also examines key requirements such as transparency, interoperability, automation, modularity, and process modelling, which are critical for orchestrating efficient and resilient production processes. Standards and typical challenges in smart manufacturing environments are addressed to contextualise the methodological and practical decisions outlined in subsequent chapters. The goal is to establish the broader context and framework within which the solutions and results of the deliverable are developed and validated.

2.1. REFLECTION OF STATE OF THE ART

A Digital Twin in the context of the NARRATE project can be described as a continuously updating, data-driven virtual replica of an entity that integrates diverse data sources such as sensor, process, environmental, and expert information to mirror real-world conditions in real time. Serving as a single source of truth, it enables simulation, analysis, and AI-driven insights to predict, compare, and optimise performance across systems and environments. In manufacturing networks Digital Twins evolve from replicas of single assets into federated, multi-scale twins that represent not only equipment, but also processes, products, and inter-organisation flows [2].

In the NARRATE project, blueprints (or blueprint frames) are programmable Digital Twin models that act as precise, modular digital representations of key manufacturing elements such as suppliers, machines, sensors, products, processes, and entire supply chains. They continuously integrate data from various systems (e.g., PLM, ERP, IoT) to create an interconnected digital ecosystem. Used within a Smart Manufacturing Network (SMN), these blueprints enable real-time monitoring, simulation, and optimisation of operations, supporting dynamic reconfiguration, Manufacturing-as-a-Service (MaaS) models, and improved agility and resilience. By structuring Digital Twins into domain-specific yet connected components, NARRATE's blueprint framework provides a holistic, adaptive, and data-driven foundation for intelligent, self-orchestrated manufacturing networks [1].

2.1.1. Process orchestration

Process orchestration or better known as business process orchestration is a coordinated approach to managing and aligning multiple automated tasks, systems, and workflows across an organisation to achieve defined outcomes. It extends beyond simple task automation by providing an end-to-end view of entire business processes, ensuring that activities across departments, applications, and data sources operate seamlessly. Through orchestration, organisations gain transparency, traceability, and control over how processes execute, enabling them to identify bottlenecks, improve decision-making, and enhance overall performance [3]. In traditional IT and business environments, process orchestration acts as the control layer between different automation technologies. It integrates systems such as ERP, CRM, HR, and data platforms to ensure smooth data and task flow. Typical orchestration platforms manage workflows like order-to-cash, procure-to-pay, and ETL data pipelines by coordinating activities such as data ingestion, quality checks, and approvals. Compared to robotic process automation (RPA), which focuses on automating discrete actions, orchestration ensures that these actions are sequenced, monitored, and governed within a resilient workflow. The result is a holistic automation strategy that combines workflow automation, system integration, collaboration, visibility, and analytics into a unified operational framework [4].

Modern process orchestration spans several domains, such as data orchestration, service orchestration, cloud orchestration, and security orchestration, where each is leveraging APIs, event-driven triggers, and containerised services. These orchestrators form the backbone of enterprise digital transformation, ensuring interoperability and continuous optimisation. Advanced systems now integrate AI-driven analytics and machine learning to enable adaptive orchestration, where processes reconfigure themselves based on workload, risk, or performance metrics. This evolution marks a shift from static workflow management toward self-optimising, intelligent operations [5]. In modern smart manufacturing, orchestration allows multiple Digital Twins representing machines, processes, and logistics to operate in concert. Each twin acts as a node within a larger cyber-physical network. This is particularly relevant in flexible manufacturing systems, where the ability to adapt and reconfigure production cells using Digital Twins reduces downtime and accelerates commissioning.

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2.1.2. Process Orchestration in the Context of Digital Twins

In the era of Industry 4.0 and cyber-physical systems, process orchestration has become a critical enabler for effective Digital Twins. While traditional orchestration coordinates software workflows, Digital Twin orchestration coordinates the interaction between physical and digital domains to maintain accuracy, consistency, and real-time responsiveness across manufacturing or service environments. In a smart manufacturing cell, for example, multiple twins representing robots, machines, conveyors, and inspection systems must operate in concert. Orchestration aligns data streams and control commands so that a change in one element (e.g., an AGV's path) automatically triggers corresponding updates in others (e.g., quality-control or logistics twins). Research such shows that multi-level orchestration, categorised by frequency of change (high-frequency sensor data, medium-frequency configurations, low-frequency structural redesigns), reduces downtime and accelerates reconfiguration [6].

Modern frameworks, including those defined in ISO 23247 [7], describe how DT orchestration integrates data acquisition, analytics, and simulation to create closed-loop control systems. Synchronisation patterns (time-driven, event-driven, hybrid) ensure that digital models remain aligned with real-world behaviour. In large-scale contexts such as smart cities, orchestration governs the interaction of heterogeneous twins (BIM, GIS, and IoT models) to optimise energy, mobility, and infrastructure operations. The current state of the art thus positions process orchestration as the central nerve system of Digital Twin ecosystems. It combines real-time data integration, semantic interoperability, and adaptive control to create systems that are not merely automated, but self-coordinating and self-optimising. As AI, edge computing, and standardisation mature, digital-twin-enabled orchestration will evolve from managing isolated workflows to orchestrating entire cyber-physical ecosystems that operate autonomously, transparently, and intelligently across their full life cycles.

2.1.3. Life Cycle Management of Digital Twins

Life Cycle Management (LCM) of Digital Twins extends the traditional paradigm of Product Life-Cycle Management (PLM) to include not only the physical artefact but also its continuously evolving digital representation. A Digital Twin must evolve in synchrony with its physical counterpart from initial creation and calibration, through operation and adaptation, to decommissioning or replacement. Where PLM manages tangible products, LCM of Digital Twins focuses on the sustained accuracy, traceability, and adaptability of the digital entity across its operational life.

According to ISO 23247, the life cycle of a Digital Twin involves maintaining data integrity, synchronisation, granularity, and security throughout its existence [8]. Continuous alignment between the physical asset and its digital reflection is essential to guarantee trustworthy analytics, simulation, and decision support. However, most standards and industrial practices still emphasise the product's life cycle, not the Digital Twin's own evolution. Their proposed life-cycle meta-layer fills this gap by introducing hierarchical abstraction levels that manage re-instantiation, versioning, and data migration when physical changes occur, ensuring that new twin versions remain compatible with preceding generations while preserving historical data.

In practical manufacturing environments, this means that when a machine tool is upgraded, its associated Digital Twin can be automatically re-instantiated with the new

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configuration and linked to previous performance data. This capability enhances traceability and allows knowledge from earlier configurations to inform the optimisation of future ones. Building on this idea, Dietz et al. [9] propose a data-driven digital-twin creation framework structured in four iterative stages that effectively mirror the twin's own life cycle:

- Condition determination: Definition of objectives, operational boundaries, and data requirements
- Acquisition: Collection of high-fidelity data via sensors, IoT, and enterprise information systems
- Processing and modelling: Transformation of raw data into functional models using AI, machine learning, or physics-based simulation
- Application and adaptation: Deployment, continuous monitoring, feedback incorporation, and refinement of the model over time

This iterative model allows for dynamic regeneration. Each new dataset or system update automatically improves the accuracy and relevance of the Digital Twin. Such adaptive LCM establishes a closed learning loop between design, operation, and optimisation.

An essential complement to LCM is the digital thread, a concept emphasised in the ISO 23247 series [10]. The digital thread represents the information backbone that interconnects multiple Digital Twins of the same asset or system across its distinct life-cycle stages. Rather than existing as isolated models such as a Design Twin, Engineering Twin, Manufacturing Twin, and Operational Twin, these representations are linked through a continuous data thread.

The digital thread ensures that information flows bidirectionally between stages:

- Insights from operational performance feedback to design and engineering for continuous improvement
- Engineering changes are propagated forward to manufacturing and maintenance
- Traceability across these transitions guarantees that every configuration and decision remain contextually anchored to its predecessors.

In practice, this means that a turbine's design-stage twin informs its engineering twin during structural analysis; the manufacturing twin uses the same core data to manage assembly tolerances; and the operational twin later uses sensor feedback to propose design refinements. The digital thread therefore acts as the unifying data fabric across all life-cycle instances, enabling knowledge continuity and cross-stage optimisation.

2.1.4. Standards

Standards form the foundation of interoperable and orchestrated Digital Twin (DT) ecosystems. They provide the common language, architecture, and data exchange protocols needed to integrate heterogeneous assets, systems, and life-cycle stages within smart manufacturing networks. The ISO 23247 series is the central framework for Digital Twins in manufacturing. It defines how DTs represent and interact with physical systems, covering general principles (Part 1), reference architecture and attributes (Parts 2–4), and the digital thread (Part 5) which links DTs across design, engineering, and

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operational stages to ensure continuous information flow and traceability. Part 6 extends this toward the composition and orchestration of multiple DTs. These standards together enable synchronised, hierarchical control and seamless reconfiguration of production systems. ISO 21597 complements this by specifying a containerised data exchange format (ICDD), allowing structured and traceable data transfer between DTs and life-cycle systems such as PLM, MES, and ERP. Similarly, ITU-T Y.3090 provides a three-layer Digital Twin network architecture that supports closed-loop, real-time communication crucial for orchestrating distributed DTs and industrial IoT environments [11].

2.1.5. AI-powered and Adaptive Orchestration

Artificial Intelligence (AI) enables autonomous and adaptive orchestration of Digital Twins by processing real-time data and learning from system dynamics to optimise operations. Attaran & Celik [2] highlight AI as one of the four core enabling technologies for DTs alongside IoT, cloud computing, and extended reality driving their analytical and predictive capabilities. AI supports:

- Predictive maintenance: Anticipating equipment failures before they occur
- Adaptive control: Optimising process parameters in real time
- Decision support: Guiding complex multi-agent systems through reinforcement learning

Han et al. [12] extend this to a hierarchical AI-driven synchronisation framework in the Metaverse, where IoT-assisted Digital Twins interact through evolutionary and differential game theory models. This structure allows Digital Twins to autonomously adjust synchronisation intensity, balancing accuracy and cost across multiple service providers. In manufacturing, adaptive orchestration enables production systems to self-organise in response to disruptions, while in smart cities, AI ensures resilience by dynamically reallocating resources (e.g., traffic flow, energy grids) based on DT feedback loops. AI-powered orchestration thus transforms DT ecosystems from reactive to proactive and self-optimising, moving toward the vision of autonomous cyber-physical intelligence.

2.1.6. Challenges

Despite significant progress, several technical and organisational challenges remain:

- Data interoperability: Heterogeneous data formats and schemas hinder seamless integration between twins (BIM, GIS, IoT, PLM).
- Scalability: As shown by Jin et al. [13], large-scale DTs such as city-level twins demand lightweight models to manage data complexity and ensure real-time responsiveness.
- Synchronisation accuracy: Maintaining high fidelity between physical and digital states is computationally intensive, especially in real-time, high-frequency systems.
- Security and trust: As DTs exchange sensitive data across cloud infrastructures, cybersecurity and access control become critical.
- Human–machine collaboration: Effective orchestration requires balancing automated decision-making with human interpretability and ethical oversight.
- Lifecycle sustainability: Long-term maintenance of DTs demands standardised methods for archiving, updating, and decommissioning legacy digital assets.

