NARRATE

Regenerative Resilient Smart Manufacturing Networks

D3.2 DIGITAL TWIN DESIGN & DEVELOPMENT (A)

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Authors	Michael Papazoglou, Amal Elgammal, Bernd Kraemer (SERV)
Reviewers	Jesús Ávila Molina (NUN) Fabio Gioachin (SYN)
Abstract	This deliverable introduces NARRATE Blueprint Frames and the Digital Twin Processing Language (DTPL), establishing a

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scalable, adaptive, and intelligent Digital Twin ecosystem for Smart Manufacturing Networks. Blueprint Frames employ a modular approach based on the Separation of Concerns principle, structuring Digital Twins for products, production processes, logistics, and machines to enhance scalability, interoperability, and adaptability. DTPL enables programmable Digital Twin behaviours, supporting AI-driven insights, real-time analytics, and dynamic resource orchestration. Together, these innovations create a self-orchestrating, AI-enhanced SMN, strengthening supply chain resilience, operational efficiency, and manufacturing interoperability

Keywords	Digital Twin, Digital Twin Processing Language, Smart Manufacturing Network, Complex Event Processing, IoT

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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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2	SCIENTIFIC ACADEMY FOR SERVICE TECHNOLOGY EV	SERV	DE
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ABBREVIATIONS

AI	Artificial Intelligence
BOM	Bill of Materials
CA	Consortium Agreement
CEP	Complex Event Processing
CFX	Connected Factory Exchange
CNC	Computer Numerical Control
DL	Deliverable leader
DM	Data Manager
DT	Digital Twin
DoA	Document of Activities. It corresponds with the Annex I to the GA
DSL	Domain Specific Languages
DTPL	Digital Twin Processing Language
EC	European Commission
ERP	Enterprise Resource Planning
GenAI	Generative Artificial Intelligence
HADEA	Health and Digital Executive Agency
IMC	Intelligent Manufacturing Custodian
IoT	Internet of Things
IIoT	Industrial Internet of Things
KPI	Key Performance Indicator
LLM	Large Language Models
MaaS	Manufacturing as a Service
MBOM	Manufacturing Bill of Materials
MDD	Model Driven Development
MDE	Model Driven Engineering
MQTT	Message Queuing Telemetry Transport
MTO	Make-to-Order
Mx	Month x
OEM	Original Equipment Manufacturer

PCo	Project Coordinator
QM	Quality Manager
SoC	Separation of Concerns
SMN	Smart Manufacturing Network
Tx.x	Task x.x
WP	Work Package

EXECUTIVE SUMMARY

This deliverable presents the design of NARRATE Blueprint Frames and Digital Twin Processing Language (DTPL), which introduce a scalable, adaptive, and intelligent Digital Twin ecosystem for Smart Manufacturing Networks. These innovations enhance supply chain resilience, operational efficiency, and real-time decision-making through modular Digital Twins and a programmable framework.

Blueprint Frames: A Modular Digital Twin Approach

Blueprint Frames employ Separation of Concerns (SoC) to model distinct SMN aspects, including products, production processes, logistics, and machines. This structured approach ensures:

- o   Scalability & Interoperability — Modular design enables seamless system integration.
- o   Agility & Adaptability — Dynamic reconfiguration in response to disruptions.
- o   Real-World Deployment — Fully integrated industrial solutions.

Digital Twin Processing Language (DTPL): A Programmable Digital Twin Framework

DTPL provides automation, execution, and real-time adaptation of Digital Twin models, offering:

- o   Flexible Programming Capabilities — Customizable and executable Digital Twin behaviours.
- o   AI-Driven Insights — Real-time analytics for predictive decision-making.
- o   MaaS-Enabled Orchestration — Dynamic resource allocation and production planning.

Strategic Impact

By integrating Blueprint Frames and DTPL, NARRATE delivers a self-orchestrating, AI-enhanced SMN, ensuring:

- o   Increased supply chain resilience through predictive monitoring.
- o   Optimized efficiency with automated workflows.
- o   Greater interoperability across manufacturing ecosystems.

The integration of Blueprint Frames and DTPL establishes a new standard for Digital Twin deployment, enabling businesses to build flexible, responsive, and intelligent manufacturing ecosystems. This innovation bridges the gap between digital modelling and real-world execution, empowering industries to achieve unprecedented levels of efficiency, adaptability, and resilience in the face of evolving market demands.

1. INTRODUCTION

Digital Twins are increasingly recognized as a transformative technology across many sectors—from manufacturing and infrastructure to urban planning and healthcare. At its core, a Digital Twin is a high-fidelity virtual replica of a physical asset, system, or process that is continuously updated with real-world data. This live connection between the physical and digital worlds allows organizations to monitor, simulate, and analyse performance in real time, leading to more informed decision-making and proactive management.

Below we provide an overview of what Digital Twins are, why they are important, and how they connect to SMNs (Smart Monitoring Networks) within the context of the NARRATE project.

1.1. WHAT ARE DIGITAL TWINS

A digital twin continuously updates itself in near real time by learning from a variety of sources, including product and material specification data, process and production data, sensor data, operational metrics, geospatial, and environmental and external data [1], [2]. It uses sensor data to monitor its operational conditions, incorporates insights from industry experts, compares performance with similar machines or fleets, and takes into account information from the larger system and environment in which it operates [1]. Digital twins are [2]:

- o *Virtual Replicas*: Digital Twins mirror physical objects or systems, capturing their current state, historical behaviour, and potential future scenarios.

- o *Data-Driven Models:* They rely on data inputs —from a variety of sensors and IoT devices— to reflect changes in real time. This continuous update mechanism ensures that the digital representation stays synchronized with its physical counterpart.

- o *Single Version of Truth:* Digital twins consolidate diverse streams of real-time data into a single, authoritative source. This unified repository serves as the definitive version of truth, enabling advanced analytics and AI algorithms to generate both predictive insights and prescriptive recommendations for optimized decision-making.

- o *Simulation and Analysis Tools:* By running simulations on the digital model, users can test different scenarios, predict outcomes, and optimize performance without risking disruption to the actual system.

1.2. IMPORTANCE & ADVANTAGES OF DIGITAL TWINS

1. *Enhanced Decision-Making:* Digital Twins provide a comprehensive view of manufacturing assets, processes and performance, enabling operators to make better-informed decisions based on real-time data and predictive analytics.

2. *Forecasting potential failures and inefficiencies*: By integrating real-time disruption data and insights into supply chain resilience, these digital models not only predict operational faults but

also identify vulnerabilities in the broader supply chain. This enables pre-emptive interventions that minimize downtime, prevent cascading supply-chain disruptions.

3. *Risk Reduction:* Simulating various operational scenarios helps identify vulnerabilities and optimize processes safely. This risk-free environment for testing new strategies minimizes the chance of costly mistakes in the physical world.

4. *Operational Efficiency:* Real-time monitoring and scenario testing facilitate continuous process improvement, helping to optimize resource use, energy consumption, and overall system performance.

5. *Cost Savings:* Through improved maintenance, optimized operations, and better planning, digital twins can significantly reduce operational expenses and extend the lifecycle of physical assets.

1.3. THE CONNECTION TO SMNs

In the NARRATE project, the integration of Digital Twins with Smart Monitoring Networks (SMNs) is fundamental to building a dynamic, data-driven model of physical systems. SMNs extend beyond traditional sensor networks—they also encompass data streams from suppliers, original equipment manufacturers (OEMs), enterprise resource planning (ERP) systems, product lifecycle management (PLM) systems, manufacturing execution systems (MES), and various IoT sources. This broad collection of high-quality, real-time data is essential for continuously updating and maintaining an accurate digital twin. Key aspects of this integration include:

1. *SMNs as Comprehensive Data Providers*: In NARRATE, SMNs gather detailed information from systems integral to supply chain and production management, but also data created through sensors and monitoring devices capturing shopfloor, environmental and operational data. This multi-faceted approach ensures that the digital twin is fed with a diverse and robust data set, forming a solid foundation for accurate modelling.

2. *Real-Time Synchronization*: The continuous stream of data from SMNs guarantees that the digital twin remains an up-to-date and precise representation of its physical counterpart. This immediate data flow allows for rapid analysis and swift decision-making, ensuring that any changes in the physical environment are reflected in real time.

3. *Enhanced Modelling and Simulation*: With access to comprehensive data from SMNs, the digital twin can simulate a wide range of scenarios accurately. This includes everyday operations as well as stress-testing conditions like peak loads, system failures, or unexpected disruptions. The enhanced simulation capabilities lead to more effective forecasting and risk management.

4. *Improved System Control and Optimization*: The insights derived from the digital twin enable operators to fine-tune the performance of the SMNs themselves. This iterative feedback loop supports smarter monitoring strategies, more efficient resource allocation, and the development of a resilient system that can better withstand operational challenges and supply chain disruptions.

5. *Application Across Diverse Domains*: Whether addressing smart city infrastructure, industrial processes, or other complex systems, the combination of digital twins and SMNs provides a powerful framework for managing modern, interconnected environments. This integration not only

drives operational efficiency but also enhances the system's ability to predict and mitigate potential failures.

In summary, the NARRATE project leverages the synergy between Digital Twins and SMNs to create a continuously updated, high-fidelity model of physical systems. This integration is pivotal for enabling real-time monitoring, enhanced simulation, and optimal control, thereby supporting both operational excellence and supply chain resilience.

1.4. THIS DELIVERABLE

This deliverable focuses on the design of a set of self-describing, actionable Digital Twin knowledge frames that leverage contextualized data in T3.1 and use advanced analytics, and AI techniques to model a Smart Manufacturing Network. The document also introduces Digital Twin processing a simple domain-specific language that could be invoked by both experts and the IMC and which is designed to facilitate the interaction, processing, control, and orchestration of Digital Twins within an SMN.

2. BLUEPRINT FRAMES IN NARRATE

NARRATE has explored the potential of representing critical data elements in abstract programmable form as digital twins [3]. These digital twins, called blueprint frames, or simply blueprints, are precise digital replicas of suppliers, equipment, IoT sensors, physical products, production processes, or even an entire supply chain [3]. They are contextualized in a digital version of their environment and continuously source data from multiple manufacturing systems. By leveraging Digital Twins, Smart Manufacturing Networks transition into highly responsive, self-orchestrated ecosystems, that provide insights and serve as an early warning system, predicting events and the likelihood they will occur, ensuring greater efficiency, agility, and resilience.

The NARRATE Digital Twin solution integrates programmable Manufacturing-as-a-Service (MaaS), enabling a shift from fixed manufacturing to flexible, service-oriented models, where manufacturers can dynamically reconfigure production lines and supplier partnerships. It allows manufacturers to virtually simulate, validate, and optimize production processes, from assembly to automation, enhancing efficiency and adaptability. MaaS models, where production capabilities are shared and reallocated, become feasible with blueprint frames providing real-time network intelligence. By projecting alternative production sequences and providing real-time visibility into manufacturing operations, the DT approach supports dynamic reconfiguration of supply chains. Leading companies are adopting this technology to ensure agility, resilience, and responsiveness to disruptions.

2.1. WHAT ARE BLUEPRINT FRAMES IN AN SMN?

In a Smart Manufacturing Network, *Blueprint Frames* are structured, modular components that define the key elements of the manufacturing ecosystem. Acting as *configurable building block*s, they

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represent various aspects of production, supply chains, and operational workflows. They rely on vast amounts of dynamically generated data from a manufacturing ecosystem's data sources (e.g., PLM, ERP, historical data, etc). They include product data, real-time sensor data, historical production data, quality data and environmental data, to create accurate virtual models of physical manufacturing systems.

Blueprint frames form a **multi-dimensional digital twin framework**, where each blueprint offers a standardized distinct perspective of an SMN while remaining interconnected to enable seamless collaboration across different factories, suppliers, and production units. This integration ensures a *holistic, adaptive,* and *highly efficient* production environment, enabling global visibility, real-time responsiveness, resilience to unexpected events, and optimization across the entire network. Blueprint Frames support the Separation of Concerns (SoC) by employing a modular Digital Twin architecture that distinctly represents different aspects of a Smart Manufacturing Network, including products, production processes, logistics, machines, and other key operational components. By structuring Digital Twins into domain-specific yet interconnected Blueprint Frames, the NARRATE framework fosters a cohesive, resilient, and programmable MaaS-driven Smart Manufacturing Network. The NARRATE blueprint frames are summarized below.