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2.1.7. Research Gaps

Across the literature and standards, key research gaps persist:

- Holistic orchestration frameworks: Few studies offer end-to-end orchestration models encompassing lifecycle management, AI-based adaptation, and cross-domain interoperability.
- Standard harmonisation: Integration between ISO, IEC, ITU, and Industry 4.0 standards remains fragmented, limiting interoperability across industries.
- Dynamic lifecycle governance: Current approaches seldom address automated lifecycle evolution of Digital Twins, particularly version control, traceability, and long-term data migration.
- Real-time performance guarantees: Synchronisation models often lack formal verification methods for latency, consistency, and quality-of-service.
- Ethical and societal considerations: AI-driven orchestration introduces new governance questions around accountability, transparency, and data ownership.
- Scalable lightweighting**:** While promising, lightweight Digital Twin models for cities or factories still struggle to retain semantic richness without compromising performance.

2.1.8. Conclusion

The state-of-the-art reveals that Digital Twin orchestration is transitioning from isolated simulations to fully integrated, intelligent ecosystems. Guided by standards such as ISO 23247 and enabled by AI, IoT, and cloud computing, Digital Twins now form the operational backbone of cyber-physical infrastructures across manufacturing, healthcare, and urban management. Future research should aim to unify lifecycle management, orchestration patterns, and AI-driven adaptability within a standardised and scalable framework. The convergence of ISO-based interoperability, real-time synchronisation, and intelligent orchestration will define the next generation of autonomous, resilient, and sustainable digital ecosystems.

2.2. REQUIREMENT FOR PRODUCTION PROCESS ORCHESTRATION

The successful orchestration of production processes within Digital Twin environments depends on fulfilling several core requirements. These requirements ensure that the physical and digital systems are connected, interoperable, and capable of autonomous decision-making across their life cycles. The following subsections outline the key prerequisites for effective production process orchestration.

2.2.1. Transparency and traceability

Transparency and traceability are foundational to orchestrated manufacturing systems. They enable end-to-end visibility across all production stages and ensure that decisions made by Digital Twins are both explainable and auditable.

- A transparent orchestration framework allows stakeholders to understand process states, data origins, and decision logic in real time

- Traceability, on the other hand, ensures that every physical event, machine action, and data update is recorded and linked to its corresponding Digital Twin entity.

According to ISO 23247, traceability is essential for process and part lineage tracking, enabling continuous monitoring of materials, equipment, and workflows across their life cycles. In practice, this is achieved through synchronised data streams and event logs that capture the state of observable manufacturing elements such as robots, machine tools, and automated guided vehicles. This transparency is not only critical for quality control and regulatory compliance, but also for enabling adaptive decision-making where Digital Twins can analyse historical data to optimise process performance dynamically.

2.2.2. Interoperability

Interoperability refers to the ability of heterogeneous systems, devices, and software components to communicate, exchange, and interpret data consistently.

- In orchestrated Digital Twin ecosystems, interoperability is achieved through standardised interfaces and data models that connect different layers of the production hierarchy from shop-floor sensors to enterprise-level planning systems (MES, ERP, PLM).

Standards such as ISO 23247, ITU-T Y.3090, and the Asset Administration Shell (AAS) define frameworks for ensuring that data semantics and exchange protocols are uniform across different vendor systems. This interoperability allows Digital Twins of machines, processes, and logistics to collaborate in real time, facilitating multi-twin orchestration. For example, in a flexible manufacturing cell, interoperable Digital Twins can align machining operations, robot trajectories, and tool management systems under a shared communication layer. Such integration minimises downtime and supports continuous reconfiguration when product variants or process parameters change.

2.2.3. Degree of automation

The degree of automation determines how effectively Digital Twins can act autonomously within the orchestrated production environment. Automation in DT orchestration ranges from rule-based control to AI-driven decision-making, where systems learn and adapt dynamically.

- Higher automation levels enable Digital Twins to autonomously monitor, predict, and optimise production performance without constant human intervention.
- This requires robust integration of Industrial IoT, AI algorithms, and machine learning models capable of processing high-frequency data from sensors and control systems.

For instance, predictive maintenance in an automated DT framework allows a machine twin to detect anomalies and trigger orchestrated responses such as scheduling repairs or adjusting production rates without interrupting the entire line. Increasing the degree of automation thus directly enhances productivity, consistency, and responsiveness in smart manufacturing.

2.2.4. Modularity and flexibility

Modularity and flexibility are prerequisites for managing frequent reconfigurations in high-mix, low-volume production environments.

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- Digital Twins must represent systems as modular, interoperable components, enabling selective updates and re-instantiation when changes occur in the physical layer.

Wallner et al. [6] emphasize that modular Digital Twin architectures simplify cell reconfiguration, allowing independent replacement or scaling of machines, tools, or software services without system-wide downtime. Flexible orchestration also supports dynamic task allocation, where resources can be reassigned in real time based on performance data or changing production goals. A modular approach promotes reusability of twin components and ensures scalability. Both are essential for adaptive manufacturing ecosystems that must evolve rapidly in response to demand volatility or supply chain disruptions.

2.2.5. Process mapping and modelling

Accurate process mapping and modelling provide the structural foundation for Digital Twin orchestration.

- They involve identifying, abstracting, and formalising all elements of a production process, such as workflows, material flows, dependencies, and constraints, into a coherent digital representation.
- Process mapping ensures that each operation, from order initiation to product delivery, is captured and visualised in the digital environment.

This enables simulation, optimisation, and real-time synchronisation between physical and digital processes. Model-based orchestration relies on hierarchical process models that link low-level operational data (e.g., sensor readings, equipment states) with high-level decision processes (e.g., scheduling, resource planning). For example, in additive manufacturing, process models can simulate temperature gradients, tool paths, and energy consumption, while orchestration mechanisms adjust real-time control parameters to ensure product quality and resource efficiency. Comprehensive process modelling thus enables predictive analytics, closed-loop control, and cross-domain coordination within Digital Twin ecosystems.

2.2.6. Standardisation

Standardisation ensures consistency, interoperability, and scalability across the Digital Twin ecosystem. It provides common reference architectures, terminologies, and communication protocols, allowing different systems and vendors to collaborate seamlessly. Through standardisation, Digital Twins can integrate data and functionality across enterprise systems (ERP, MES, PLM) and shop-floor automation (CNC, PLC). Moreover, standards facilitate benchmarking, validation, and certification of Digital Twin implementations, ensuring that orchestration remains reliable, secure, and compliant across industries. By adhering to international standards, production systems can achieve cross-domain orchestration, enabling collaborative manufacturing networks and digital supply chains that transcend organisational boundaries.

2.3. DIGITAL TWIN SYNCHRONISATION PATTERNS

A central question in the deployment of DTs for manufacturing and industrial applications is whether all relevant system and process data should always be mapped into and maintained within Digital Twins (comprehensive or "full" mapping), or whether data

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should be represented situationally, only when required for specific use cases, operational triggers, or decision contexts (selective or event-driven mapping).

2.3.1. Full Data Mapping Approach

Comprehensive mapping seeks to persistently ingest and maintain the maximum amount of available system data within the DT, ideally always capturing the entire state of the physical asset or system. Proponents argue that this approach allows for a "true" virtual representation, enabling deep analytics, predictive maintenance, and broad-ranging simulation scenarios [2, 14]. The benefits are seen in applications where historical tracking, forensic analysis, and complex "what-if" scenarios require access to the full information context.

However, persistent full mapping comes at the cost of massive data volumes, infrastructure demands, and significant data management complexity. Ouedraogo et al. [15] identify that "the infrastructure required to constantly process and update large volumes of data from multiple sensors is complex and demands substantial computational and storage resources". Similar concerns are noted in Lin et al. [16], who argue that "resource usage scales poorly with update rates and object counts," leading to scalability bottlenecks and increased likelihood of data synchronisation errors.

2.3.2. Situational or Event-Driven Data Mapping

Selective or context-driven data mapping, by contrast, advocates for populating the Digital Twin only with those data points relevant to the current process, decision, or operational scenario. Industrially grounded research by Dietz et al. [9] demonstrates this approach in the context of special engineering and manufacturing: While Digital Twins, in theory, can represent all operational and sensor data, practitioners highlight scalability and integration manageability as key determinants. Experts from German manufacturing firms caution that "maintaining a persistently updated, complete Digital Twin for all assets creates prohibitive demands on data management and IT infrastructure." Instead, they recommend event-driven or use-case-focused mapping as an effective balance: only data needed for maintenance forecasting, process optimisation, or disturbance response is integrated at runtime. According to Alghamdi and Albassam [17], synchronisation strategies for DTs can be "time-driven, event-driven, hybrid, or adaptive, with event-driven updates conserving bandwidth and resources, especially during periods where no significant change occurs". Jin et al. [13] further document lightweighting strategies for DT information models, which reduce computational burden while maintaining functional accuracy for most operational decisions. This perspective is reinforced in industrial-scale Digital Twin deployments, where updating all data in real time is neither practical nor necessary for many use cases [15, 18].

Situational mapping is particularly advantageous in dynamic, distributed, or resource-constrained environments: it allows for rapid scaling, easier integration, and more agile data management. It also mitigates quality risks associated with "garbage in, garbage out" when poor-quality or stale data is unnecessarily ingested. Critically, modern DT architectures now leverage adaptive schemes, where data ingestion is prioritised based on real-time triggers, thresholds, or detected anomalies [12].

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2.3.3. Scientific Evaluation and Recommendation

Contemporary research and advanced industrial practice favour a hybrid, adaptive approach that combines the strengths of both paradigms. While complete data mapping is superior for simulation-rich, forensic, and regulatory applications, situational/event-driven mapping offers compelling efficiency and operational viability for most day-to-day manufacturing scenarios [13, 14]. Industrial guidelines and leading DT platforms explicitly advocate for context-aware, use-case-driven data mapping to ensure resource efficiency, scalability, and system resilience.

3. INTEGRATION INTO SMN-ARCHITECTURE

Smart Manufacturing Networks (SMNs) represent a fundamental evolution of industrial production systems by integrating advanced digital technologies, Cyber-Physical Systems, and artificial intelligence. According to the International Telecommunication Union (ITU), SMNs are defined as "manufacturing systems that utilise data-driven approaches to meet the changing demands and requirements of customers and markets" [19]. These systems are characterised by collaborative, fully integrated, and responsive manufacturing operations capable of dynamically adapting to changing market conditions.

The evolution toward fully integrated, intelligent manufacturing ecosystems positions SMNs as the essential infrastructure for delivering the seamless orchestration, real-time adaptability, and sustainable operations that characterise advanced smart manufacturing implementations.

3.1. DESCRIPTION OF THE SMN ARCHITECTURE IN RELATION TO PRODUCTION PROCESS GENERATION

The NARRATE Smart Manufacturing Network (SMN) is a sophisticated cyber-physical system architecture that enables autonomous, adaptive, and resilient manufacturing operations by integrating advanced digital technologies and intelligent orchestration mechanisms. The system architecture (Figure 1) comprises several interconnected components that collectively provide the foundation for Manufacturing-as-a-Service (MaaS) capabilities and dynamic production process orchestration.

The Intelligent Manufacturing Custodian (IMC) functions as the central hub, coordinating all system interactions and serving as the primary decision-making entity through its AI-enhanced capabilities. Connected directly to the IMC is the Neuro-Symbolic Question Answering (NSQA) system, which enables natural language interaction between pilot users and the manufacturing network, allowing for intuitive human-machine communication.

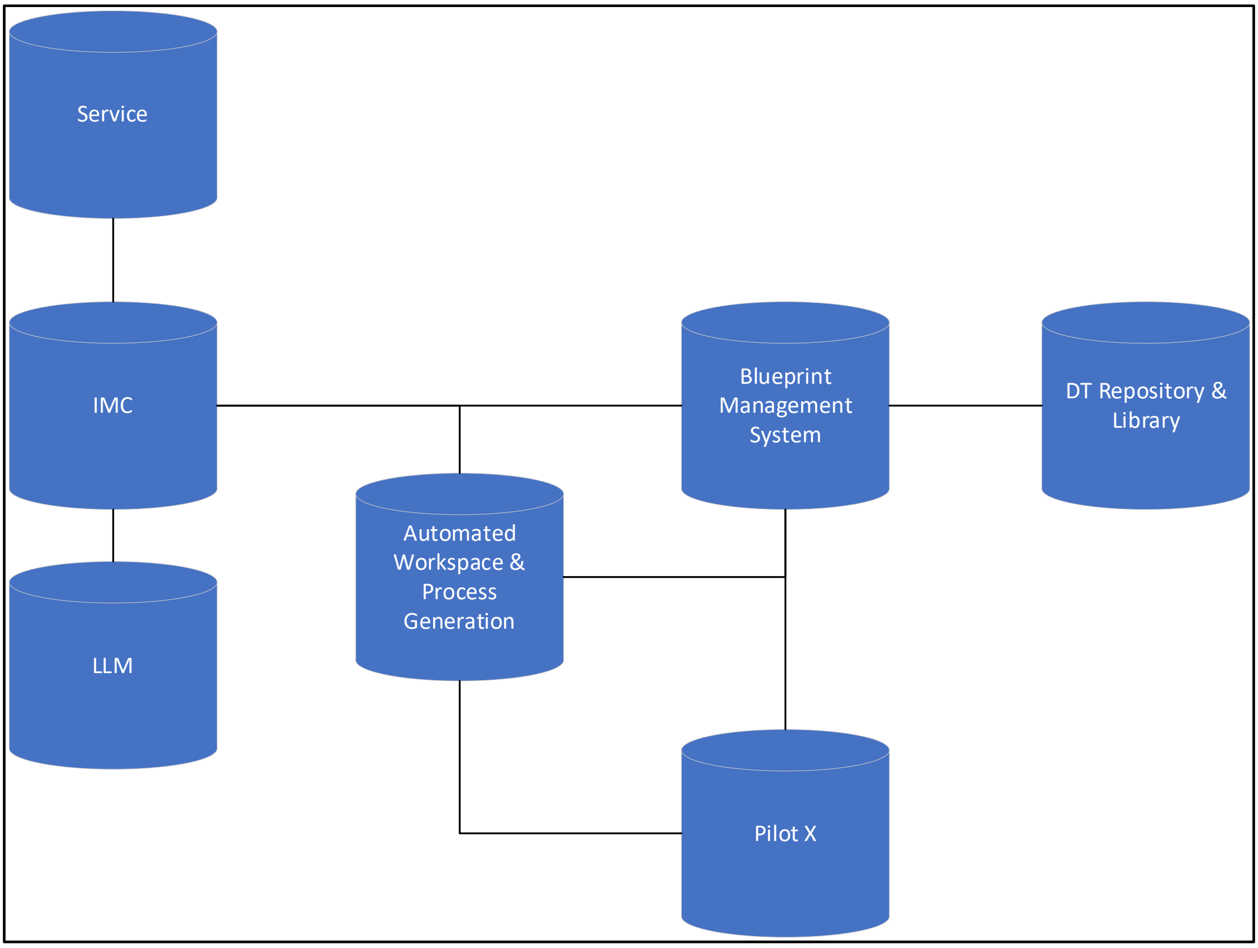

FIGURE 1: CORE COMPONENTS OF THE NARRATE ARCHITECTURE, BASED ON [12]

Supporting the core orchestration capabilities are several specialised Building Blocks, including "Production Planning & Process Routing System & Algorithmic Reconfiguration of Production" that provides intelligent production planning algorithms, "Intelligent Logistics and Warehousing modules" that optimise supply chain and inventory management, and "End-to-end AI-driven Visibility Platform and support DSS" that delivers comprehensive visibility and decision support across the manufacturing.

The system architecture also incorporates "Resilience Strategy Tool, Risk Identification and Monitoring Tool, and Supplier and SMN Risk Assessment Tool", which provides comprehensive risk management and resilience capabilities through complex event processing and stress testing functionalities.

The Digital Twin Repository and Library is the central component of data management and contains various blueprint types. Examples include the following:

- the Production Plan Blueprint, which manages assembly sequences and production processes,
- the Product Blueprint, which stores information on product families and material definitions,
- and the Providers Blueprint, which manages data on suppliers and partner networks. These blueprints are managed across various systems.

Requests can be sent directly from the IMC or managed via Automated Workflows and Production Process Orchestration. This system serves as an execution engine for translating digital representations of the most diverse corporate resources into actionable manufacturing processes. In addition, this system can be used to initially create DTs based on specific use cases and modify them later in the lifecycle.

This integrated architecture enables the NARRATE system to function as a self-orchestrating intelligent manufacturing ecosystem, where pilot users can interact through intuitive interfaces while the system automatically manages complex production workflows, adapts to changing conditions, and optimises performance across multiple organisational boundaries through its federated approach to smart manufacturing operations.

3.1.1. Use of blueprints

The NARRATE SMN architecture centres on the seamless integration of Blueprint Frames to enable the dynamic orchestration of production processes. This integration operates through three core mechanisms that transform individual Digital Twin components into coordinated manufacturing workflows.

Blueprints in the NARRATE project (Figure 2) are modular digital representations or "frames" that serve as the structural foundation for modelling and orchestrating all key elements of a SMN. Each blueprint defines and encapsulates a specific aspect of the production ecosystem, such as suppliers, manufacturing processes, logistics, products, sensor data, quality, or sustainability, using up-to-date data from a wide variety of sources, including IoT sensors, ERP, MES, and supply chain systems.

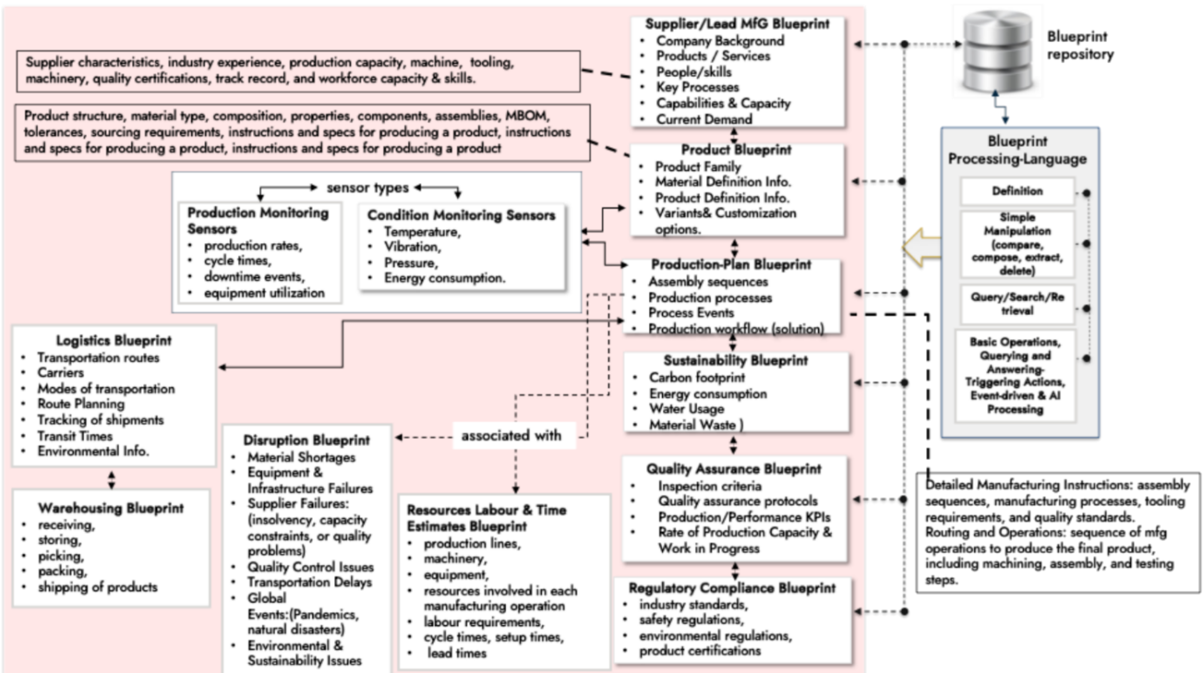

FIGURE 2: BLUEPRINTS IN A SMART MANUFACTURING NETWORK [12]

Functionally, blueprints provide standardised, actionable building blocks that can be combined and dynamically reconfigured to reflect the current state and needs of the manufacturing network. They enable the continuous monitoring and real-time control of physical processes by mirroring equipment status, inventory, material flows, and even disruptions. Through this approach, blueprints form a multi-dimensional Digital Twin layer, with each frame delivering a distinct, interoperable perspective of the network, ensuring

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holistic visibility, rapid adaptation, and semantic consistency across production, suppliers, and logistics.

Technically, blueprints are integrated in the Blueprint Management System (BMS), which supports the lifecycle operations (creation, update, composition, deletion, and retrieval) of each frame and synchronises them with live data streams. The NARRATE Digital Twin Processing Language (DTPL) acts as the programmable interface layer, enabling both automated orchestration and context-aware reasoning by the system and its human operators.

In summary, blueprints in NARRATE enable the modelling, real-time management, and intelligent orchestration of all relevant entities and processes within a Smart Manufacturing Network.

3.1.2. Interface description

Within the NARRATE project, a significant challenge arises because the used ERP system provides only a REST API for data access. However, this REST API is not directly compatible with the interface specifications defined in the Federated Data Integration Framework (FDIF) as described in Deliverable D3.1(a) [20]. The FDIF relies on semantically rich and standardised protocols for data ingestion and communication, which differ in format and structural requirements from the ERP's REST API responses.