2.1.1. Blueprint Structure

1. **Supplier data —** The Supplier Frame provides real-time insights into lead manufacturer and supplier capabilities, lead times, reliability, and sustainability practices, enabling manufacturers to assess risks and optimize sourcing. The Supplier Frame describing a lead manufacturer includes customer-specific requirements: such as custom dimensions, materials, finishes, colours, and optional features. By continuously updating supplier status and inventory availability, it supports proactive decision-making in response to disruptions, demand fluctuations, and sustainability goals

2. **SMN data —** The SMN Frame defines a specific SMN in terms of the lead manufacturer and a set of suppliers involved in it, using information contained in the Supplier Frame.

3. **Product Design & Specifications —** The Product Frame digitally defines product specifications, materials, components, Manufacturing Methods: Processes such as Computer Numerical Control machining, injection moulding, 3D printing, etc., and design tolerances, ensuring precision, quality, and customization options. CNC machine is an automated manufacturing tool that uses computer programming to control machining processes such as cutting, milling, drilling, and engraving with high precision. The Product Frame also includes Material Composition data: type, grade, and supplier information of raw materials and Bill of Materials (BoM) data: a detailed list of components, sub-assemblies, and raw materials. By maintaining a comprehensive digital record, manufacturers can enhance quality assurance, streamline production, and meet regulatory standards efficiently.

4. **Production Data —** The Production Frame models and optimizes the workflow steps involved in fabrication, assembly, and quality control, machinery, resource allocation (machines, tools, and automation systems), and material usage, ensuring efficient, data-driven manufacturing. By leveraging real-time insights, it helps provide critical information about capacity, cycle times, throughput, and energy consumption, enabling continuous improvement and adaptive

production. It also supports predictive maintenance, minimizing downtime and maximizing productivity through optimized scheduling and resource utilization.

5. **Real-Time Sensor Data—** are continuously collected from IoT sensors embedded in machinery and equipment, this frame provides instant insights into machine performance, environmental conditions, and production parameters. It enables real-time fault detection, predictive maintenance, and operational optimization, ensuring maximum efficiency, reduced downtime, and enhanced manufacturing resilience. This frame encompasses two subframes:

   - **Production Monitoring Sensors** which track cycle times, throughput, material usage, and quality metrics, ensuring smooth workflows and process efficiency.
   - **Condition Monitoring Sensors** which detect vibration, temperature, pressure, and wear, enabling early fault detection and predictive maintenance to prevent breakdowns and extend equipment lifespan.

6. **Logistics data —** Include supplier data, demand forecasting, inventory levels, transportation, route planning, and delivery schedules. The Logistics Frame optimizes inventory, storage, and transportation by analysing stock levels, route planning, costs, and demand forecasts. It enables just-in-time inventory management, reducing lead times and storage costs while ensuring timely material availability. This frame enhances supply chain efficiency, responsiveness, and balance between supply and demand.

7. **Warehousing data —** warehousing data typically encompasses a wide range of real-time information that supports efficient operations, inventory management, and overall supply chain visibility. It contains operational data such as data on order pick, pack, and ship cycles. In addition, it may include task assignments, work orders, and throughput rates for various warehousing operations.

8. **Quality Assurance data —** The Quality Assurance Frame ensures product quality and process efficiency by tracking real-time metrics, defect rates, compliance, and productivity. It enables early issue detection, reducing waste and optimizing performance while maintaining regulatory and customer standards. This frame drives consistent quality, operational excellence, and continuous improvement across manufacturing.

9. **Sustainability data —** The Sustainability Blueprint Frame aggregates real-time information on environmental impacts and sustainable practices across the supply chain. By monitoring metrics such as carbon footprint, energy consumption, waste generation, material waste and emissions, it enables manufacturers to identify inefficiencies and implement greener practices.

10. **Disruption data —** the Disruption Blueprint Frame serves as a structured framework for identifying, analysing, and mitigating potential disruptions across the SMN. It contains Material Shortages, Equipment and Infrastructure Failures, Supplier Failures: (insolvency, capacity constraints, or quality problems), Quality Control Issues, Transportation Delays, Environmental & Sustainability Issues.

11. **Resources data —** the Resources Blueprint contains data about production lines, machinery, equipment, resources involved in each manufacturing operation, labour requirements, cycle times, setup times, and lead times.

12. **Regulatory Compliance data —** the Regulatory Compliance Blueprint contains information about industry standards, safety regulations, environmental regulations, product certifications.

2.1.2. Blueprint Operations

Blueprint frames are not only structure-oriented they also encompass operations that are directly relevant to their content, much like messages in object-oriented programming languages. This aspect is currently under development and will undergo iterative refinements to enhance its effectiveness and applicability. The evolution of this component is driven by the need for rigorous experimentation and continuous feedback from pilot stakeholders who will test and validate these concepts in real-world industrial environments. By introducing advanced ideas within an operational setting, we aim to bridge the gap between theoretical innovation and practical implementation. This process not only ensures that the developed solutions are aligned with industry needs but also fosters a deeper understanding of how such concepts can be seamlessly integrated into existing workflows. In the following we provide an example of the blueprint operations for the Production Plant Blueprint.

Recall that the Production Plan Blueprint Frame defines how an ordered product will be manufactured, integrating production workflows, machine operations, and scheduling. It supports operations like (in pseudo-code):

o Resource Availability (Machine, Worker, Task): The operation checks the availability of machines and workers for a specific task, e.g., wood cutting.

o Machine & Workforce Assignment (Machine, Worker, Task, Workload): The operation assigns tasks such as wood cutting, sanding, assembly based on availability and workload.

o Production Scheduling (Product, Allocated Resources, Production Line): The Digital Twin schedules a specific task, e.g., wood cutting and assembly for a cot, based on real-time machine availability.

- Customization Handling (Product, Product Models) - which calls operation Production Scheduling: Adjusts production paths for different customized products, e.g., cot models (crib-style, convertible, eco-friendly materials).
Example: If a customer orders a custom-sized cot with an oak finish, the Production Plan Digital Twin schedules cutting, sanding, and finishing operations while optimizing machine usage.

o Alerts (Product, Potential Disruption Event): Signals a potential disruption after receiving a signal from the Disruption Blueprint. For instance, wear on tools (e.g., saw blades reaching wear threshold).
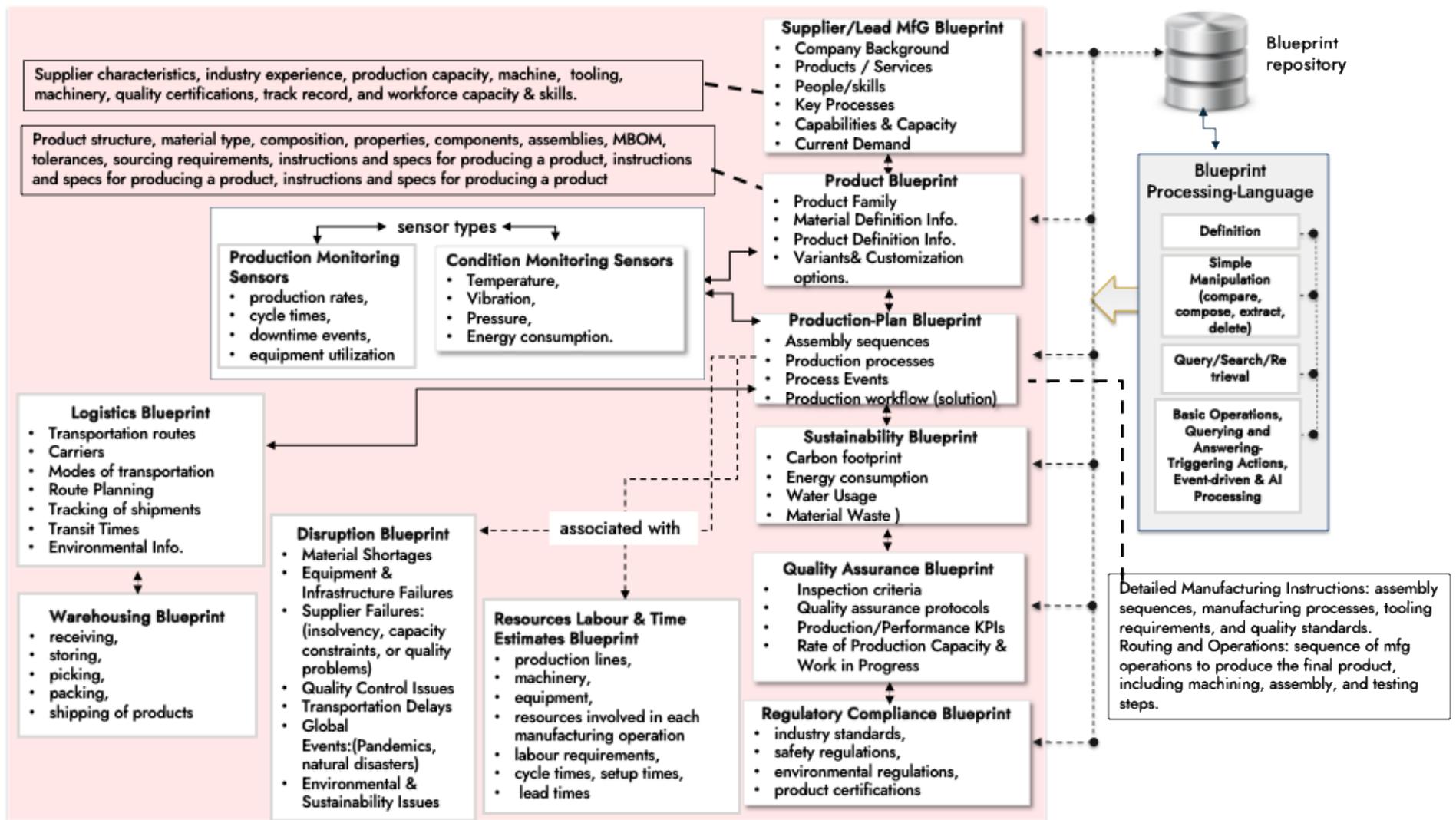
FIGURE 1 BLUEPRINTS IN A SMART MANUFACTURING NETWORK.

2.2. HOW DO BLUEPRINT FRAMES RELATE TO DIGITAL TWINS?

Blueprint frames serve as the **data foundation** for **Digital Twins** in an SMN. By digitizing and structuring these frames, Digital Twins can:

1. **Create User-Friendly Virtual Models of Production Systems**
   - Digital Twins leverage blueprint frames to generate real-time, interactive virtual representations of products, processes, quality characteristics, and supply chains. These virtual models feature intuitive, User-Friendly Dashboard (graphical interface), enabling users to easily navigate, analyse, and interact with real-time data. Production engineers and managers can navigate production stages via a graphical Digital Twin interface and can therefore simulate, test, and optimize production scenarios in an accessible digital environment before real-world implementation.

2. **Enable Adaptive and Programmable Manufacturing**
   - Since blueprint frames define process logic and resource configurations, Digital Twins can dynamically adjust production workflows based on demand, machine availability, or supply chain disruptions.
   - This supports Manufacturing-as-a-Service, where production capabilities are reconfigurable across an SMN.

3. **Optimize Operations Through Data-Driven Insights**
   - Digital Twins leverage blueprint frames to monitor and analyse manufacturing KPIs, identifying inefficiencies and opportunities for improvement.
   - AI-driven models — developed in WP4 to work with the IMC - can then suggest adjustments to processes, material usage, or logistics for improved performance.

4. **Enhance Interoperability & Collaboration**
   - Standardized blueprint frames ensure that multiple factories, suppliers, and logistics providers can seamlessly integrate into the SMN.
   - Digital Twins act as a central intelligence hub, synchronizing data across different production sites.

5. **Support Resilience & Proactive Decision-Making**
   - By continuously updating blueprint frames with real-time data, Digital Twins anticipate disruptions and recommend mitigation strategies.
   - Manufacturers can model alternative production sequences, supplier options, and logistics routes to maintain operational continuity.

2.3. SIGNIFICANCE OF FRAMES AND THEIR INTER-RELATIONSHIPS

Blueprint frames serve as configurable building blocks that encapsulate distinct yet interconnected aspects of production, supply chains, and operational workflows within a Smart Manufacturing Network. Each blueprint frame represents a structured layer of information —ranging from material flow and equipment status to supplier relationships and disruption risks— allowing users to navigate through the complexities of modern manufacturing environments. These frames are not isolated; they

are dynamically linked, forming a knowledge network that continuously evolves as new data flows in. Through this interconnected system, both human operators and the Intelligent Manufacturing Custodian (IMC) can traverse and analyse different layers of information, gaining a global, abstract view of the SMN. This holistic perspective enhances situational awareness, enables data-driven decision-making, and fosters proactive responses to emerging challenges, ultimately leading to a more resilient, adaptive, and optimized manufacturing ecosystem as described below.