This incompatibility means that the ERP data cannot be ingested directly into the FDIF or into the Blueprint frames without additional transformation. To address this, the project developed a dedicated middleware tool designed specifically to act as a data translation and integration bridge. This tool reads operational and transactional data from the ERP system according to the requirements derived from the use case and mapped user stories. It then transforms the extracted data into the required formats and semantic structures compliant with FDIF specifications and the internal schema of the Blueprint framework.

By enabling this seamless conversion, the tool ensures that ERP-derived information, such as inventory levels, production orders, and supplier status, is accurate and timely represented within the SMN's Digital Twin ecosystem. This mechanism is critical for maintaining the consistency and synchronisation of operational data across the network and for enabling automated decision-making and process orchestration based on reliable, up-to-date information sourced from existing enterprise systems.

In summary, the development of this ERP data adapter mitigates the interface incompatibility challenge, providing a robust and scalable integration point that enhances the fidelity and effectiveness of blueprint orchestration to support NARRATE's manufacturing use cases.

4. CONCEPT

Production Process Orchestration forms a part of intelligent manufacturing control in Smart Manufacturing Networks (SMNs). It represents the coordinated and adaptive management of multi-stakeholder manufacturing processes, with a typical example being the entire production chain from order confirmation through product delivery. Within the NARRATE context, this orchestration is realised through the innovative Blueprint Frame system, which provides Digital Twins of all critical manufacturing components in a

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structured, modular form.

The orchestration functions through the dynamic creation and linking of Blueprint Frames at specific moments in the production process. For example, when a customer orders a custom children's crib, an end-to-end digital representation of the entire manufacturing process is automatically generated. This includes:

- Product Blueprint: Digital definition of product specifications, materials, manufacturing processes, and design tolerances
- Supplier Blueprints: Real-time insights into supplier capacities, delivery times, and availability (e.g., oak wood from Supplier A, metal fittings from Supplier B)
- Production Blueprint: Modelling of work processes including CNC machining, assembly, and quality control
- Logistics Blueprint: Optimisation of inventory levels, transport routes, and delivery schedules

The orchestration is not static but continuously adapts to real-time changes. When, for example, Supplier A reports a delay, the system automatically activates alternative blueprints and executes a seamless rerouting to backup suppliers. This self-orchestrating capability is enabled by the Intelligent Manufacturing Custodian (IMC), which functions as the central intelligence across the entire blueprint landscape.

Through this blueprint-based orchestration, a fully transparent and programmable production ecosystem emerges, providing Manufacturing-as-a-Service (MaaS) capabilities and enabling unprecedented agility and resilience in complex manufacturing networks. The aim of Task 3.4 is to provide data and create blueprints for specific situations. The following chapters describe the various use cases and their requirements to determine which data should be processed in which system architecture.

4.1. USE CASE DESCRIPTION

Within the NARRATE project, a diverse portfolio of use cases has been defined to demonstrate the orchestration of digital blueprint frames across different industrial scenarios. These use cases are taken from real industry partners and span areas such as supply chain resilience, automation of manufacturing networks, and intelligent response to disruptions. Prominent use cases include improving automation and supply-chain resilience in furniture manufacturing (MEDWOOD), networked 3D printing for distributed production (AIDIMME), and establishing a flexible, disruption-resilient supply chain in the electronics and automation sector (BUDATEC). While the initial implementation focus is on the BUDATEC scenario, as it allows the use of an in-house ERP system to compensate for suboptimal data availability and to iteratively enrich the dataset with information from other partners, the resulting solution is designed to be fully applicable and usable for all project participants.

For the specific illustration of blueprint orchestration, the use case "Resolving Production Bottlenecks" is chosen. This scenario focuses on using Digital Twins and blueprint-driven workflows to identify, analyse, and mitigate production bottlenecks in real-time, thereby increasing throughput and operational flexibility. The relevance and implementation of this approach are most clearly demonstrated by BUDATEC's set of user stories (BUD_08, BUD_11, and BUD_17). A detailed description can be found in Chapter 7.1.

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- BUD_08: obtain a single view for performance measurements to inspect production times, and get a central error overview for production and commissioning clearly deriving improvements
- BUD_11: get feedback on the processes and products to continuously improve products and processes
- BUD_17: real-time project status tracking to recognise time and cost-relevant issues as soon as possible

Through these user stories, NARRATE showcases how blueprint orchestration provides a data-driven backbone for proactively solving operational challenges. The use of modular, updatable blueprints enables BUDATEC to adapt manufacturing flows, deploy alternative production paths, and maintain supply chain continuity with minimal manual intervention, all while ensuring transparency for users at every decision point.

4.2. REQUIREMENTS & KPIS

For the selected user stories, requirements were defined in D1.1 [21] to describe users' needs and expectations for the systems to be developed.

In all three cases, the primary role addressed is that of the Managing Director, with the overarching goal of enabling actionable, data-driven decision-making through enhanced feedback and transparency regarding production and product performance.

- BUD_08 focuses on aggregating performance indicators and real-time information from suppliers for the continuous monitoring of deliveries. The user story emphasises the need for a single view on performance measurement (including production times and error overview) that supports the identification of process improvements. Key functional requirements are automatic assessment of relevant delivery data and intuitive feedback mechanisms, with KPIs including ~60% reduction in production time and ~30–35% reduction in stored capital or improved disruption identification.
- BUD_11 details requirements for managing feedback both on processes and products, with the system expected to enable real-time supplier information, feedback sheets, and interfaces for visualising actionable results across organisational units. The focus is on supporting continuous improvement through transparent information flows between the supplier, the internal organisation, and the customer. Here, the KPIs reflect ~60% reduction in production time, ~30% less stored capital, and notable improvements in on-time delivery and machine lifespan.
- BUD_17 targets real-time project status tracking to minimise project and cost delays by providing up-to-date insights into potential supply chain disruptions. The functional requirements specify the comparison of practical and planned project work, notification functionality, and inclusion of cost/time-relevant KPIs linked to projects and orders. This supports rapid identification and response to production delays, with a particular emphasis on integrating supplier data regarding potential bottlenecks.

Across all three user stories, the consistent limitation noted is related to data. Specifically, the identification and integration of relevant, high-quality information to support effective monitoring, feedback, and decision-making. The data flows defined in the user stories highlight the importance of real-time interfaces between suppliers, the company and the customer, and show how blueprint-driven Digital Twins must enable bidirectional, context-dependent information exchange that meets the changing requirements of

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modern smart manufacturing. In the following, the focus will be on User Case BUD_17.

4.3. DATA SOURCES AND THEIR INTEGRATION

The data specified in user stories within the NARRATE project should be directly mapped to the data structures and semantic content of the blueprints used in the Digital Twin framework. Each user story typically expresses operational needs or decision support requirements from the perspective of end users or system stakeholders. For example, real-time monitoring of delivery status, tracking production delays, or providing a comprehensive overview of key performance indicators (KPIs).

To fulfil these user-driven requirements, blueprints act as standardised digital representations that organise, aggregate, and contextualise the necessary data elements from various physical and information systems (such as ERP, MES, SCM, or IoT platforms). The process involves translating user story requirements into specific objects, entities, and attributes within the blueprint schema. For example, a user story requesting real-time insight into production delays will map to blueprint fields that capture current order status, timestamps for planned versus actual milestones, and notifications of disruptions.

This tight coupling ensures that all relevant information for process monitoring, analytics, and visualisation is structured and made available in alignment with the user's operational goals. Furthermore, by synchronising blueprint instances with live operational data, the system allows users to interactively explore, analyse, and respond to changing production or supply chain scenarios exactly as envisioned in the originating user stories. In essence, the blueprints serve as a semantic and technical bridge, translating the high-level intent of user stories into actionable, traceable, and reliable information structures within the NARRATE Digital Twin ecosystem.

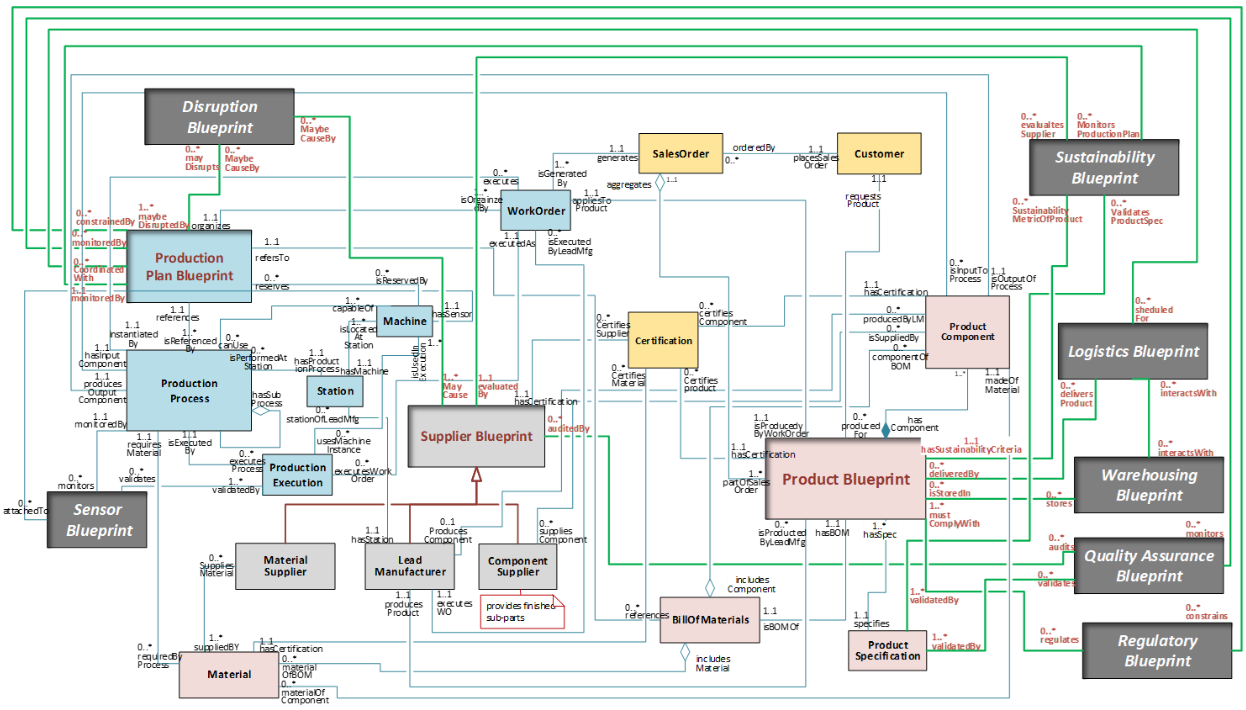

FIGURE 3: CONCEPTUAL MODEL OF THE NARRATE PRODUCTION VIEW (SERV)

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This data must be prepared so it can be integrated into the blueprints shown in Figure 3. Each of the blueprints shown serves as a template for storing a wide variety of data. Figure 4 shows examples of the information that can be stored in the blueprints for the production plan and product.

Production-Plan Blueprint
- Assembly sequences
- Production processes
- Process Events
- Production workflow (solution)

Product Blueprint
- Product Family
- Material Definition Info.
- Product Definition Info.
- Production Capability Info.
- Costing & Pricing info.

FIGURE 4: SAMPLE DATA FROM THE BLUEPRINTS (SERV)

4.4. SYSTEM ARCHITECTURE

The attached system architecture, shown in Figure 5, provides a structural overview of the NARRATE platform and its modular integration within the project's overall vision for Smart Manufacturing Networks. This architecture serves as the technical backbone for orchestrating Digital Twins, blueprints, and data-driven decision support in pilot scenarios like those described for BUDATEC and other industry partners.

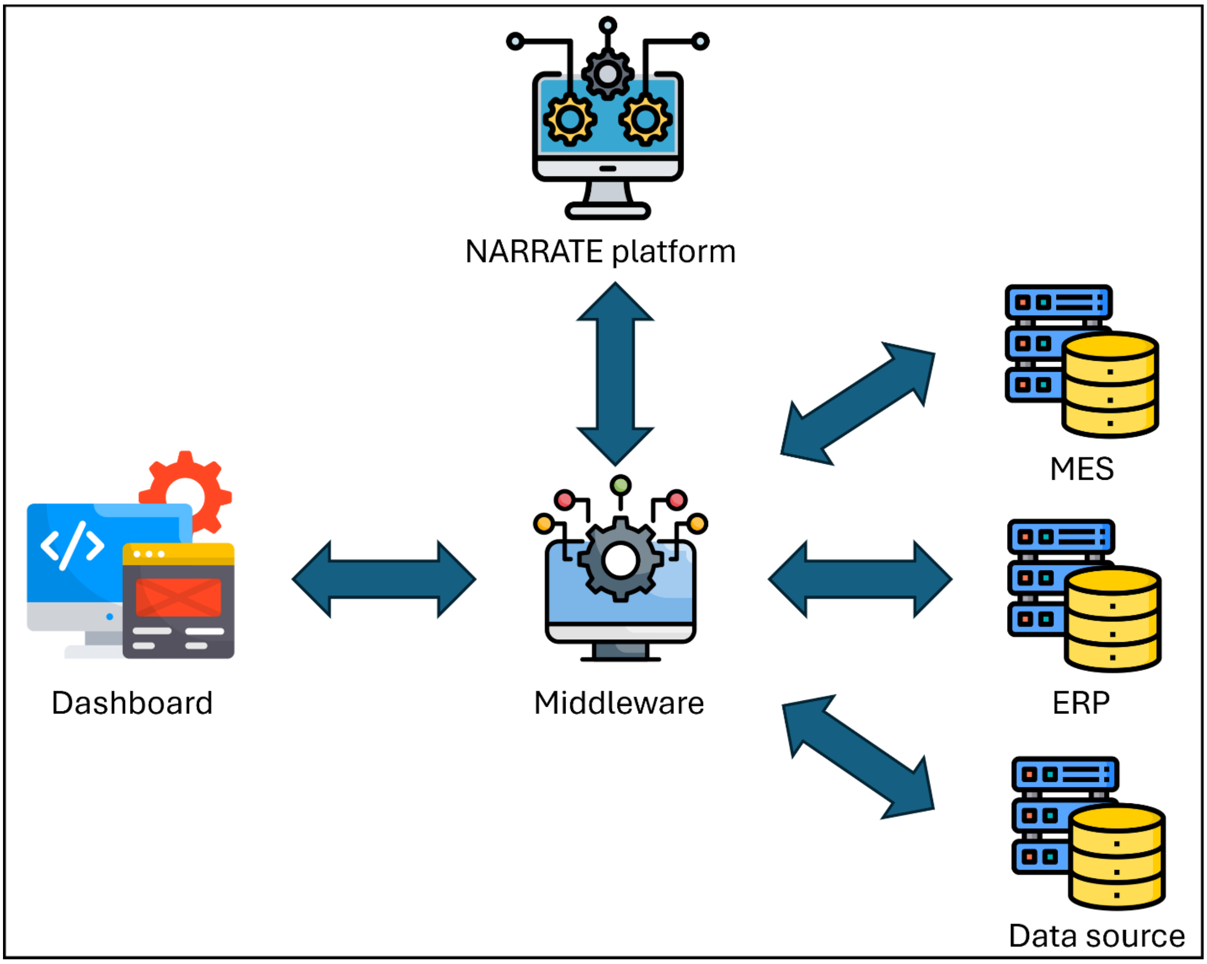

FIGURE 5 SYSTEM ARCHITECTURE

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Central to the architecture is the coordinated interplay among various subsystems: data sources (e.g., ERP, MES, IoT sensors), integration layers (e.g., the Federated Data Integration Framework, FDIF), and the core NARRATE platform components that manage Digital Twins, orchestrate blueprinting, and provide analytics and visualisation. Interfaces ensure seamless data flow and semantic harmonisation across operational, informational, and decision-making layers.

4.4.1. Middleware

The middleware serves as the central component of the proposed solution and should be able to access a company's various data sources to extract the relevant data for the blueprints. To do this, the middleware must include software adapters that meet the requirements and conditions of the connected systems. Furthermore, the middleware will process the data for transfer to the blueprint repository.

4.4.2. Dashboard

The dashboard is currently used to control and monitor process orchestration. These functions will be covered by other systems on the NARRATE platform later in the project. A user story is to be selected in the dashboard, whereupon the corresponding data is displayed in the dashboard and transferred from the middleware to the NARRATE platform.

The system is designed to support both real-time and historical data usage, enabling adaptive workflows, predictive analytics, and event-driven process management. This technical foundation reflects NARRATE's emphasis on modularity, interoperability, and extensibility, allowing pilot users to realise agile, resilient manufacturing processes through configurable blueprint frames, seamless integration of heterogeneous data, and support of Manufacturing-as-a-Service (MaaS) business models.

By mapping this architecture to concrete use cases, NARRATE demonstrates how Digital Twin ecosystems can enable real-time production optimisation, proactive disruption management, and end-to-end operational transparency in next-generation industrial networks.

5. IMPLEMENTATION

In the current implementation phase of the NARRATE project, the primary focus is on validating the feasibility of the developed concept in a practical setting. To achieve a clear, manageable, and demonstrable result in this early stage, only a single user story is selected for implementation. This targeted approach ensures that the fundamental principles of the NARRATE platform can be rigorously tested before scaling up to more complex scenarios or additional requirements.

The procedure consists of five well-structured steps:

- Selection of the user story: A representative and relevant user story is chosen based on pilot partner input and project priorities, ensuring that the initial proof-of-concept addresses tangible operational needs within the smart manufacturing context envisioned in NARRATE.

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- Definition of blueprints and data requirements: The most pertinent blueprints and specific data points needed to support the chosen user story are identified. This ensures that all architectural design and middleware integration tasks are directly aligned with real-world process requirements.
- Development of a tailored system architecture: A functional system architecture is created, connecting the data sources, blueprint management components, and decision logic while adhering to the modular and interoperable standards central to the NARRATE framework.
- Implementation of middleware and dashboard: Dedicated integration middleware and a dashboard prototype are developed to facilitate efficient data exchange, transformation, and user-centric presentation of information, allowing stakeholders to interact with the system and monitor process performance in real-time.
- Extraction and validation of data: The final step involves reading data from the connected source systems, populating the blueprints, and verifying the accuracy and completeness of results. This feedback enables iterative refinement and lays the groundwork for broader system rollout.

This focused prototyping approach directly aligns with NARRATE's overall aim: to accelerate the deployment of intelligent, resilient manufacturing networks by ensuring that new technical concepts are robustly validated against operational reality before large-scale adoption. By demonstrating that the solution can be mapped to a concrete user story, with seamless blueprint orchestration, middleware integration, and actionable data insights, the project ensures a scalable foundation for future Digital Twin-driven innovation.

5.1. SELECTION OF THE USER STORY

In User Story BUD_17, the objective is to enable real-time project status tracking to identify time- and cost-relevant delays as early as possible. To fulfil these requirements, a range of data types must be collected, integrated, and analysed within the Digital Twin system.

Specifically, the following categories of data are necessary:

- Delivery and Logistics Data: Primarily managed in Supply Chain Management (SCM) systems and Warehouse Management Systems (WMS). These systems track delivery schedules, shipment statuses, and logistics events.
- Production Scheduling Data: Stored in Manufacturing Execution Systems (MES) and, for higher-level planning, in Enterprise Resource Planning (ERP) systems. MES capture real-time production progress and deviations, while ERP manages master production schedules and resource planning.
- Project Management and Order Data: Handled by Project Management Systems (PMS) or modules within ERP systems. These track project milestones, progress, and relate work orders to specific projects and customers.
- Notification and Deviation Records: Often captured in MES, ERP, and specialised Workflow/Business Process Management (BPM) tools, which generate, log, and distribute alerts about deviations and exceptions.
- KPI Data: Aggregated across MES, ERP, and Business Intelligence (BI) platforms, where key performance indicators are calculated, visualised, and reported.

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- Supplier/Partner Communication Data: Managed in Supplier Relationship Management (SRM) systems, specialised EDI (Electronic Data Interchange) platforms, or via the supplier modules of ERP/SCM systems. These store exception messages, order confirmations, and other inter-organisational communications.

By aggregating data from these categories, the system supports automated comparisons of practical performance against planned schedules, provides notification functionality for critical deviations, and ensures that every stakeholder can access up-to-date, actionable information about project risks and delivery impacts. The integration of such multi-sourced data is essential for effective, real-time decision support as envisioned in User Story BUD_17.

5.2. DEFINITION OF BLUEPRINTS AND DATA REQUIREMENTS

For this implementation scenario, only blueprints that are natively supported and stored in the existing ERP system are to be implemented, as this system is already available and has been populated with representative dummy data from BUDATEC.

Given these constraints, the selection of blueprints should be limited to the following ERP-relevant domains:

- Product: Capturing the structure of a product and its components as defined in the ERP's Bill of Materials (BOM). It lists all assemblies, parts, and quantities needed to manufacture the product in a hierarchical format, enabling transparent tracking, planning, and inventory management directly within the ERP using BUDATEC's representative product data
- Order Management: Capturing all order-related data from the ERP, including project assignments, customer details, work order status, and order timelines. This supports project status tracking and delivery scheduling.
- Production Planning: Focusing on data structures maintained in the ERP for manufacturing scheduling, resource allocation, production milestones, and lead times. By extracting planned versus actual completion dates and resource deviations, this blueprint provides core input for delay analysis.
- Supplier Interaction: Reflecting purchase orders, delivery notes, confirmations, and exception notifications that are typically managed in ERP supplier modules. This facilitates real-time feedback on incoming goods and any disruptions in the procurement process.

By focusing the blueprint implementation purely on ERP-sourced data, the project ensures that the information pathways are practical, testable, and directly aligned with BUDATEC's operational reality. The use of dummy data further enables iterative development, testing, and refinement of integration logic, dashboard visualisation, and decision support functionality, thereby maximising the relevance, feasibility, and transparency of the resulting Digital Twin solution without the need for additional system integrations at this stage.