- o **Sensor & Production Synergy:** Real-time equipment data from the **Sensor Frame** informs the **Production Frame**, enabling **predictive maintenance** and minimizing downtime. For example, sensors on CNC machines cutting cot frames can detect tool wear, triggering automated adjustments to avoid production delays.

- o **Supplier & Logistics Synergy:** The **Supplier Frame** feeds real-time material availability data into the **Logistics Frame**, ensuring seamless inventory management. For instance, if a supplier of organic wood experiences a delay, logistics can adjust shipping schedules to maintain a steady supply chain for cot production.

- o **Product & Performance Synergy:** The **Product Frame** sets design and quality standards, while the **Quality Assurance Frame** monitors real-time compliance. For example, automated quality checks on bespoke cots can detect paint inconsistencies or structural weaknesses, prompting immediate process adjustments to maintain premium craftsmanship.

- o **Production & Logistics Synergy:** The **Production Frame** updates the **Logistics Frame** on inventory needs and order fulfillment. For example, if an influx of custom cot orders requires additional storage, logistics can dynamically allocate warehouse space and optimize delivery routes for on-time shipment.

This seamless data integration across blueprint frames ensures efficient workflows, high-quality production, and a resilient supply chain in bespoke child cot manufacturing.

Blueprint frames in an SMN provide the modular structure that enables Digital Twins to function as intelligent, real-time orchestration systems. By integrating these frames, DTs transform static manufacturing models into dynamic, adaptive, and resilient networks, ensuring seamless collaboration and optimized production across the supply chain.

In an SMN, blueprints are designed to integrate live data from IoT sensors, along with historical data, enabling dynamic updates to the digital twin's state and behaviour in real-time. This rich historical insight, combined with real-time data, enables the SMN to anticipate challenges and helps provide a holistic and up-to-date view of manufacturing conditions and maintain operational stability. This allows manufacturers to identify potential bottlenecks, mitigate risk, and optimize workflows before disruptions occur.

A key innovation in NARRATE is the use of a special-purpose digital twin language that operates directly on blueprint frames. This language unlocks a wealth of critical insights, including supplier shortages, product and machine defects, sustainability conditions, and environmental impacts. By offering a comprehensive, up-to-the-minute view of the production ecosystem, these blueprints empower decision-makers with the knowledge needed to proactively adjust strategies, enhance supply chain resilience, and drive sustainable manufacturing practices.

Blueprint frames are programmable statically typed objects in a Digital Twin Processing Language, see section-3, ensuring strict type consistency and early error detection. This enhances reliability when processing real-time data from IoT, simulations, and AI analytics. In Digital Twin environments, static typing maintains data integrity across manufacturing assets, reducing runtime errors and enabling seamless orchestration within a Smart Manufacturing Network. By combining the robustness of static typing with the dynamic adaptability of Digital Twins, DTPL enables efficient, high-assurance decision-making in complex industrial ecosystems.

2.4. PAIRING BLUEPRINTS WITH AI TECHNOLOGIES

In NARRATE, blueprints are not only dynamic data repositories, but also powerful enablers of AI-driven decision-making explored in WP4. By integrating real-time blueprint insights with advanced AI algorithms, the SMN can automatically detect potential disruptions, predict supply chain inefficiencies, and recommend optimal responses. AI-enhanced analytics leverage the historical and real-time data within blueprints to proactively resolve supplier shortages, mitigate machine failures, and adapt to environmental constraints. Additionally, AI-driven optimization allows for readjustment of production schedules and supply chain configurations, ensuring the network remains agile, resilient, and continuously aligned with operational goals.

As an example, Generative AI can significantly enhance smart manufacturing and smart manufacturing networks SMNs that incorporate digital twins by offering various capabilities that improve efficiency, collaboration, and decision-making. Generative AI (GenAI) and blueprints can work symbiotically to enhance intelligence and adaptability in a SMN. Blueprint Frames act as virtual representations of physical assets, processes, and operations, continuously collecting and structuring rich descriptive data—such as product specifications, production timelines, supplier details, logistics, and overall supply chain dynamics. By integrating Large Language Models (LLMs), this wealth of information can be analysed, contextualized, and transformed into actionable insights. LLMs enable blueprints to go beyond data-driven modelling, providing deep contextual reasoning to identify trends, anticipate risks, and optimize decision-making. This fusion shifts blueprints from passive data repositories to dynamic, context-aware systems capable of adapting to real-time changes in complex manufacturing environments. Contextual reasoning LLMs in T3.3 can process and interpret vast amounts of data, enabling Digital Twins to:

o **Understand and interpret contextual insights** from diverse sources (e.g., maintenance logs, production data, supply chain updates).
o **Generate human-readable explanations and recommendations** based on real-time DT data.
o **Improve predictive accuracy** by integrating historical patterns, external factors and operational conditions.

For example, in a Smart Manufacturing Network for furniture production, an LLM can analyse supply chain disruptions, and IoT sensor data to predict delays and suggest optimal scheduling adjustments.

2.5. DIGITAL TWIN INTEROPERABILITY STANDARDS

In the realm of smart manufacturing, the implementation of digital twins is guided by several prominent

standards that ensure interoperability, and efficiency. In smart manufacturing, interoperability standards and protocols are essential for seamless communication between diverse equipment and systems. Standards facilitating this interoperability are Open Platform Communications Unified Architecture (OPC UA), MTConnect, the Connected Factory Exchange (CFX) by the IPC Consortium and the ISO 23247 Standard. As the OPC UA and the MTConnect standards have been presented in D3.1 this deliverable will focus on the CFX and ISO 23247 standards.

2.5.1. OPC UA and MTConnect

OPC UA

OPC UA is a platform-independent, service-oriented architecture that enables secure and reliable data exchange across various industrial devices and systems. It provides a comprehensive framework for modeling information, ensuring consistent data representation and communication.

MTConnect

MTConnect is a manufacturing interoperability standard that provides a semantic vocabulary for manufacturing equipment to provide structured, contextualized data in a non-proprietary format. It defines a read-only communication standard, allowing devices to present data uniformly.

What is the difference between OPC and MTConnect?

OPC UA is a machine to machine and machine to enterprise communication protocol for industrial automation. Thus, it ensures diverse automation systems are compatible with one another within a unified architecture that facilitates interoperability. On the other hand, MTConnect provides a machine to machine or machine to enterprise communication vocabulary that ensures equipment with similar standardized functions can communicate.

What this means is that OPC UA creates an enabling environment consisting of diverse equipment with varying network and communication technologies to communicate while MTConnect is basically the standardized language these equipment use in communicating. Thus, MTConnect is extensible and can be integrated into OPC UA.

2.5.2. Connected Factory Exchange (CFX)

IPC CFX is an industry-developed standard that facilitates the exchange of information between manufacturing processes and systems. It provides a plug-and-play solution for assembly manufacturing, ensuring seamless communication throughout the entire factory.

Key Features:

o **Plug-and-Play Connectivity:** Enables easy integration of equipment and systems without extensive configuration.
o **Real-Time Data Exchange:** Facilitates immediate sharing of information across processes.
o **Standardized Protocol:** Utilizes a common communication protocol to ensure compatibility.

Application in Smart SMNs:

IPC CFX streamlines the flow of information between machines, systems, and processes, reducing the complexity of data integration. It supports real-time decision-making by providing accurate and timely data, thereby enhancing production efficiency and product quality.

2.5.3. The ISO 23247 Standard

The ISO 23247 standard, entitled "Automation systems and integration — Digital twin framework for manufacturing," provides a structured approach to implementing digital twins in manufacturing settings. It is organized into multiple parts, each addressing specific aspects of the framework:

1. **Part 1: Overview and General Principles** — This section introduces the fundamental concepts, terminology, and foundational principles of the digital twin framework for manufacturing **iso.org**
2. **Part 2: Reference Architecture** — It details a reference architecture, outlining the essential components and their interactions within a digital twin system tailored for manufacturing applications **cdn.standards.iteh.ai**
3. **Part 3: Digital Representation of Manufacturing Elements —** This part specifies the digital representation of various manufacturing elements, ensuring consistency and interoperability across different systems **iso.org**
4. **Part 4: Information Exchange** — It focuses on the mechanisms and protocols for effective information exchange between digital twins and other systems within the manufacturing environment **iso.org**

By adhering to the ISO 23247 standard, manufacturers can develop digital twins that enhance visibility into processes and execution, thereby improving operational efficiency and business collaboration.

2.5.4. The Synergy between the Selected Standards

Table 1 presents a comprehensive matrix highlighting the primary features of four pertinent standards: OPC UA, MTConnect, ISO 23247, and Connected Factory Exchange (CFX).

Feature	OPC UA	MTConnect	ISO 23247	Connected Factory Exchange (CFX)
Purpose	Facilitates secure and reliable data exchange across various industrial devices and systems.	Provides a standardized vocabulary for manufacturing equipment to present data uniformly	Offers a framework for creating digital twins in manufacturing environments	Enables seamless information exchange between manufacturing processes and systems.
Architecture	Platform-independent, service-oriented architecture	Defines a read-only communication standard using HTTP and XML	Comprises multiple parts detailing architecture, terminology and methodologies.	Provides a plug-and-play solution for assembly manufacturing.

Key Features	- Platform independence. - Robust security measures - Scalability	- Standardized vocabulary - Simplicity in implementation - Extensibility	- Comprehensive framework - Standardized approach - Focus on interoperability	- Plug-and-play connectivity - Real time data exchange - Standardized communication
Application in Smart Manufacturing	Enables real-time data acquisition and control, allowing monitoring and management of equipment performance and production workflows	Collects and analyzes data from diverse equipment, providing insights into machine utilization and performance.	Enhances visibility into processes and execution, improving operational efficiency and collaboration	Streamlines information flow between machines, systems, and processes, supporting real-time decision-making.
Interoperability	Integrates with MTConnect via the MTConnect-OPC UA Companion Specification.	Can be integrated into OPC UA to enhance interoperability.	Aligns with existing standards to ensure consistency across various systems and processes	Designed do work seamlessly with other manufacturing standards and protocols

<div align="center">TABLE 1 PRIMARY FEATURES OF FOUR PERTINENT STANDARDS.</div>

To support the NARRATE blueprints, which focus on creating regenerative and resilient SMNs, the above standards can be utilized in the following manner:

1. **ISO 23247: Digital Twin Framework for Manufacturing**

   ISO 23247 provides a comprehensive framework for developing digital twins in manufacturing. By adhering to this standard, NARRATE can ensure a structured approach to creating digital representations of manufacturing processes, facilitating real-time monitoring and proactive decision-making **cdn.standards.iteh.ai**

2. **Open Platform Communications Unified Architecture (OPC UA)**

   OPC UA is a platform-independent, service-oriented architecture that enables secure and reliable data exchange across various industrial devices and systems. Implementing OPC UA within NARRATE's framework can facilitate seamless communication between diverse equipment and systems, ensuring interoperability and efficient data exchange **opcfoundation.org**

3. **MTConnect**

   MTConnect provides a standardized vocabulary for manufacturing equipment to present data uniformly. Integrating MTConnect into the NARRATE's architecture can enable consistent data collection and analysis from various equipment, enhancing machine utilization and performance monitoring **mtconnect.org**

4. Connected Factory Exchange (CFX) by IPC Consortium

IPC CFX is an industry-developed standard designed to facilitate the exchange of information between manufacturing processes and systems. Incorporating CFX into NARRATE's blueprint can streamline information flow between machines, systems, and processes, supporting real-time decision-making and enhancing production efficiency.

During the next phase, these standards will undergo a rigorous evaluation and assessment to determine their suitability as an implementation framework for Blueprints and the Digital Twin Processing Language (DTPL). This process will identify the most robust and adaptable standards, ensuring seamless integration, interoperability, and optimal performance within the SMN.

The blueprint frames have undergone rigorous assessment and iterative refinement through in-depth collaboration with pilot stakeholders and technical partners. This preliminary version remains a dynamic, evolving framework, continuously evaluated and enhanced to guarantee a precise and unambiguous implementation in the next phases of the project.

2.6. RELATION TO EXISTING RESEARCH

Digital twin technology has emerged as a transformative force in networked supply chains and smart manufacturing, offering virtual replicas of physical systems to enhance operational efficiency and resilience. This literature review examines recent scientific advancements in this domain, highlighting both the benefits and challenges associated with these approaches.

Work on DTs in NARRATE has been influenced by several established concepts within the digital twin and smart manufacturing community. While the concept of DTs has been around for quite some time [4], many literary examples of DTs are highly application-specific and narrow in focus [5] and [6]. Despite the promising potential of digital twins in networked supply chains and smart manufacturing, a lack of consensus on standardized approaches persists, and large-scale, fully realized implementations remain limited [7]. While various studies on DT exist, widespread implementation is yet to be achieved. Many proposed concepts remain in the experimental phase, with few fully integrated solutions in real-world industrial settings [8]. One of the primary reasons is that companies struggle to define the implementation scope where DTs will create tangible business value [1].