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TABLE 1: BLUEPRINTS

	Blueprints
Product	Bill of materials
	Product
	Product Component
Order Management	Sales Order
	Customer
Production Planning	Work Order
	Production Plan
	Production Process
	Machine
Supplier	Supplier

The blueprints shown in Table 1 are enriched with a wide variety of data points. The BOM for a product is presented here as an example:

TABLE 2: BOM-RELATED DATA

Datatype	Description
String item	The name of the product to which the BOM belongs.
Double quantity	The number of finished products that need to be manufactured for this BOM.
List<items>	A list of all individual parts or sub-assemblies that belong to this BOM.
List<operation>	A list of all processes necessary to manufacture this product.

The data type List indicates that a collection of further blueprints is addressed there. In the item list, blueprints in the Product Component category are referenced.

TABLE 3: ITEM-RELATED DATA

Datatype	Description
String name	The name of the corresponding product/item.
String owner	The owner/creator of the entry in the ERP system.
String creation	The time at which the item was created.
String modified	The time at which the last change was made to the item.
String modified_by	Who made the change?
Int docstatus	Indicates the processing status of a document or data record and is essential for process control, tracking and linking follow-up actions.

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Int idx	The field is used to control the order of entries in so-called child tables (subtables). It is a numeric column that is assigned to each row within sub-lists and determines the order in which entries are displayed or processed in the user interface.
String naming_seriers	The field defines the number range or naming scheme according to which documents such as invoices, quotations, orders, etc. are automatically assigned a unique, sequential ID.
String item_code	It is the unique identifier (ID) for an item in the system. Each item, whether it is a product, service, raw material or fixed asset, is assigned its own item_code when it is created, which is used internally for unique identification and for all references and transactions (e.g. quotations, orders, stock movements).
String item_name	This field stands for the plain text description of an item, i.e. the readable name as it appears on invoices, quotations or delivery notes, for example. The item name can be freely chosen and serves to name the item in a way that is understandable for users, customers and partners – in contrast to the item_code, which is used for technical purposes and for unique identification.
String stock_uom	The 'stock_uom' field in ERPNext specifies the standard stock unit of measure for an item and the unit of measure in which the item is stored and booked in the warehouse. Examples include 'piece', 'kilogram', 'litre', or 'metre', depending on how the item is physically handled.
String description	Additional descriptions that describe the item in more detail.
Double standard_rate	This field represents the standard price of an item, i.e. the basic purchase price or value at which the item is typically listed in the system. This price is stored in the item master record, serves as a guide for calculations, and is often used for stock valuations or pre-assignments in purchase documents.
List<supplier>	A list of suppliers who can deliver this item.

Table 3 lists all data points that are currently considered relevant for an item. Here, too, there is a list that refers to the respective suppliers stored in the ERP system in the present case.

5.3. DEVELOPMENT OF A TAILORED SYSTEM ARCHITECTURE

This section presents the detailed system architecture (Figure 6) developed for the NARRATE platform, which builds directly upon the general architecture introduced in Section 4.4 (Figure 5). While the general system architecture provides a high-level perspective on the integration of key platform components, such as the NARRATE platform itself, middleware, dashboards, and various data sources (e.g., ERP, MES), the detailed architecture refines these components. It clarifies the technical and informational interactions necessary to implement the use cases and blueprint orchestration envisioned for NARRATE.

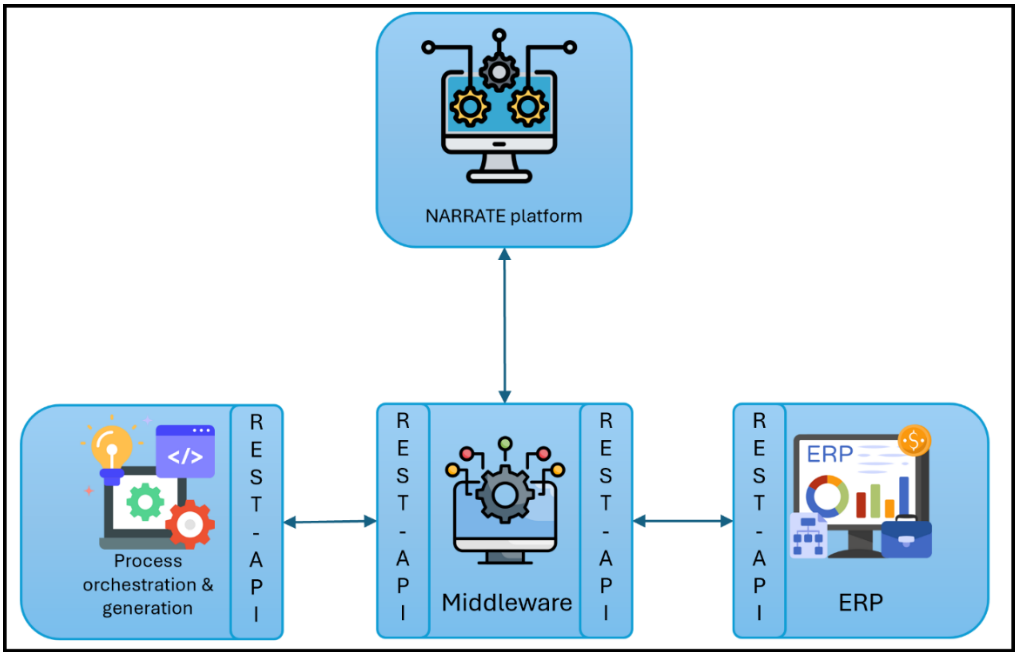

FIGURE 6: DETAILED SYSTEM ARCHITECTURE

REST APIs [22] were chosen as the primary integration method due to their compatibility with the current ERP system. The API design, realised primarily in Java (using frameworks such as Spring Boot and libraries for JSON [23]/YAML [24] binding), intentionally follows modular and extensible patterns to enable the straightforward addition of further data sources or system interfaces in the future. The ERP system, as the central enterprise data repository, and the process orchestration modules are linked to the middleware via these standardised REST APIs.

The middleware itself is implemented in Java, leveraging established open-source libraries and frameworks for robust data exchange, semantic transformation, and protocol adaptation. Examples include Jackson for serialisation and comprehensive validation frameworks complying with interoperability standards. For the dashboard and platform frontends, web technologies including JavaScript (React [25], Ant Design [26]) were employed to ensure a seamless user experience and direct interoperability with the REST endpoints.

This architecture enables seamless integration of real process data, blueprint execution logic, and Digital Twin representations, while ensuring that all communication adheres to interoperability standards. The NARRATE platform thus can orchestrate production processes, perform cross-domain data analytics, and support real-time decision-making. By clearly structuring the flow of data, from source systems through middleware to high-level platform services, the solution facilitates traceability, scalability, and robust system extensibility. This level of detail is necessary for the practical realisation and future expansion of blueprint-driven, resilient Smart Manufacturing Networks within the NARRATE project context.

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5.4. IMPLEMENTATION OF MIDDLEWARE AND DASHBOARD

The development of the middleware and dashboard was initiated to establish a controlled technical environment for testing the core integration and data-processing principles of the NARRATE architecture. This development phase aimed to ensure that data originating from the ERP system could be efficiently accessed, standardised, and formatted for blueprint population within the NARRATE platform.

The middleware was conceived as the central integration layer, acting as a bridge between various data sources and the blueprint framework. Its development focused on modularity, scalability, and transparency, allowing the integration of ERP data through REST APIs while maintaining the ability to adapt to future data sources. The implementation followed a stepwise engineering process, from defining data structures and services to implementing and testing core data flows, to guarantee flexible, reusable components for ongoing system validation.

The dashboard was developed in parallel to support the middleware implementation as a data validation and verification tool. Its function is to visualise data retrieved from the ERP and processed by the middleware, providing a clear overview for consistency checks, debugging, and feasibility tests. It allows developers and project partners to verify data transformation and integration logic transparently throughout the middleware workflow.

While the middleware will remain a fundamental technical component of the NARRATE architecture, the dashboard serves as an auxiliary testing instrument. It provides valuable insights during the pilot and validation stages, however, is not intended to serve as a permanent part of the NARRATE platform interface. Together, both elements formed a controlled testbed for verifying interoperability, data handling, and blueprint integration.

5.4.1. Middleware

During the development of the middleware, the team followed a structured, iterative approach that emphasised modularity, clarity of data flows, and alignment with blueprint requirements for the NARRATE platform. The process started with a requirements analysis focused on blueprint data, yielding entities such as items (products), bill of materials (BOMs), work orders, operations, suppliers, and workstations. These core domain concepts were modelled as Java classes and mapped to a hierarchy of REST API endpoints, for example, via controllers like ItemController, WorkOrderController and SupplierController. Each REST endpoint represented a distinct business domain essential for blueprint creation.

The middleware modularisation was realised through specific Maven modules:

- data_types: Defines core domain types (Item, BOM, WorkOrder, Operation, Supplier) in Java 21. Uses Jackson annotations (version 2.15.x) for robust JSON and YAML binding as well as JUnit 4.11 for unit and integration testing. The module is configured with Maven compiler level 1.8 to ensure compatibility and stability.
- process_control: Implements business logic in Java 21 and references internally managed artefacts (rest_controller and data_types, both at version 2.0), promoting architectural separation and reusability. JUnit 4.11 supports test-driven development and continuous verification. The module maintains a lightweight footprint by outsourcing REST and Data Transfer Objects (DTO) definitions.

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- rest_controller: Provides the REST layer using Spring Boot 3.4.5 (spring-boot-starter-web) for embedded HTTP server support. Integrates both DTO definitions from data_types and business logic from process_control. Jackson is employed for serialisation, and JUnit 4.11 for endpoint testing.
- rest_openapi: Implements the OpenAPI specification using Java 21, enabled by Maven compiler options. Utilises Spring Boot 3.4.5 for both web and validation capabilities, alongside Jackson modules for YAML serialisation and extended datatype support (JSR310, nullable). Integration with the springdoc-openapi-starter-webmvc-ui library realises auto-generation of interactive API documentation (Swagger UI). Jakarta/Javax Validation APIs and Hibernate Validator ensure robust bean validation, while the module also references custom process_control logic. Test cases are managed via spring-boot-starter-test.

After the domain modelling phase, service classes such as ItemService and WorkOrderService were implemented. These encapsulate the logic for fetching, validating, and transforming ERP data (including dummy datasets), ensuring that input from ERP-native formats is systematically mapped to the standardised object schema required by Digital Twin blueprints. Special attention was paid to datatype definitions across all modules: they were designed generically and in alignment with both ERP source structure and blueprint schema in order to function as a semantic bridge between heterogeneous ERP data and interoperable, blueprint-ready middleware objects.

Throughout the process, iterative testing and validation were continuously performed at module and integration levels, leveraging JUnit-based automated tests and runtime verification. Dashboard visualisations and Digital Twin processes dictated much of the structure and transformation logic. Feedback loops with blueprint designers and reference data from BUDATEC led to continuous adjustments in data mapping, service logic, and REST API design aspects.

All four functional modules are fully implemented in Java, with configuration and dependency management handled exclusively via Maven. This modular, standards-based setup ensures transparency, maintainability, and extensibility for future development and integration within the NARRATE platform.

This methodical, step-by-step approach ensured that the middleware not only facilitated seamless ERP integration, but also produced robust, reusable data types capable of populating digital blueprints efficiently. The result is a middleware layer that delivers clean, blueprint-ready objects for downstream production orchestration, analytics, and user feedback, forming a core enabler of NARRATE's Digital Twin ecosystem.

5.4.2. Dashboard

The dashboard developed within the context of the NARRATE project serves as a central instrument for the verification and validation of data managed by the middleware layer. Its principal objective is to provide developers and project partners with a transparent and interactive means of visualising how information originating from the enterprise resource planning (ERP) system and supplementary data sources is processed, normalised, and subsequently made available through the middleware's REST API endpoints.

Throughout the development process, the dashboard has functioned as an essential feedback mechanism, facilitating the inspection, navigation, and validation of key data structures such as items, bills of materials (BOMs), work orders, and suppliers. This validation occurs prior to the transmission of data to the Digital Twin platform for blueprint instantiation. The implemented core functionalities comprise tabular and hierarchical visualisations, data drilldowns, and provenance tracing, enabling users to trace information flows from the ERP system through to the intermediary API interface.

From a technical perspective, the dashboard is implemented as a modular web application developed entirely in JavaScript, encompassing both backend and frontend components. The backend, located in backend/src/server.js, employs the Express framework as its HTTP server. It integrates auxiliary middleware such as CORS and Morgan for cross-origin request handling and request logging, respectively. Data exchange with the ERP layer is facilitated via Axios, while environment variables are managed using dotenv. Nodemon is employed during local development to support live reloading and thereby improve development efficiency.

The frontend architecture is based on React, utilising component-driven design principles to ensure maintainability and reusability. The Ant Design library, complemented by its associated icon package, provides a coherent and professional visual framework that supports the presentation of complex data structures, including nested tables and hierarchical trees. Styling is implemented using modular CSS files (frontend/src/App.css, index.css), ensuring consistency and separation of presentation concerns. Axios is again used on the client side to enable asynchronous communication with the backend services.

The build and development pipeline is managed by Vite, which provides an optimised bundling process and fast development server capabilities, enriched through the @vitejs/plugin-react integration for JSX handling and hot module replacement. Code quality assurance is maintained through ESLint in conjunction with React-specific plugins, ensuring adherence to coding standards and long-term maintainability.

Given this role, the dashboard is not intended to become a permanent or central component of the NARRATE platform's user interface. Instead, it has been designed as a temporary, auxiliary application for feasibility studies, integration tests, and development-phase debugging. In future deployments, as blueprint orchestration and platform interfaces become more mature and integrated, the dashboard may be phased out or replaced by specialised analytics, monitoring, or operational frontends tailored to end-user needs. Its contribution thus lies in speeding up iteration, safeguarding data integrity, and supporting a robust transition from concept validation to productive blueprint-driven manufacturing.

In summary, the development of the middleware and dashboard achieved its primary goal of enabling robust, transparent integration between the ERP system and the blueprint-driven NARRATE platform. The middleware was successfully designed and implemented as a modular, scalable connector layer, capable of extracting, transforming, and harmonising business-critical data into blueprint-ready formats. Parallel to this, the dashboard provided essential support as a validation tool, allowing developers and project partners to monitor, inspect, and verify the correctness and completeness of all relevant data objects throughout the integration process. Together, these components established a stable technical foundation for further system evolution and laid the groundwork for reliable and extensible data flows within future NARRATE deployments. The use of the dashboard for internal validation ensures high data quality and builds confidence for the subsequent productive integration of blueprint functionality.

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5.5. EXTRACTION AND VALIDATION OF DATA

In the following chapter, the process for accessing and validating ERP data using the middleware and dashboard is described in detail, drawing on the provided sequence diagram (Figure 7) for illustration.

When a user interacts with the dashboard to request information about a specific work order, the dashboard sends an API request to the middleware. The middleware, acting as an orchestrator, relays this request to the ERP system. Upon receiving the response for the specific work order, the middleware initiates two key aggregation steps, as depicted in the diagram.

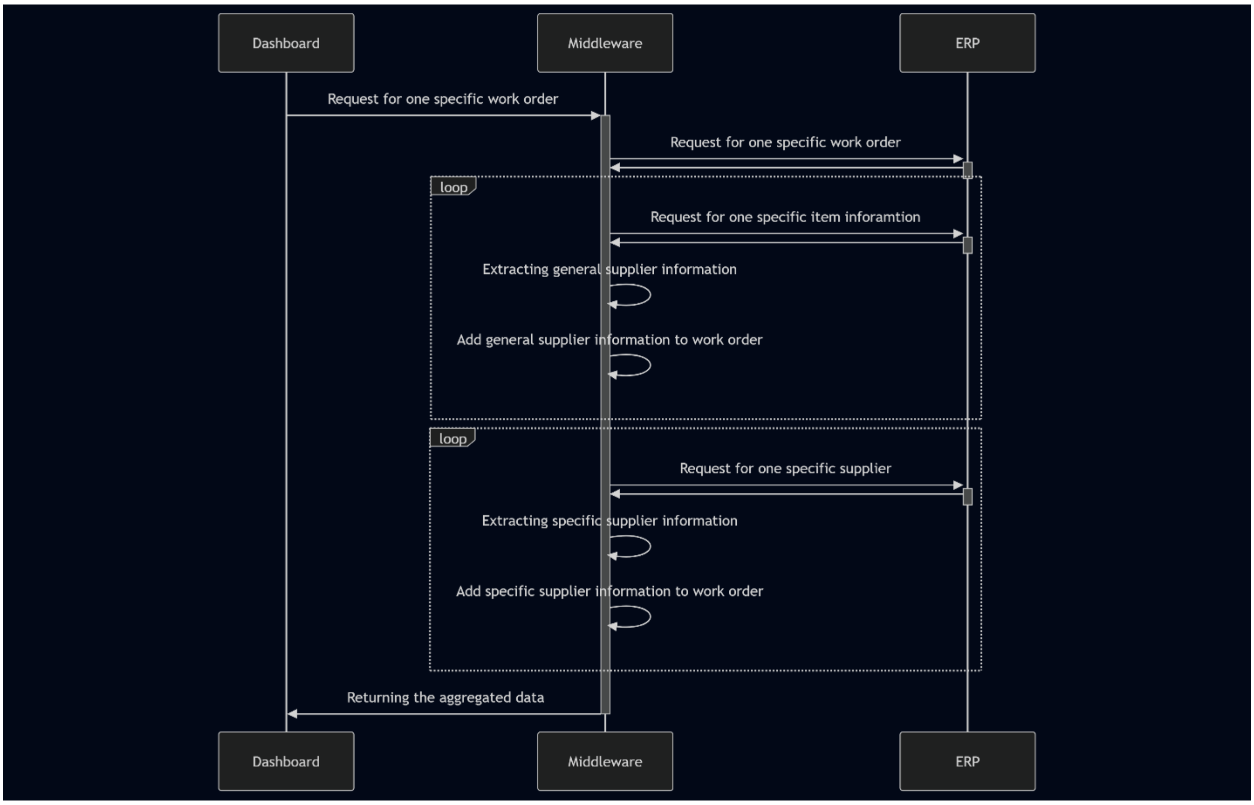

FIGURE 7: SEQUENCE DIAGRAM

First, for each relevant item linked to the work order, the middleware requests detailed item information from the ERP and extracts associated general supplier information. This supplier data is then looped into the work order context, ensuring that the work order representation includes a comprehensive summary of item suppliers.

Second, the middleware performs an additional information loop, querying for each specific supplier related to the work order. Detailed supplier records are requested from the ERP, extracted, and integrated into the overall work order context.

Once both general and specific supplier information has been aggregated and combined with the work order data, the middleware packages all relevant data and returns it to the dashboard. On the dashboard, this aggregated data can then be intuitively visualised and inspected by users, allowing them to verify the correctness and completeness of the entries. Users are thus empowered to ensure that all relationships between work orders, items, and suppliers are accurate and that the data mapping between ERP and middleware matches the operational expectations.

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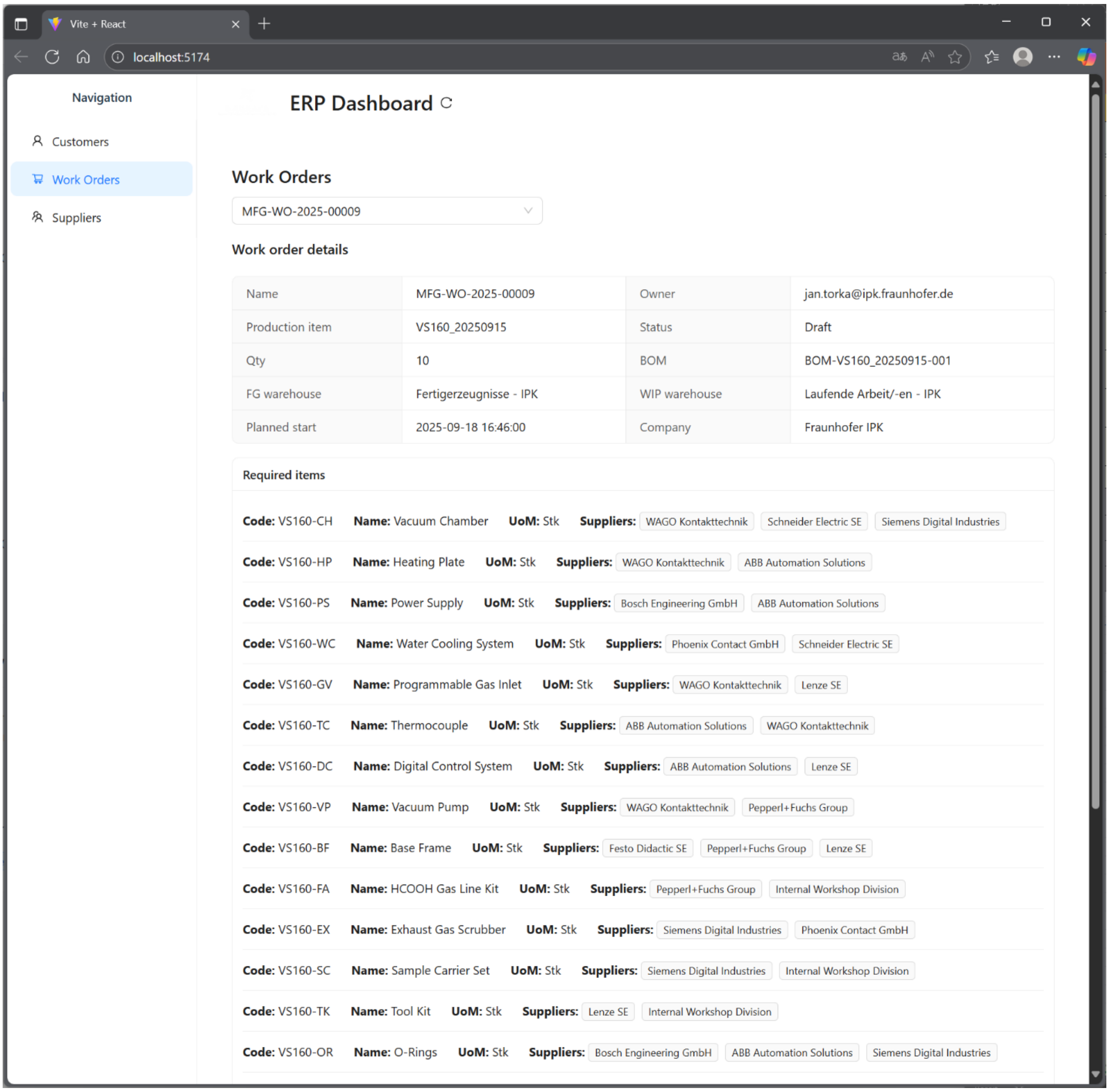

FIGURE 8: SCREENSHOT OF THE DASHBOARD

The results of this data retrieval and aggregation process are graphically presented in the dashboard interface (Figure 8), allowing users to efficiently review and verify both the correctness and completeness of the ERP-derived information. The dashboard organises key work order details, required items, and all linked supplier data in a transparent, user-friendly manner, making discrepancies or missing data immediately visible. For users seeking technical depth or detail, an excerpt of the underlying JSON file that forms the basis of this display can be found in section 7.2 of this deliverable. Please note that this excerpt shows only a small section of the JSON response, which in full contains more than 1,000 elements.