Modern product development processes increasingly integrate Model-Driven Engineering (MDE) [9], [10] and Model-Driven Development (MDD), where models serve as the primary development artifacts, replacing conventional document-based approaches [11]. MBSE enhances traditional systems engineering by elevating the level of abstraction and promoting the use of structured, standardized models over unstructured documentation. This shift fosters greater consistency, traceability, and automation in system design, resulting in improved decision-making, reduced development time, and enhanced adaptability to complex engineering challenges.

These advancements are particularly relevant in the context of Smart Manufacturing Networks, where MDE and MDD play a crucial role in designing, optimizing, and managing interconnected production systems. In smart factories, MDE facilitates the integration of Digital Twins, providing real-time insights into manufacturing processes and supply chain dynamics [12]. By leveraging cyber-physical models, MDE supports predictive analytics, system-wide simulations, and automated decision-making, fostering

agility and resilience in networked supply chains [13], [14].

The NARRATE project builds upon these principles by introducing Blueprint Frames—an innovative DT paradigm based on MDE and MDD that offers a holistic, real-time representation of supply chain networks [3]. Unlike traditional DT implementations, NARRATE's Blueprint Frames provide:

o *A holistic view of supply chain operations*, integrating real-time data from diverse production sources to enhance situational awareness and proactive decision-making.
o *A programmable MaaS approach*, enabling dynamic reconfiguration of manufacturing assets and flexible, demand-driven production planning.
o *Resilience through predictive analytics*, leveraging AI-driven forecasting to mitigate disruptions and optimize supply chain performance.
o Fully integrated solutions in real-world industrial settings, ensuring that Blueprint Frames are not merely theoretical constructs but actively deployed to improve manufacturing resilience and efficiency.

Furthermore, model-driven approaches enhance interoperability among MaaS platforms. MaaS represents a paradigm shift in modern manufacturing, emphasizing the sharing of networked production infrastructures to enable dynamic reconfiguration and optimization of workflows [15].

Domain-Specific Languages (DSLs) also play a crucial role in Model-Driven Engineering for digital manufacturing [16]. They provide tailored, high-level abstractions that align with industry-specific requirements. Unlike general-purpose programming languages, DSLs simplify complex modelling tasks, making it easier for domain experts to define, configure, and optimize manufacturing processes without deep technical expertise [17]. DSLs enable:

o Precise modelling of smart manufacturing workflows, ensuring seamless integration with Digital *Twins and Industrial IoT (IIoT) platforms.*
o *Automated generation of executable models, reducing human errors and ensuring consistency in production systems.*
o *Dynamic customization* and interoperability in MaaS environments, facilitating adaptive production and supply chain coordination.

The authors in [17] introduced a model-driven engineering approach that leverages DSLs to facilitate collaborative product-service design and customization by operating on blueprint frames. This approach employs a view-based modelling technique, enabling stakeholders to manage evolving and unforeseen requirements effectively. A prototype implementation demonstrated the approach's applicability across four industrial pilot cases as part of the H2020 project ICP4Life (**www.icp4life.eu**).

Building on this foundation, the Digital Twin Processing Language in NARRATE extends these capabilities to support intelligent supply chain resilience. By integrating real-time data analytics, predictive modelling, and adaptive decision-making, this enhanced framework enables more robust, responsive, and intelligent supply chain management, ensuring greater adaptability to disruptions and improved operational efficiency.

The NARRATE project aligns with existing research by emphasizing the integration of DTs to enhance supply chain resilience. Similar to the frameworks proposed by [18], NARRATE focuses on creating transparent and resilient supply chain systems through advanced analytics and modelling techniques.

The project's emphasis on data visibility and AI solutions mirrors the findings of [19], highlighting the critical role of DTs in information and risk management across various industries. Furthermore, NARRATE's use of AI in conjunction with DTs to predict and mitigate disruptions aligns with the insights in [20] on the role of AI in enhancing supply chain resiliency.

In summary, the NARRATE project embodies the principles identified in prominent research by leveraging DTs, AI, and Big Data to create regenerative, resilient, and SMN. A DT will be largely based on extensions of work in the H2020 project ICP4Life (icp4life.eu), which includes formal DT models for products, assets — including sensors — production and, performance. It will offer a single source for data, facts, "truth" & intelligence that will be used by the IMC for improved decision-making [3], [17]. By introducing Blueprint Frames, a holistic and programmable MaaS-driven approach, NARRATE enhances supply chain resilience and fosters a new era of intelligent, self-orchestrating manufacturing ecosystems.

3. THE DIGITAL TWIN PROCESSING LANGUAGE

The Digital Twin Processing Language in NARRATE is a simple domain-specific language that could be **invoked both by experts and the IMC**, which is designed to facilitate the interaction, processing, control, and orchestration of DTs within an SMN. In NARRATE, DTPL can process Smart Manufacturing Network blueprints, which serve as digital representations of the entire manufacturing ecosystem. These blueprints encapsulate a vast amount of structured information, making them navigable to extract key insights about the network, including details about the lead manufacturer (OEM) and its suppliers as shown in Figure 1. Some of the salient characteristics of DTPL include:

1. **Semantic Awareness & Interoperability**
   - DTPL enables seamless communication between a variety of blueprint frames across and within a specific manufacturing domain.
   - It incorporates ontology-based representations to standardize data exchange.
2. **Event-Driven Processing**
   - It supports *event-based triggers* allowing the IMC to react dynamically to production changes (using complex event processing languages, such as ESPER or PERSEO).
   - Facilitates the IMC to conduct *predictive and prescriptive analytics* by integrating IoT sensor data, machine logs, and external disruptions.
3. **Modular & Extensible Syntax**
   - The language supports *modular programming* to define reusable components for DTs behaviours.
   - It can be extended with domain-specific extensions for different manufacturing contexts.
4. **Integration with MaaS Principles**
   - DTPL is designed to work alongside MaaS principles, enabling programmable workflows for distributed manufacturing [21].
5. **Graph-Based and Workflow-Oriented Modelling**
   - The language could adopt a user-friendly *graph-based structure* to represent Digital Twin interactions, dependencies, and workflows.

Declarative and Context-Aware Syntax: The language would feature a declarative syntax that

focuses on *what* the user wants to accomplish (e.g., "optimize production schedule under current conditions"), rather than *how* to accomplish it [22]. Additionally, it would be context-aware, meaning that it can adapt workflows and simulations based on the current operating conditions, system states, or external inputs.

3.1. NAVIGABILITY OF DTPL-PROCESSED BLUEPRINTS

The DTPL's advanced navigation capabilities enable DTPL to traverse a vast network of interconnected blueprint frames, seamlessly mapping dependencies and extracting critical insights. DTPL enables the querying, traversal, and visualization of digital blueprints, providing a dynamic view of the SMN's structure, dependencies, and performance metrics.

This dynamic exploration empowers both the IMC and human decision-makers with enhanced situational awareness, fostering smarter, data-driven decisions in complex manufacturing environments. Key information extracted from blueprints using navigation include:

1. **Lead Manufacturer (OEM) & Suppliers' Profile**
   - Identity and credentials of the Lead Manufacturer and Suppliers
   - Manufacturing capabilities (e.g., production capacity, specialization, automation level)
   - Geographic location and logistics data
   - Key performance indicators (KPIs) of the Lead Manufacturer such as production efficiency, defect rates, and energy consumption
   - Certifications & compliance with industry standards
2. **Supplier Network & Dependencies**
   - Supplier classification (tier-1, raw material providers, logistics partners)
   - Material flow tracking, showing how components move across the supply chain
   - Supplier performance metrics, including reliability, quality scores, and delivery timelines
   - Risk assessment based on external factors (e.g., geopolitical risks, supply chain disruptions)
3. **SMN Operational and Predictive Insights**
   - Real-time monitoring of production lines using IoT-integrated digital twins
   - Predictive maintenance alerts, flagging potential machine failures before they occur
   - Bottleneck detection, identifying inefficiencies in the production workflow
   - Resource utilization insights, showing how production loads are distributed across different suppliers
   - Sustainability metrics, such as CO_2 footprint tracking across the SMN.

How This Benefits Smart Manufacturing Networks

The DTPL presents a number of benefits for manufacturing eco-systems.
- Transparency & Traceability — Stakeholders can easily navigate the SMN to access accurate supplier and OEM data.
- Resilience & Risk Management — Identifies vulnerabilities in the supply chain and enables proactive decision-making.
- Enhanced Collaboration — Ensures seamless data exchange between partners, reducing inefficiencies and miscommunications.

These features will be revisited and further elaborated in *3.3. Parts of the DTPL.*

3.2. PRACTICAL EXAMPLE: BESPOKE COT MANUFACTURING WITH DTPL
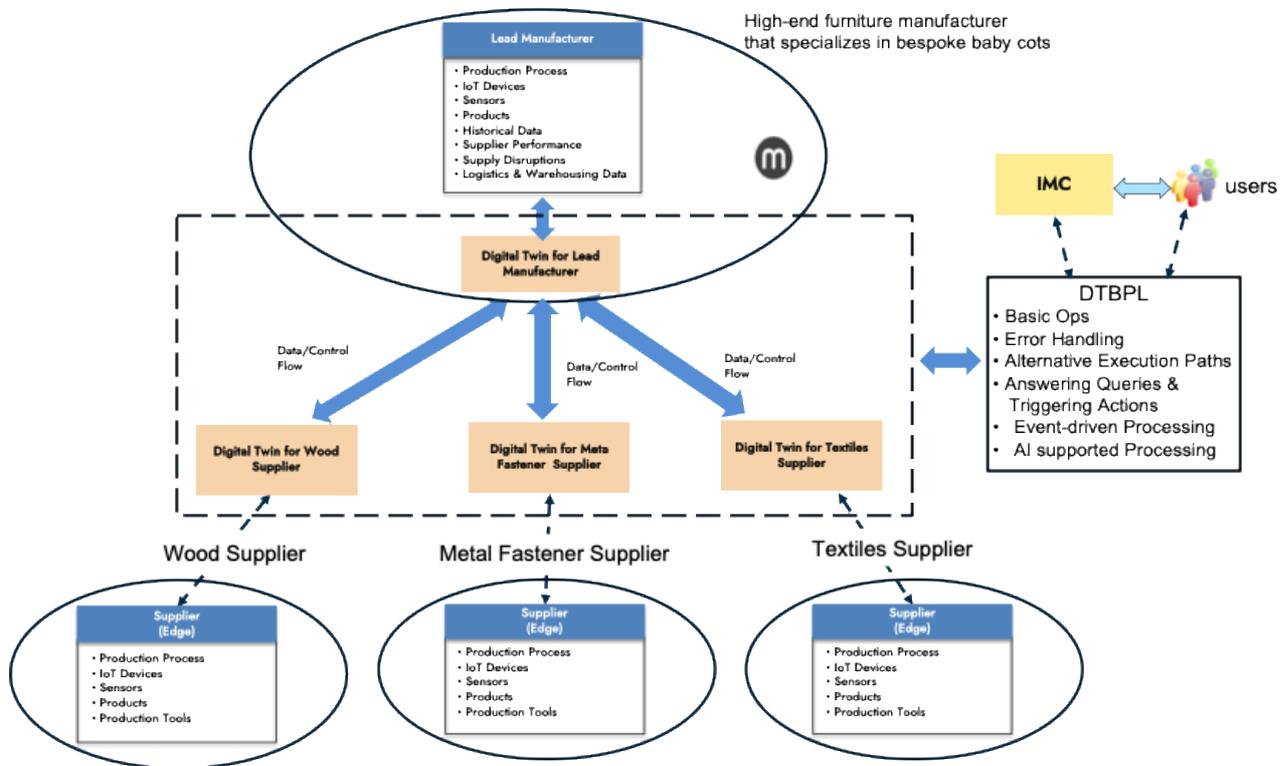
FIGURE 2 SMN OF A BESPOKE BABY COT MANUFACTURING INVOLVING WOOD, METAL FASTENER AND TEXTILE SUPPLIERS.

In this example, the lead manufacturer (OEM) manages the production of bespoke baby cots, while various suppliers provide materials (wood, metal, textiles) and services (cutting, finishing, delivery). The example shown in Figure 2 is intended to illustrate how the IMC (Intelligent Manufacturing Custodian) navigates these connections using DTPL. It shows how the lead manufacturer coordinates with material suppliers and production nodes.