6. CONCLUSIONS AND OUTLOOK

The outcomes and insights documented in this deliverable highlight the crucial role of Digital Twins as foundational building blocks for resilient, adaptive, and intelligent production workflows in smart manufacturing networks. The modularisation and orchestration concepts developed within NARRATE empower organisations to move beyond isolated digital representations, enabling interconnected data ecosystems and real-time production process optimisation. With advanced integration of standards (such as ISO 23247 and OPC UA), Digital Twin-driven automation supports both technical interoperability and cross-domain synchronisation, ensuring consistency and quality throughout the product lifecycle.

Key technical advances, such as automated Digital Twin generation, modular orchestration frameworks, and standardised lifecycle management, address critical challenges of scalability, traceability, and flexibility. These solutions facilitate rapid reconfiguration, predictive maintenance, and the dynamic adaptation of process parameters, promoting both operational efficiency and sustainability. By leveraging holistic lifecycle management concepts and standardised information models, NARRATE establishes the basis for continuous improvement, knowledge retention, and robust decision support in manufacturing environments.

While this deliverable focuses on the creation and initial orchestration of Digital Twins, the subsequent Deliverable D3.4(b) will extend the orchestration concept to cover the full spectrum of CRUD operations (Create, Read, Update, Delete). In D3.4(b), Digital Twins of entities will be leveraged not only for initial generation but also as the central mechanism for dynamically controlling, updating, and managing the lifecycle of product and process instances throughout the Smart Manufacturing Network. This will enable comprehensive operational steering via orchestrated entity management, bridging the gap between digital representation and physical execution for all core lifecycle phases.

Looking forward, the convergence of Digital Twins with harmonised standards and advanced virtualisation technologies will further accelerate the adoption of smart manufacturing strategies. Future research and implementation activities should extend scalable orchestration approaches, explore multi-twin coordination across value networks, and enhance real-time analytics capabilities. As Digital Twin ecosystems mature, they will unlock new opportunities for integrated product-service platforms, sustainable operations, and cross-sector collaboration, solidifying their role as the "central nerve system" of Industry 4.0 and beyond.

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7. APPENDIX A

7.1. DETAILED USER STORIES BASED ON D1.1

ID 8	Pilot #3 BUD			
Identification (role):	Managing Director	Functional Requirements:		Priority:
Performance (KPI):		R8.1	real-time information from supplier for monitoring of deliveries	M
Reduction of the production time	~60%	R8.2	assessment of relevant information and should be able to derive improvements	M
Reduction of the stored capital / Reduction in identification of potential disruptions	~30% / ~35%			
Improvement of on -time delivery rate	~10%			
User story:	As managing director, I would like to have a single view for performance measurements in order to be able to see production t imes, central error overview for production and commissioning clearly and to derive improvements.			
Operational:	Limitations:			
	Data related limitations			

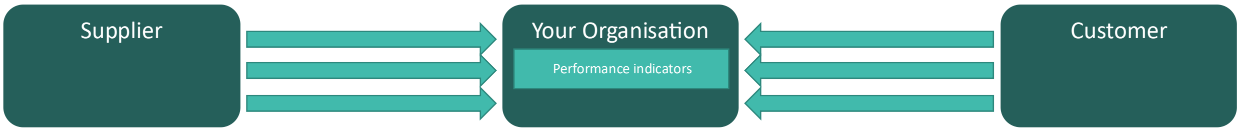

FIGURE 9: BUD USER STORY #8 [12]

ID 11	Pilot #3 BUD			
Identification (role):	Managing Director	Functional Requirements:		Priority:
Performance (KPI):		R11.1	real-time information from supplier for monitoring of deliveries	M
Reduction of the production time	~60%	R11.2	feedback sheet	M
Reduction of the stored capital	~30%	R11.3	overview interface for ownorganisation with results	M
Improvement of on -time delivery rate / Lifespan extension of the machine	~10%			
User story:	As Managing Director, I would like feedback on the processes and products so that we can continuously improve our products and processes			
Operational:	Limitations:			
	Data related limitations			

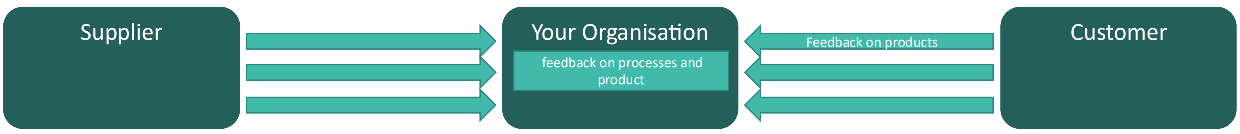

FIGURE 10: BUD USER STORY #11 [12]

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ID	17	Pilot #3 BUD			
Identification (role):		Managing Director	Functional Requirements:		Priority:
Performance (KPI):			R17.1	real-time information from supplier for monitoring of deliveries	M
Reduction of the production time		~60%	R17.2	comparison of practical and planned project work and notification functionality for deviations	M
Reduction of the stored capital / Reduction in identification of potential disruptions		~30-35%	R17.3	inclusion of cost and time relevant KPIs connected to project and orders	M
Improvement of on -time delivery rate		~10%			
User story:	As managing director, I want a real-time project status tracking in order to recognize time and cost-relevant as soon as possible.				
Operational:		Limitations:			
similar to US 16		identification of relevant information for project delays			

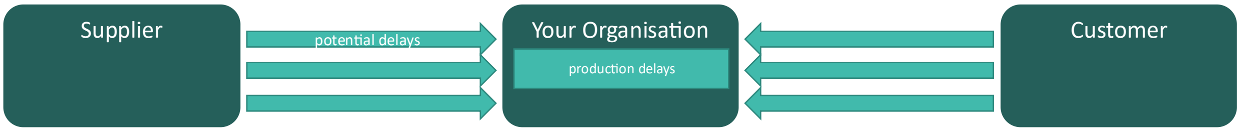

FIGURE 11: BUD USER STORY #17 [12]

7.2. PROCESSED OUTPUT OF THE BOM INFORMATION


```
{
    "name": "MFG-WO-2025-00009",
    "owner": "jan.torka@ipk.fraunhofer.de",
    "production_item": "VS160_20250915",
    "status": "Draft",
    "qty": 10,
    "bom_no": "BOM-VS160_20250915-001",
    "fg_warehouse": "Fertigerzeugnisse - IPK",
    "wip_warehouse": "Laufende Arbeit/-en - IPK",
    "planned_start_date": "2025-09-18 16:46:00",
    "company": "Fraunhofer IPK",
    "pathToSTL": null,
    "meanderType": null,
    "required_items": [
        {
            "name": "4hfr45kvk0",
            "owner": "jan.torka@ipk.fraunhofer.de",
            "creation": "2025-09-18 16:47:07.094224",
            "modified": "2025-09-18 16:47:07.094224",
            "modified_by": "jan.torka@ipk.fraunhofer.de",
            "docstatus": 0,
            "idx": 1,
            "naming_series": null,
            "item_code": "VS160-CH",
            "item_name": "Vacuum Chamber",
            "item_group": null,
            "stock_uom": "Stk",
            "description": "50 mm internal height, stainless steel construction",
            "standard_rate": null,
            "supplier_items": [
                {
```


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```
        "supplierName": "WAGO Kontakttechnik",
        "supplierType": null,
        "name": "lj60fqhhor",
        "owner": "jan.torka@ipk.fraunhofer.de",
        "creation": "2025-09-15 13:53:21.815991",
        "modified": "2025-10-09 11:09:43.048797",
        "modified_by": "jan.torka@ipk.fraunhofer.de",
        "docstatus": 0,
        "idx": 1,
        "naming_series": null,
        "supplier": "SUP007",
        "country": null,
        "supplier_name": null
    },
    {
        "supplierName": "Schneider Electric SE",
        "supplierType": null,
        "name": "lj6tvs3qjj",
        "owner": "jan.torka@ipk.fraunhofer.de",
        "creation": "2025-09-15 13:53:21.815991",
        "modified": "2025-10-09 11:09:43.048797",
        "modified_by": "jan.torka@ipk.fraunhofer.de",
        "docstatus": 0,
        "idx": 2,
        "naming_series": null,
        "supplier": "SUP006",
        "country": null,
        "supplier_name": null
    },
    {
        "supplierName": "Siemens Digital Industries",
        "supplierType": null,
        "name": "lj6nckdii5",
        "owner": "jan.torka@ipk.fraunhofer.de",
        "creation": "2025-09-15 13:53:21.815991",
        "modified": "2025-10-09 11:09:43.048797",
        "modified_by": "jan.torka@ipk.fraunhofer.de",
        "docstatus": 0,
        "idx": 3,
        "naming_series": null,
        "supplier": "SUP003",
        "country": null,
        "supplier_name": null
    },
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        "supplierName": "WAGO Kontakttechnik",
        "supplierType": null,
        "name": "l78sg2epad",
        "owner": "jan.torka@ipk.fraunhofer.de",
        "creation": "2025-09-15 13:53:22.349838",
        "modified": "2025-10-09 11:09:04.863216",
```


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```
                    "modified_by": "jan.torka@ipk.fraunhofer.de",
                    "docstatus": 0,
                    "idx": 2,
                    "naming_series": null,
                    "supplier": "SUP007",
                    "country": null,
                    "supplier_name": null
                }
            ]
        }
    ]
}
```


LISTING 1: TRUNCATED RESULT OF THE ORCHESTRATED DATA FROM THE ERP

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