Scenario: Bespoke Cot Order with DTPL in Action

A high-end furniture company specializes in bespoke baby cots. A customer orders a customized cot with specific dimensions, materials, and a unique finish. DTPL processes the blueprints, enabling:

1. **Lead Manufacturer Identifies Requirements**
   - DTPL retrieves product specifications and matches the order with suitable suppliers.
   - The Intelligent Manufacturing Custodian analyses available stock, sourcing wood from Supplier A, metal fasteners from Supplier B, and custom textiles from Supplier C using BPTL operations described below in *3.3. Parts of the DTPL*.
2. **Supplier Coordination**
   - DTPL verifies supplier capacity and procures materials.
   - If a supplier faces delays, the IMC invokes DTPL operations to suggest an alternative supplier. This is described in example 1 in *3.4. Answering Blueprint queries & triggering actions.*
3. **Production Workflow Optimization**
   - The cutting and shaping unit are assigned tasks based on real-time machine availability.

- IoT sensors monitor cutting precision, while predictive maintenance alerts prevent machine failures (see *3.5.2. Multi-Twin Interactions for Predictive Maintenance).*

4. Assembly & Quality Control
- The IMC uses DTPL operations to ensure the Lead manufacturer assembly line receives components on time, adjusting schedules if delays occur.
- AI-driven quality checks (issued by the IMC and its algorithms in WP4) detect defects in materials or workmanship before finalizing production.

5. Final Delivery & Logistics
- The finished cot is assigned an optimal logistics partner based on cost, availability, and real-time delivery tracking.

The following subsection introduces the key components of the Digital Twin Processing Language, accompanied by representative and practical examples. These examples demonstrate how DTPL can be effectively applied within the customized cot order scenario described earlier, showcasing its capabilities in real-time decision-making, adaptive manufacturing, and seamless supply chain coordination. The DTPL examples presented in the following operate on the blueprint frame definitions shown in *Figure 1.*

3.3. PARTS OF THE DTPL

The DTPL is designed to have three parts outlined below.

3.3.1. Basic Operations

The main basic operators are as follows:

o *Blueprint CRUD operators*: these provide the necessary constructs to Create (Define), Read, Update and Delete the blueprint frames or their attributes as described above.

o *Simple Blueprint manipulation operators*: these provide a set of operators for users and stakeholders to *retrieve* existing blueprints contained in a Blueprint Repository to *compare*, *compose,* and *extract* information from blueprints. Blueprint composition employs the *compose* operation to *interconnect* a set of blueprints end-to-end by describing all of their characteristics, parts, services, quality and operational aspects.

o Other basic operators include storing (publishing), retrieving and authenticating blueprint definitions from a Blueprint Repository.

The example below defines several very simple blueprints for the bespoke baby cot SMN in *Figure 2*.

3.3.2. Blueprint Definitions

The following table defines several blueprint frames associated with the baby cot example.

TABLE 2 DEFINITION OF BLUEPRINT FRAMES FOR THE BABY COT EXAMPLE.

```
DEFINE PRODUCT BespokeCot {
    dimensions: { length: 120cm, width: 60cm, height: 80cm }
    material: { wood: "Oak", fasteners: "Steel Bolts", fabric: "Organic Cotton" }
    finish: "Non-toxic White Paint"}
```

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```
DEFINE BLUEPRINT TYPE SUPPLIER LeadManufacturer {
    type: "Baby Cot Supplier"
    location: "Spain"
    capacity: "200 units/day"
    lead_time: "15 days"}

DEFINE BLUEPRINT TYPE SUPPLIER SupplierA {
    type: "Wood Supplier"
    material: "Oak"
    location: "Germany"
    capacity: "500 units/day"
    lead_time: "3 days"}

DEFINE BLUEPRINT TYPE SUPPLIER SupplierB {
    type: "Fasteners Supplier"
    material: "Steel Bolts"
    location: "Italy"
    capacity: "1000 units/day"
    lead_time: "2 days"}

DEFINE BLUEPRINT TYPE SUPPLIER SupplierC {
    type: "Fabric Supplier"
    material: "Organic Cotton"
    location: "Portugal"
    capacity: "700 meters/day"
    lead_time: "4 days"}

DEFINE BLUEPRINT TYPE PROCESS CuttingStage {
    input: "Oak Wood from SupplierA"
    output: "Precision-cut cot panels"
    machine: "CNC Router #5"
    estimated_time: "2 hours"
    failure_tolerance: "0.01mm"}

DEFINE BLUEPRINT TYPE PROCESS AssemblyStage {
    input: ["Precision-cut panels", "Steel Bolts from SupplierB"]
    output: "Assembled Cot Frame"
    station: "Robotic Assembly Line #3"
    estimated_time: "3 hours"}

DEFINE BLUEPRINT TYPE PROCESS FinishingStage {
    input: ["Assembled Cot Frame", "Non-toxic White Paint"]
    output: "Final Cot"
    station: "Spray Booth #2"
    estimated_time: "2 hours"}

DEFINE BLUEPRINT TYPE PRODUCTION_PLAN Cot_Production {
```

UK Research and Innovation, Horizon Europe Guarantee.

```
step1: REQUEST SupplierA.material IF inventory_check(Wood) < 10
step2: REQUEST SupplierB.material IF inventory_check(Fasteners) < 50
step3: REQUEST SupplierC.material IF inventory_check(Fabric) < 20
step4: EXECUTE CuttingStage
step5: EXECUTE AssemblyStage AFTER CuttingStage
step6: EXECUTE FinishingStage AFTER AssemblyStage
step7: SCHEDULE DELIVERY customer_id="COT1001"}
```

Explanation of the DTPL Elements follows:

Product Definition (DEFINE BLUEPRINT TYPE PRODUCT) — Specifies dimensions, materials, and finishing details.

Supplier Mapping (DEFINE BLUEPRINT TYPE SUPPLIER) — Captures supplier capabilities, locations, and lead times.

Process Definitions (DEFINE BLUEPRINT TYPE PROCESS) — Defines each step, including inputs, outputs, machines, and quality checks.

Production Workflow (DEFINE BLUEPRINT TYPE) — Specifies the logic of when to order materials, execute manufacturing steps, and schedule deliveries.

3.3.3. Extending DTPL with Error Handling & Alternative Execution Paths

To make the bespoke cot manufacturing process more resilient, we will enhance the DTPL syntax with:

- *Supplier Failure Handling* — If a supplier is delayed, DTPL automatically switches to an alternative supplier.

- *Production Line Adaptability* — If a machine fails, the workflow reroutes tasks to backup machines.

- *Real-Time Monitoring & Alerts* — Integrates IoT-based failure detection and triggers contingency actions.

The following code snippet extends the definition of bluprints with error handling and alternative execution paths. This code snippetdeals with different kinds of failures such as:

- Alternative Supplier Selection (alternative:)
  If SupplierA is delayed, DTPL automatically switches to SupplierD.
  The same logic applies for fasteners and fabric, ensuring continuity in production.

- Machine/Station Failure Handling (fallback_machine, fallback_station)
  If CNC Router #5 fails, DTPL reroutes the task to CNC Router #7.
  If the robotic assembly line malfunctions, the task shifts to Manual Assembly Line #2.

- Automatic Recovery for Production Errors (TRY…CATCH)
  If a machine fails during execution, DTPL catches the failure and reassigns the task.
  If a quality check fails, the product automatically re-enters the finishing stage for corrections.

```
DEFINE BLUEPRINT TYPE SUPPLIER SupplierD {
    type: "Wood Supplier"
    material: "Oak"
    location: "Poland"
    capacity: "300 units/day"
    lead_time: "5 days"}


DEFINE BLUEPRINT TYPE SUPPLIER SupplierE {
    type: "Fasteners Supplier"
    material: "Steel Bolts"
    location: "France"
    capacity: "900 units/day"
    lead_time: "3 days"}


DEFINE BLUEPRINT TYPE SUPPLIER SupplierF {
    type: "Fabric Supplier"
    material: "Organic Cotton"
    location: "Spain"
    capacity: "500 meters/day"
    lead_time: "5 days"}


DEFINE BLUEPRINT TYPE PROCESS CuttingStage {
    input: "Oak Wood from SupplierA OR SupplierD"
    output: "Precision-cut cot panels"
    machine: "CNC Router #5"
    estimated_time: "2 hours"
    QUALITY ASSURANCE.failure_tolerance: "0.01mm"
    fallback_machine: "CNC Router #7"}


DEFINE BLUEPRINT TYPE PROCESS AssemblyStage {
    input: ["Precision-cut panels", "Steel Bolts from SupplierB OR SupplierE"]
    output: "Assembled Cot Frame"
    station: "Robotic Assembly Line #3"
    estimated_time: "3 hours"
    fallback_station: "Manual Assembly Line #2"}


DEFINE BLUEPRINT TYPE PROCESS FinishingStage {
    input: ["Assembled Cot Frame", "Non-toxic White Paint"]
    output: "Final Cot"
    station: "Spray Booth #2"
    quality_check: "Yes"
    estimated_time: "2 hours"
    fallback_station: "Manual Finishing Bay #1"}


DEFINE BLUEPRINT TYPE PRODUCTION PLAN Cot_Production {
    step1:
```

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```
IF LOGISTICS.inventory_check(Wood) < 10 THEN
  REQUEST SupplierA.material
ELSE IF SupplierA.status == "Delayed" THEN
  REQUEST SupplierD.material


step2:
 IF LOGISTICS.inventory_check(Fasteners) < 50 THEN
   REQUEST SupplierB.material
 ELSE IF SupplierB.status == "Delayed" THEN
   REQUEST SupplierE.material


step3:
 IF LOGISTICS.inventory_check(Fabric) < 20 THEN
   REQUEST SupplierC.material
 ELSE IF SupplierC.status == "Delayed" THEN
   REQUEST SupplierF.material


step4:
 TRY EXECUTE CuttingStage
 CATCH failure THEN EXECUTE CuttingStage.fallback_machine


step5:
 TRY EXECUTE AssemblyStage AFTER CuttingStage
 CATCH failure THEN EXECUTE AssemblyStage.fallback_station


step6:
 TRY EXECUTE FinishingStage AFTER AssemblyStage
 CATCH failure THEN EXECUTE FinishingStage.fallback_station


step7:
 IF quality_check(Final Cot) == "Fail" THEN
   REWORK FinishingStage
 ELSE
   SCHEDULE DELIVERY customer_id="COT1001"}
```

Two important DTPL operations that are for error handling and specifying alternative execution paths in Table 3 are TRY EXECUTE and TRY CATCH. Their purpose is explained below.

TRY EXECUTE — Handling Specific Process Execution Failures
Purpose

o   The TRY EXECUTE command **attempts to run a specific manufacturing process**.

o   If the process **fails** (due to machine failure, resource unavailability, or sensor error), the system **switches** to a backup process or alternative execution path.

Example from the DTPL Code

```
TRY EXECUTE CuttingStage
CATCH failure THEN EXECUTE CuttingStage.fallback_machine
```

How It Works

1. DTPL attempts to run the CuttingStage process.
2. If CNC Router #5 malfunctions, the failure is captured by CATCH failure.
3. The workflow switches to CNC Router #7, ensuring the process continues.

TRY.CATCH — Generalized Failure Handling

Purpose

- TRY.CATCH is a more *generalized failure-handling mechanism* used in the DTPL workflow.
- It can handle any type of failure, including machine breakdowns, supply chain delays, quality check failures, or data inconsistencies.
- When an error occurs, DTPL executes an alternative process or mitigation strategy.

Example from the DTPL Code

```
TRY EXECUTE AssemblyStage AFTER CuttingStage
CATCH failure THEN EXECUTE AssemblyStage.fallback_station
```

How It Works

1. DTPL **executes the assembly process** once the cutting stage is completed.
2. If **a robotic assembly line fails**, the CATCH failure condition is triggered.
3. The system **redirects the task** to a **manual assembly line (fallback_station)** to keep production running.

TABLE 4 KEY DIFFERENCES BETWEEN TRY EXECUTE AND TRY CATCH

Feature	TRY EXECUTE	TRY CATCH
Scope	Used to execute and recover from a specific process failure	Handles any failure scenario in a broader workflow
When It Triggers	If the specified process fails	If any unexpected failure occurs in the workflow
Fallback Mechanism	Switches to backup machines, stations, or processes	Executes alternative recovery strategies
Example Use	Machine breakdown, switching from CNC Router #5 to CNC Router #7	Supplier failure, switching from SupplierA to SupplierD

Why TRY CATCH & TRY EXECUTE Are Critical for SMNs

Ensures Production Continuity — Machines and suppliers can fail, but manufacturing should never stop.

Minimizes Downtime — Automatic fallback execution prevents bottlenecks.

Improves Supply Chain Resilience — If a supplier fails, DTPL re-routes procurement dynamically.

3.4. ANSWERING BLUEPRINT QUERIES & TRIGGERING ACTIONS

Below are some example DTPL queries and operations that illustrate how the language can be used by users, apps or the IMC to detect and remedy potential disruptions. The code snippet below aligns

with the principles of Event-Condition-Action (ECA) rules commonly used in rule-based systems, particularly in an SMN.

We assume that the SMN in the following examples is related to the Medwood pilot in WP5. In the examples that follow, the Digital Twins play a crucial role in providing the IMC with the necessary data to perform simulations and what-if scenarios. These simulations enable the IMC to evaluate different production and supply chain scenarios, ultimately identifying the most optimal course of action for the Lead Manufacturer's production engineers. It is essential to clarify that the IMC does not autonomously adjust parameters, reconfigure production settings, or implement changes across the supply chain. Rather, its function is to offer informed guidance, allowing production engineers to make well-supported decisions based on comprehensive simulations and scenario analyses.

---

1. Detecting a Delay in Raw Material Delivery

DTPL Query: Check if any supplier shipments are delayed /* **Event** */

```
SELECT shipment_id, supplier, expected_arrival, delay_time
FROM SMN(Medwood SupplyChain.LOGISTICS_SERVICES)
WHERE status = "delayed";
```

DTPL Action: Reallocate stock from an alternate supplier

```
IF EXISTS(                                          /* Condition */
    SELECT * FROM SMN(Medwood SupplyChain).LOGISTICS_SERVICES
    WHERE status = "delayed"
) THEN
    UPDATE SMN(Medwood SupplyChain.LOGISTICS_SERVICES /* Action */
    SET supplier = "Alternative_Supplier_X"
    WHERE shipment_id = {delayed_shipment_id};
END IF;
```

This example identifies a delayed shipment and switches to an alternative supplier to prevent a production halt.

How It Works:

- **IoT Sensors & ERP Systems**:
  - GPS trackers in delivery trucks provide real-time location and ETA updates.
  - Supply chain ERP (Enterprise Resource Planning) systems log shipment statuses.
- **IMC (Intelligent Manufacturing Custodian)**:
  - The IMC monitors supply chain data and predicts delays using AI models trained on historical data.
- **IMC Decision-Making**:
  - The IMC AI model evaluates *alternative suppliers* based on availability, costs, and transit time.
  - If the delay is critical, the IMC proposes triggering the DTPL action to *switch suppliers dynamically*.

Outcome: Supply chain resilience improves, avoiding disruptions in manufacturing.

---

2. Predicting Machine Failure and Scheduling Maintenance

DTPL Query: Check machine health status and predict failures

```
SELECT machine_id, health_status, predicted_failure_time
FROM SMN(Medwood SupplyChain.SUPPLIER.DISRUPTION)
```

```
WHERE health_status < 50% AND predicted_failure_time < NOW() + INTERVAL 24 HOURS;
```

DTPL Action: Schedule maintenance before failure
```
IF EXISTS(
    SELECT * FROM SMN(Medwood SupplyChain.SUPPLIER.RESOURCE)
    WHERE health_status < 50% AND predicted_failure_time < NOW() + INTERVAL 24 HOURS
) THEN
    CALL RESOURCE.Machine.ScheduleMaintenance(machine_id, "urgent");
    UPDATE SMN(Medwood SupplyChain.RESOURCE.Machine)
    SET RESOURCE.Machine.status = "under_maintenance"
    WHERE RESOURCE.Machine.machine_id = {affected_machine};
END IF;
```

This example detects potential machine failures in advance and proactively schedules maintenance.

How It Works:

- **IoT Sensors (Predictive Maintenance)**:
  - Sensors monitor vibration, temperature, energy consumption, and wear levels in machines.
- **AI-Driven Failure Prediction**:
  - IMC AI models analyse historical failures and real-time sensor data to predict potential breakdowns.
- **IMC Decision-Making**:
  - If a machine is at risk, the IMC proposes to a human expert scheduling preventive maintenance through DTPL.
- **IMC Automated Workload Redistribution**:
  - The IMC proposes adjusting production schedules to ensure minimal downtime.

Outcome: Unplanned downtime is reduced, improving efficiency and cost savings.

---

3. Resolving Production Bottlenecks

DTPL Query: Identify production line slowdowns
```
SELECT line_id, cycle_time, avg_cycle_time
FROM SMN(Medwood SupplyChain.SUPPLIER.ProductionMonitoringSensors)
WHERE cycle_time > avg_cycle_time * 1.2;
```

Action: Optimize workload distribution
```
IF EXISTS(
    SELECT * FROM SMN(Medwood SupplyChain.SUPPLIER.ProductionMonitoringSensors)
    WHERE cycle_time > avg_cycle_time * 1.2
) THEN
    CALL ReallocateWorkload(line_id, "available_machines"); /* this is a binding to IMC code */
END IF;
```

This example detects inefficiencies in production lines and dynamically redistributes workload.

How It Works:

- **IoT Sensors on Production Lines**:

- o Track cycle times, throughput, and machine availability in real-time.
- **IMC AI Bottleneck Detection**:
  - o AI compares current cycle times to historical trends and identifies slowdowns.
- **IMC & Autonomous Decision-Making**:
  - o If a production line is slowing down, the IMC proposes triggering DTPL actions to *reallocate workloads dynamically* across nearby production lines.
  - o The IMC updates factory operators and proposes *shifting workloads* to less busy machines.

Outcome: Production efficiency improves by redistributing workloads in real time.

---

4. Mitigating Transportation Disruptions
DTPL Query: Detect delivery route issues (e.g., traffic, weather conditions)
SELECT delivery_id, route_status, estimated_delay
FROM SMN(Medwood SupplyChain.LOGISTICS_SERVICES)
WHERE route_status = "high_traffic" OR estimated_delay > 30;

DTPL Action: Reroute affected deliveries
IF EXISTS(
   SELECT * FROM DigitalTwin(Medwood SupplyChain.LOGISTICS_SERVICES)
   WHERE route_status = "high_traffic" OR estimated_delay > 30
) THEN
   CALL RecalculateOptimalRoute(delivery_id); /* this is binding to IMC code */
END IF;

This example detects transportation disruptions and reroutes deliveries in real time.

How It Works:

- **IoT & GPS Sensors**:
  - o Provide real-time data on traffic, road conditions, and estimated arrival times.
- **IMC AI-Powered Route Optimization**:
  - o AI models *predict congestion patterns* and suggest *alternative routes*.
- **IMC Decision-Making**:
  - o The IMC tests alternative routes and suggests DTPL actions to *reroute affected deliveries dynamically*.

Outcome: Avoids delays in material delivery, ensuring smooth production flow.

---

5. Adapting to Changes in Demand
DTPL Query: Monitor customer demand fluctuations
SELECT product_id, current_demand, avg_demand
FROM DigitalTwin(Medwood SupplyChain.SUPPLIER)
WHERE supplier_id="lead manufacturer" AND current_demand > avg_demand * 1.5;

DTPL Action: Increase production capacity dynamically
IF EXISTS(
   SELECT * FROM SMN(Medwood SupplyChain. SUPPLIER)

```
    WHERE supplier_id="lead manufacturer" AND current_demand > avg_demand * 1.5
) THEN
    UPDATE SMN(Medwood SupplyChain.Blueprint.SUPPLIER.PRODUCTIONPLAN)
    SET production_rate = production_rate * 1.2
    WHERE product_id = {high_demand_product};
END IF;
```

This example ensures that manufacturing adapts dynamically to sudden spikes in demand.

How It Works:

- **IoT & Market Data Feeds**:
  - Smart retail and e-commerce platforms track real-time product sales.
- **AI Demand Forecasting**:
  - AI predicts **demand surges** based on sales trends, seasonality, and consumer behaviour.
- **IMC & Dynamic Production Planning**:
  - The IMC modifies production schedules in the Digital Twins to increase output just-in-time.
- **IMC Automated Manufacturing Adjustments**:
  - The IMC adjusts production rates in the Digital Twins, which it proposes to users.

Outcome: Manufacturers meet demand spikes without overproducing or underproducing.

TABLE 5 SUMMARY: DTPL'S ROLE IN THE SMART MANUFACTURING NETWORK.

Scenario	IoT Integration	AI Decision-Making	IMC Role
Raw Material Delays	GPS shipment tracking	Predicts supplier risks	Switches to an alternative supplier
Machine Failures	Vibration/temperature sensors	Predicts breakdowns	Schedules preventive maintenance
Production Bottlenecks	Real-time cycle time monitoring	Detects slowdowns	Redistributes workloads
Transport Disruptions	GPS & traffic data	Reroutes deliveries	Updates logistics dynamically
Demand Fluctuations	Sales data	Predicts demand spikes	Adjusts production rates

The DTPL enables intelligent querying and real-time decision-making within the IMC. By leveraging blueprints, the IMC can proactively detect, analyse, and mitigate potential disruptions, ensuring resilient and efficient supply chain and production processes.

In summary, the Digital Twin Processing Language is the bridge between IoT-generated data, AI-driven predictions, and IMC-enabled decision-making. It ensures that the SMN can dynamically adapt to changes, mitigating disruptions and improving efficiency.

3.5. ADVANCED EVENT-DRIVEN & AI-SUPPORTED PROCESSING FOR COMPLEX IMC SCENARIOS

To enhance NARRATE's DTPL, we introduce advanced syntax extensions that enable multi-step automation, complex condition handling, event-driven triggers, and AI-driven optimization.

3.5.1. Event-Driven DTPL for Real-Time Decision Making

Scenario: If a critical supplier delay is detected, trigger a multi-step remediation plan.

- **DTPL Use Case**: Detecting supplier delays and selecting an alternative supplier dynamically.
- **AI Model Used**: Supplier Risk Prediction & Recommendation System

DTPL Syntax

```
ON EVENT SupplyChain.TransortationDelayDetected(shipment_id)
WHEN delay_time > INTERVAL 48 HOURS
DO
    IMC-CALL NotifyStakeholders(shipment_id, "High Priority");
    IMC-CALL AI_SelectAlternativeSupplier(shipment_id);
    IMC-UPDATE SMN(Medwood SupplyChain)
    SET supplier = AI_SelectAlternativeSupplier.output
    WHERE shipment_id = {shipment_id};
END EVENT;
```

Training Data	Historical supplier reliability, delivery times, past disruptions, weather & geopolitical risks
Inputs	Supplier performance scores, lead time estimates, route conditions, cost factors
Outputs	Risk probability score, alternative supplier recommendation

How It Works:

- ON EVENT SupplyChain.DelayDetected(shipment_id) → Listens for real-time shipment delays.
- WHEN delay_time > INTERVAL 48 HOURS → Triggers only if delay is severe.
- CALL AI_SelectAlternativeSupplier(shipment_id) → Uses AI to find the best alternative.
- UPDATE DigitalTwin(SupplyChain) → Switches the supplier automatically.

Enhancement: IMC AI-powered supplier selection ensures the best alternative is chosen dynamically.

3.5.2. Multi-Twin Interactions for Predictive Maintenance

Scenario: If one machine shows early failure signs, redistribute workload to others.

- DTPL Use Case: Detecting early machine degradation and scheduling maintenance.
- AI Model Used: Time-Series Deep Learning for Failure Prediction

DTPL Syntax

```
ON EVENT FactoryFloor.MachineHealthDegrading(Resources.machine_id)
```

```
WHEN health_status < 40% AND predicted_failure_time < NOW() + INTERVAL 12 HOURS
DO
    IMC-CALL AI_PredictLoadBalance(machine_id);
    IMC-UPDATE SMN(Medwood SupplyChain. SUPPLIER.RESOURCE)
    SET workload_distribution = IMC_PredictLoadBalance.output
    WHERE affected_machines IN (IMC_PredictLoadBalance.affected_machines);
    IMC-CALL ScheduleMaintenance(machine_id, "urgent");
    UPDATE SMN(Medwood SupplyChain.SUPPLIER.RESOURCE)
    SET status = "under_maintenance"
    WHERE machine_id = {machine_id};
END EVENT;
```

Training Data	IoT sensor data (vibration, temperature, energy consumption, pressure)
Inputs	Real-time sensor readings, historical failure patterns, workload levels
Outputs	Failure probability, remaining useful life (RUL), optimal maintenance time

How It Works:

- o Detects degrading machine health via IoT sensors.
- o Uses AI (AI_PredictLoadBalance) to redistribute workloads to minimize disruptions.
- o Automatically schedules preventive maintenance.

Enhancement:

IMC *AI-powered load* balancing ensures efficient workload distribution across multiple production lines.

3.5.3. Dynamic Resource Allocation in an SMN

Scenario: If demand spikes for **custom furniture components**, dynamically allocate raw materials.

- o **DTPL Use Case:** Redistributing workloads in case of a production bottleneck.
- o **AI Model Used:** AI algorithms for Workload Balancing

DTPL Syntax

```
ON EVENT SMN(Medwood SupplyChain).SUPPLIER.DemandSurge(product_id)
WHEN current_demand > avg_demand * 1.5
DO
    IMC_CALL OptimizeMaterialAllocation(product_id);
    UPDATE SMN(Medwood SupplyChain)
    SET allocated_materials = IMC_OptimizeMaterialAllocation.output
    WHERE product_id = {product_id};


    IMC_CALL RescheduleProduction(product_id);
    UPDATE SMN(Medwood SupplyChain).SUPPLIER.PRODUCTIONPLAN)
    SET production_rate = IMC_RescheduleProduction.output
    WHERE product_id = {product_id};
END EVENT;
```

Training Data	Factory production cycle times, resource availability, historical bottlenecks
Inputs	Current machine workload, downtime risk, alternative machine capacity
Outputs	Optimal workload distribution strategy

How It Works:

- IMC analyses demand fluctuations.
- IMC optimally reallocates raw materials across factories, which it proposes to the users.
- IMC reschedules production dynamically to prevent bottlenecks, which it proposes to the users.

Enhancement:

Autonomous decision-making across multiple Blueprints.

Real-time adaptation to fluctuating customer demand.

3.5.4. AI-Assisted Smart Routing for Logistics

Scenario: If real-time traffic or weather conditions **threaten on-time delivery,** AI finds the best **alternative route.**

- **DTPL Use Case**: Rerouting deliveries due to traffic, weather, or roadblocks

AI Model Used: Reinforcement Learning for Dynamic Routing Optimization.

DTPL Syntax

```
ON EVENT LOGISTICS.SUPPLIER.RouteDisruption(delivery_id)
WHEN route_status = "high_traffic" OR estimated_delay > 30
DO
   IMC_CALL RecalculateOptimalRoute(delivery_id);
   IMC_UPDATE SMN(Medwood SupplyChain).LOGISTICS.SUPPLIER)
   SET route = IMC_RecalculateOptimalRoute.output
   WHERE delivery_id = {delivery_id};

   IF IMC_RecalculateOptimalRoute.output = "no viable route" THEN
      IMC_CALL NotifySupplier(delivery_id, "Delivery Delayed - No Alternative Route Available");
   END IF;
END EVENT;
```

Training Data	GPS tracking data, historical traffic patterns, weather reports
	Real-time traffic data, road conditions, fleet availability
Outputs	Optimized delivery routes, estimated new arrival times

3.5.5. Self-Healing Manufacturing Lines (Autonomous Recovery)

Scenario: If a production line fails, shift production dynamically and notify maintenance.

- **DTPL Use Case**: Detecting demand spikes and adjusting production rates dynamically
- **AI Model Used**: Transformer-Based Demand Forecasting

DTPL Syntax

```
ON EVENT
SMN(Medwood SupplyChain.SUPPLIER.RESOURCE.PRODUCTIONLINE.LineFailure(line_id))
WHEN downtime_expected > INTERVAL 1 HOUR
DO
   IMC_CALL FindBackupProductionLine(line_id);
   IMC_UPDATE SMN(Medwood SupplyChain.Blueprint(Supplier.ProductionPlan))
   SET active_line = IMC_FindBackupProductionLine.output
   WHERE affected_line = {line_id};

   CALL NotifyMaintenanceTeam(line_id, "Critical Failure - Immediate Attention Needed");
END EVENT;
```

Training Data	Sales data, economic trends, seasonality patterns
	Market demand trends, real-time order volumes, competitor pricing
Outputs	Demand surge probability, optimal production rate adjustment

How It Works:

- Detects failures instantly via IoT sensors.
- AI identifies backup production lines.
- Production is automatically rerouted, avoiding downtime.

Enhancement:

IMC AI algorithm *optimizes recovery speed*, choosing the best alternative.

3.5.6. AI-Driven Energy Optimization for Sustainable Manufacturing

Scenario: If energy usage exceeds thresholds, reduce non-essential operations.

- **DTPL Use Case:** Reducing energy consumption by adjusting non-critical operations.
  AI Model Used: Deep Reinforcement Learning for Energy Efficiency

DTPL Syntax

```
ON EVENT
SMN(Medwood SupplyChain.SUPPLIER.EnergyMonitor.ThresholdExceeded(supplier_id)
WHEN energy_usage > max_energy_limit
DO
   IMC_CALL OptimizeEnergyConsumption(supplier_id);
   UPDATE SMN(Medwood SupplyChain.Medwood SupplyChain.SUPPLIER)
   SET operational_mode = IMC_OptimizeEnergyConsumption.output
   WHERE supplier_id = {supplier_id};
   IF IMC_OptimizeEnergyConsumption.output = "shutdown_non_critical_machines" THEN
      IMC_CALL NotifyOperators(supplier_id, "Energy Reduction Measures Activated");
   END IF;
END EVENT;
```

Training Data	IoT energy meters, historical consumption patterns, machine usage logs
	Factory power consumption, non-essential machine status, electricity pricing
Outputs	Optimal power allocation, machine shutdown recommendations

How It Works:

- Monitors real-time energy usage from IoT sensors.
- AI optimizes power allocation by shutting down non-essential machines.
- If necessary, alerts operators to manually adjust settings.

Enhancement: Supports sustainability goals by minimizing energy waste.

3.6 CONCLUSIONS & RECOMMENDATIONS

This version of the Digital Twin Processing Language represents an early-stage, experimental design, developed primarily for evaluation and refinement rather than immediate full-scale implementation. It serves as a preliminary prototype, continuously assessed and enhanced through ongoing collaboration with pilot stakeholders and technical support teams.

The primary objective of this design phase is to gather extensive feedback from industry experts, end users, and technical evaluators to ensure that DTPL is both precisely defined and practically applicable within real-world Smart Manufacturing Network environments. This iterative refinement process will focus on identifying potential limitations, optimizing language constructs, and ensuring seamless integration with the blueprint digital twin framework.

To ensure its robustness and practicality, the DTPL will undergo rigorous testing in pilot settings, where stakeholders will evaluate its effectiveness in modular digital twin orchestration, real-time adaptability, and automated decision-making. This assessment will focus on how DTPL interoperates with the Intelligent Manufacturing Custodian, ensuring seamless integration, dynamic responsiveness, and optimized decision workflows within the Smart Manufacturing Network. Insights gained from these evaluations will guide further refinements, ensuring that the final version aligns with industry requirements, technical feasibility, and business value.

It is important to emphasize that this version of DTPL **will not be implemented in its entirety** at this stage. Instead, it will undergo a structured validation process to determine its *usability, efficiency*, and *extensibility* before a final decision is made regarding its full development and deployment. The iterative nature of this approach guarantees that DTPL evolves into a robust, unambiguous, and industry-ready solution capable of driving next-generation smart manufacturing and supply chain resilience.

4.   THE BLUEPRINT MANAGEMENT SYSTEM

The Blueprint Management System (BMS) is a foundational component of NARRATE's Blueprint Frames, responsible for managing, orchestrating, and evolving Digital Twin models dynamically. As the operational backbone of both Blueprint Frames and the Digital Twin Processing Language, *the BMS implementation shall ensure that Digital Twins remain adaptive, scalable, and securely managed while enabling DTPL to function effectively on blueprint definitions.*

By integrating AI-driven analytics, Manufacturing-as-a-Service orchestration, and Industrial IoT connectivity, the BMS transforms Blueprint Frames into fully operational, real-world solutions. It facilitates seamless coordination across Smart Manufacturing Networks, ensuring that Digital Twins not only reflect real-time conditions but also drive intelligent decision-making and automated optimizations.

4.1. KEY ELEMENTS OF THE BLUEPRINT MANAGEMENT SYSTEM

Key Elements of the Blueprint Management System

1. **Digital Twin Repository and Version Control**
   - *Purpose:* Stores and manages multiple versions of Digital Twin models, ensuring traceability and iterative refinements.
   - *Connection to Blueprint Frames:* Supports the evolution of Blueprint Frames, allowing companies to refine supply chain models based on historical performance and real-time feedback.
   - *Integration with Digital Twin Programming Language:* Enables versioned scripting and automation of Digital Twin configurations for various production scenarios.

2. **Manufacturing-as-a-Service (MaaS) Orchestration Layer**
   - *Purpose:* Facilitates on-demand and flexible manufacturing by integrating diverse production facilities into a unified network.
   - *Connection to Blueprint Frames:* Provides programmable MaaS capabilities, ensuring seamless reconfiguration of production workflows.
   - *Integration with DTPL:* Uses DTPL scripting to automate the reallocation of resources within the manufacturing network, optimizing efficiency and minimizing downtime.

3. **Real-Time Data Ingestion and Industrial IoT Integration**
   - *Purpose:* Collects real-time data from sensors, production lines, and logistics systems.
   - *Connection to Blueprint Frames:* Ensures continuous synchronization between physical and digital assets, allowing Blueprint Frames to function as accurate, real-time reflections of operations.
   - *Integration with DTPL:* Provides a programmatic interface for ingesting, processing, and responding to real-time sensor data, enabling intelligent automation.

4. **AI-Powered Decision Support and Optimization Module**
   - *Purpose:* Uses IMC AI-driven analytics to optimize production planning, logistics, and supply chain configurations.
   - *Connection to Blueprint Frames:* Embeds AI-enhanced intelligence into Blueprint Frames, enabling self-orchestrating Smart Manufacturing Networks.
   - *Integration with DTPL:* Automates decision-making processes by executing predefined adaptive algorithms written in DTPL, ensuring continuous supply chain resilience.

5. **Security and Access Control Framework**
   - *Purpose:* Ensures data integrity, user authentication, and secure access to Digital Twin models.
   - *Connection to Blueprint Frames:* Implements role-based access control for collaborative supply chain management, allowing different stakeholders to interact with Blueprint Frames based on predefined permissions.

- *Integration with DTPL:* Enforces secure execution of DTPL-based automation scripts, ensuring compliance with industry regulations.

4.1.1 Blueprint Management System Implementation Plans

The Blueprint Frames and the Digital Twin Processing Language (DTPL) in NARRATE will be implemented using OWL (Web Ontology Language) and SPARQL to ensure a flexible, semantically rich, and query-driven representation of Digital Twins. OWL enables formal knowledge representation, ensuring that digital twin models are highly structured, interoperable, and machine-readable, while SPARQL allows for efficient querying and reasoning over these ontologies.

Reasons for OWL/SPARQL Implementation

- *Semantic Interoperability* — OWL enables explicit modeling of relationships, constraints, and dependencies, ensuring that Blueprint Frames remain consistent across the Smart Manufacturing Network.
- *Dynamic Querying and Reasoning* — SPARQL provides powerful querying mechanisms, allowing for real-time data retrieval, rule-based reasoning, and automated decision-making.
- *Extensibility with Event Processing* — The OWL/SPARQL implementation can be easily extended with ESPER, a complex event processing (CEP) engine in WP2. This integration allows for real-time event handling, supporting predictive analytics and automated responses to dynamic changes in the supply chain.

Blueprint Frames as Object-Oriented Constructs

Blueprint Frames resemble objects in an object-oriented programming language, encapsulating both attributes (state) and operations (behaviour). Since OWL/SPARQL is declarative, it requires integration with an *imperative programming language* for more sophisticated processing and interaction with external systems.

Interfacing OWL/SPARQL with an Imperative Language

To bridge the gap between OWL/SPARQL and imperative programming, there are two potential approaches:

- Python Binding via SPARQLWrapper — This is a lightweight Python wrapper for executing SPARQL queries remotely. It provides a simple way to interact with SPARQL endpoints but has limited functionality for complex data manipulation (https://cm-well.github.io/CM-Well/DeveloperGuide/DevGuide.CallingJavaScalaFunctionsFromSPARQLQueries.html).
- Java Binding via Custom Functions — A Java function (packaged as a JAR file) can be called directly from SPARQL queries, enabling greater flexibility in processing query results and performing advanced operations (https://cm-well.github.io/CM-Well/DeveloperGuide/DevGuide.CallingJavaScalaFunctionsFromSPARQLQueries.html).

Given the greater flexibility and richer feature set provided by Java, we anticipate using Java as the primary binding for OWL/SPARQL. This approach will allow each Blueprint Frame to function as a pseudo-object, encapsulating both data (attributes) and behaviour (methods), ensuring a more expressive and powerful implementation within the NARRATE framework.

4.2. BESPOKE BABY COT MANUFACTURING USE CASE DIAGRAM

In this section we provide three practical use cases in the context of bespoke baby cot manufacturing scenario. A use case diagram in Figure 3 illustrates how different actors interact within a Digital Twin-driven SMN using the Digital Twin Processing Language.

Key Elements in the Bespoke Cot Manufacturing Process:
Actors and Their Roles:
- *Customer:* Requests a customized baby cot, specifying design, materials, and features.
- *Logistics Service*: Handles and resolves transportation disruptions affecting material and product deliveries using the Logistics blueprint.
- Lead Manufacturer: Oversees production, ensures smooth workflow adaptation, and interacts with suppliers.
- *Supplier*: Provides raw materials (wood, fabric, fasteners, etc.) and manages blueprint modifications for custom designs.

Use Case#1: Product Request, Blueprint Generation & SMN Initiation
1. Pre-Initiation Phase: Customer Order & ERP Validation (Outside the scope of NARRATE)

A customer initiates an order for a bespoke baby cot, specifying:

- Dimensions, materials, finishes, and accessories.
- Special requirements (e.g., eco-friendly materials, reinforced safety features).

The ERP system validates the order, ensuring feasibility based on:

- Material availability within the supply chain.
- Production capacity of the Lead Manufacturer.
- Supplier constraints (e.g., lead times, quality standards, and production capabilities).

If the order meets feasibility criteria, it will be assigned to a production line, ensuring that Smart Manufacturing Network resources are efficiently allocated.

2. Blueprint Initiation & Lead Manufacturer Assignment

Once the order is validated, the blueprint initiation phase begins:

- A Lead Manufacturer Blueprint is created to define core production responsibilities of the lead manufacturer.
- The bespoke baby cot's design specifications are input into the Lead Manufacturer's Product Blueprint, ensuring alignment with available materials and manufacturing capabilities.
- The order is assigned to an appropriate production line within the Lead Manufacturer, utilizing the Production-Plan Blueprint to schedule *operations*.
- *Quality characteristics are stored within the Quality Assurance Blueprint to track compliance and standards.*
- *The choice of eco-friendly materials, carbon footprint, energy consumption, waste generation is recorded in the Sustainability blueprint while* the reinforced safety features are recorded in the Regulatory Compliance Blueprint.

3. Resource Allocation & Real-Time Monitoring

The Blueprint Management System dynamically allocates resources based on real-time data from the Lead Manufacturer's Resource Blueprint, which includes:

- Machine availability (idle *vs. occupied production units).*
- Workforce capacity (available skilled labour).
- Estimated lead times based on workload distribution.

4. Supplier Selection & SMN Expansion

The Blueprint Management System identifies and selects appropriate suppliers based on:

- Material availability & quality standards.
- Production capabilities of each supplier.
- Lead times & logistical feasibility.
- Upon selection, the Blueprint Management System initiates supplier orders, triggering multiple supplier-specific blueprints including the:
- Supplier Blueprint: Defines the supplier's role in the network.
- Product Blueprint: Outlines the supplier's material or component contributions.
- Production-Plan Blueprint: Ensures a supplier's alignment with the manufacturer's production plan.
- Quality Assurance Blueprint: Maintains product consistency and compliance.
- Logistics Coordination & Full SMN Formation
- To ensure timely procurement and material delivery, the system initiates a Logistics Blueprint, which:
- Establishes optimal transportation routes and schedules.
- Accounts for potential disruptions (e.g., supplier delays, transportation failures).
- Ensures real-time tracking of inbound materials and components.
- At this stage, a fully functional Smart Manufacturing Network (SMN) is established, comprising:
- The Lead Manufacturer and its production blueprints.
- Appropriate suppliers and their respective blueprints.
- A logistics provider ensuring seamless material flow.
- Outcome & Benefits of the Use Case
- The modular and dynamic SMN structure enables rapid adaptation to customer-driven customization.
- End-to-end real-time visibility ensures smooth coordination between manufacturers, suppliers, and logistics providers and their respective blueprints.
- Blueprint-driven production enhances agility, efficiency, and resilience, reducing lead times and mitigating risks.

Use Case#2: Simple Retrieval

Retrieve Blueprints:

- The blueprint management system facilitates version control, comparison, and composition of blueprints to refine and customize designs collaboratively using the basic querying and storing operators in section 3.3.1.
- Manufacturers can update or merge blueprint versions, ensuring seamless adaptation to new design requests.

Use Case#3: Handling Disruptions in an SMN Using Blueprint Frames

The following is a simplified use case about handling two simple types of disruptions in an SMN. This use case ensures that the SMN remains resilient and adaptive despite disruptions, maintaining efficiency and customer trust.

1. **Triggering Event: Detection of a Disruption**
   - A disruption event is detected within the Smart Manufacturing Network. This could be due to:
     - **Machine Failure**: A key production machine at the Lead Manufacturer malfunctions, delaying production.
     - **Supplier Delay**: A supplier fails to meet the agreed production deadline due to capacity constraints, raw material shortages, or quality issues.

2. **Blueprint Activation & Analysis of Impact**

The Disruption blueprint immediately updates the affected blueprints to reflect the disruption and triggers the IMC to apply corrective actions using real-time analytics.

Machine Failure:
   - The Lead Manufacturer's Production-Plan Blueprint updates production schedules to account for downtime.
   - The Resource Blueprint assesses alternative production lines, checking machine availability and workforce capacity.
   - The Disruption Blueprint informs the IMC, which identifies repair strategies, expected downtime, and resource needs.

Supplier Delay:
   - The Supplier Blueprint flags the delay, triggering a review of backup suppliers in the network.
   - The Logistics Blueprint updates transportation schedules based on the new supplier lead times.
   - The Quality Assurance Blueprint checks if alternative suppliers meet product specifications.

3. **Decision-Making & Adaptive Response**

Machine Failure Response:
   - If a backup production line is available, the system reallocates the workload, modifying the Production-Plan Blueprint accordingly.
   - If in-house recovery is not possible, the system checks alternative manufacturing partners within the SMN and engages a MaaS provider.
   - The Quality Assurance Blueprint ensures that process changes do not compromise product specifications.

Supplier Delay Response:
   - The BMS assesses alternative suppliers from the network and, if necessary, triggers new supplier orders.
   - The updated Supplier Blueprint integrates the new supplier's data into the supply chain.

4. **Production Plan Adaptation**
   - The IMC dynamically adjusts manufacturing workflows based on supplier availability, workload balancing, and predictive maintenance.
   - If a material is unavailable, the IMC suggests alternative suppliers or material substitutions to avoid delays.

- The adapted Production Plan blueprint includes supplier changes, workload balancing, and maintenance scheduling, which are essential for smooth production.
- The IMC uses real-time data from the Resource blueprint and Production Plan blueprint to balance workloads between machines and optimize production schedules.

5. **Execution & Continuous Monitoring**
   - The IMC invokes the BMS to make automated adjustments to the Production-Plan Blueprint, Resource Blueprint, and Logistics Blueprint to ensure minimal disruption.
   - The IMC continuously monitors the situation and refines decisions based on new data.

6. **Outcome & Benefits**
   - Reduced Downtime: Machine failures are mitigated through rapid reassignment of workloads.
   - Supply Chain Resilience: The system dynamically adjusts to supplier failures without compromising product delivery.
   - Optimized Decision-Making: Blueprint-driven insights enable proactive and automated responses, enhancing production efficiency.
   - Improved Customer Satisfaction: Delays are minimized, and customers are informed in real-time about order status updates.

Key Insights from the Use Case Diagram:
- Adaptive Manufacturing:
  - Digital Twins continuously monitor the status of materials, machines, and logistics to dynamically adjust production schedules in response to disruptions.
- Collaborative Blueprint Management:
  - Suppliers and manufacturers can co-develop and refine blueprints, ensuring that bespoke baby cot designs meet customer specifications without delays.
- Supply Chain Resilience:
  - The BPMS actively mitigates transportation delays, supplier failures, and material shortages by rerouting deliveries, sourcing alternative suppliers, and adjusting production priorities.
- Predictive Maintenance and Sustainability:
  - Smart monitoring is continuously fed with real-time data from the condition and production monitoring sensor blueprints, the disruption blueprint and the Resources blueprint to prevent machine failures, ensuring efficient production.
  - The IMC with the help of the Sustainability Blueprint optimizes energy consumption, reducing waste and promoting sustainable production practices.

The use case diagram in Figure 3 illustrates the above use cases in the context of blueprint frames and the DTPL.
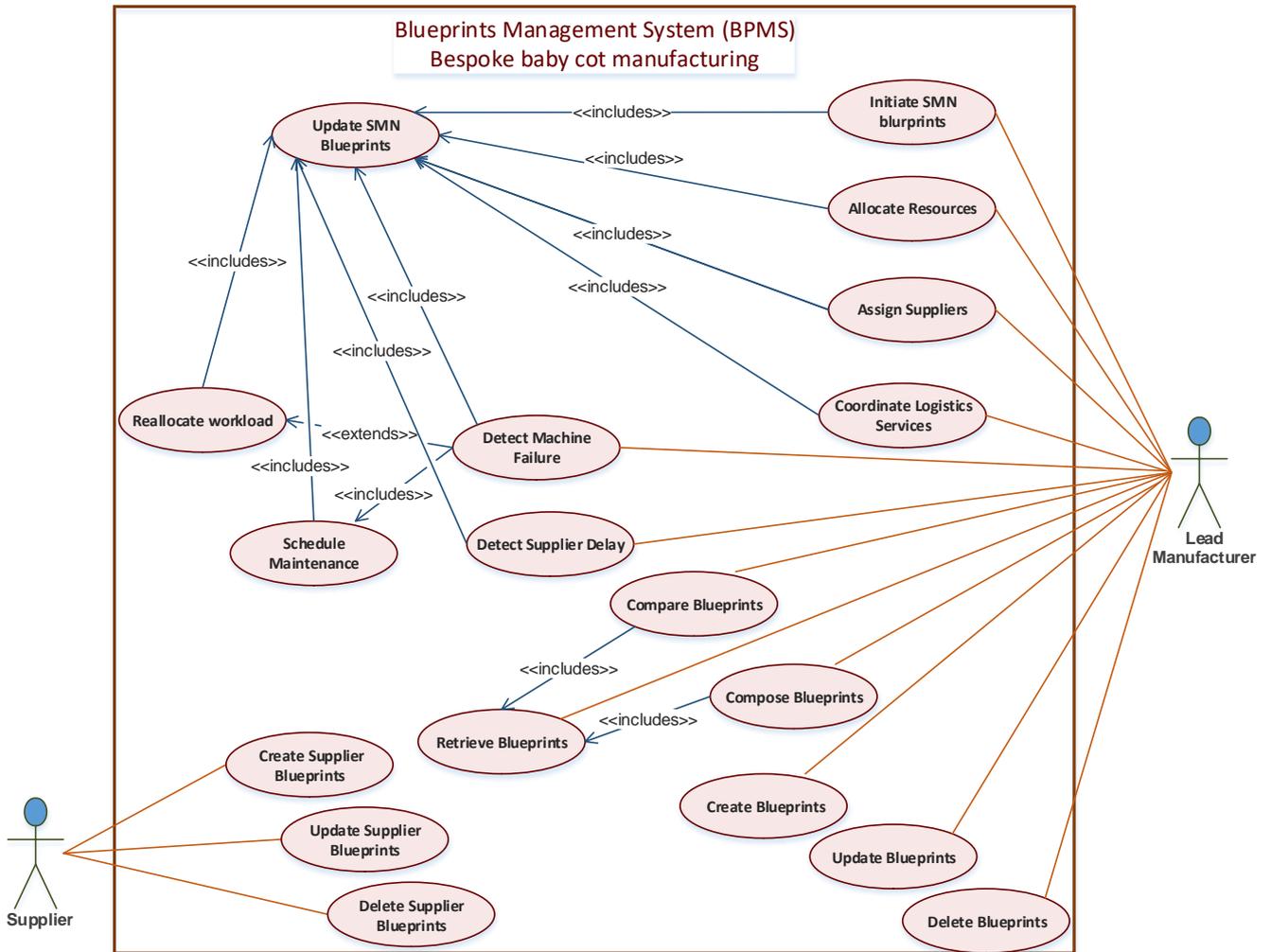
FIGURE 3 USE CASE DIAGRAM OF THE DIGITAL TWINS & DTPL PROCESSING SYSTEM

4.3. BEHAVIOURAL DIAGRAMS

In the following we present activity diagrams and sequence diagrams of basic BTPL operations to improve understandability.

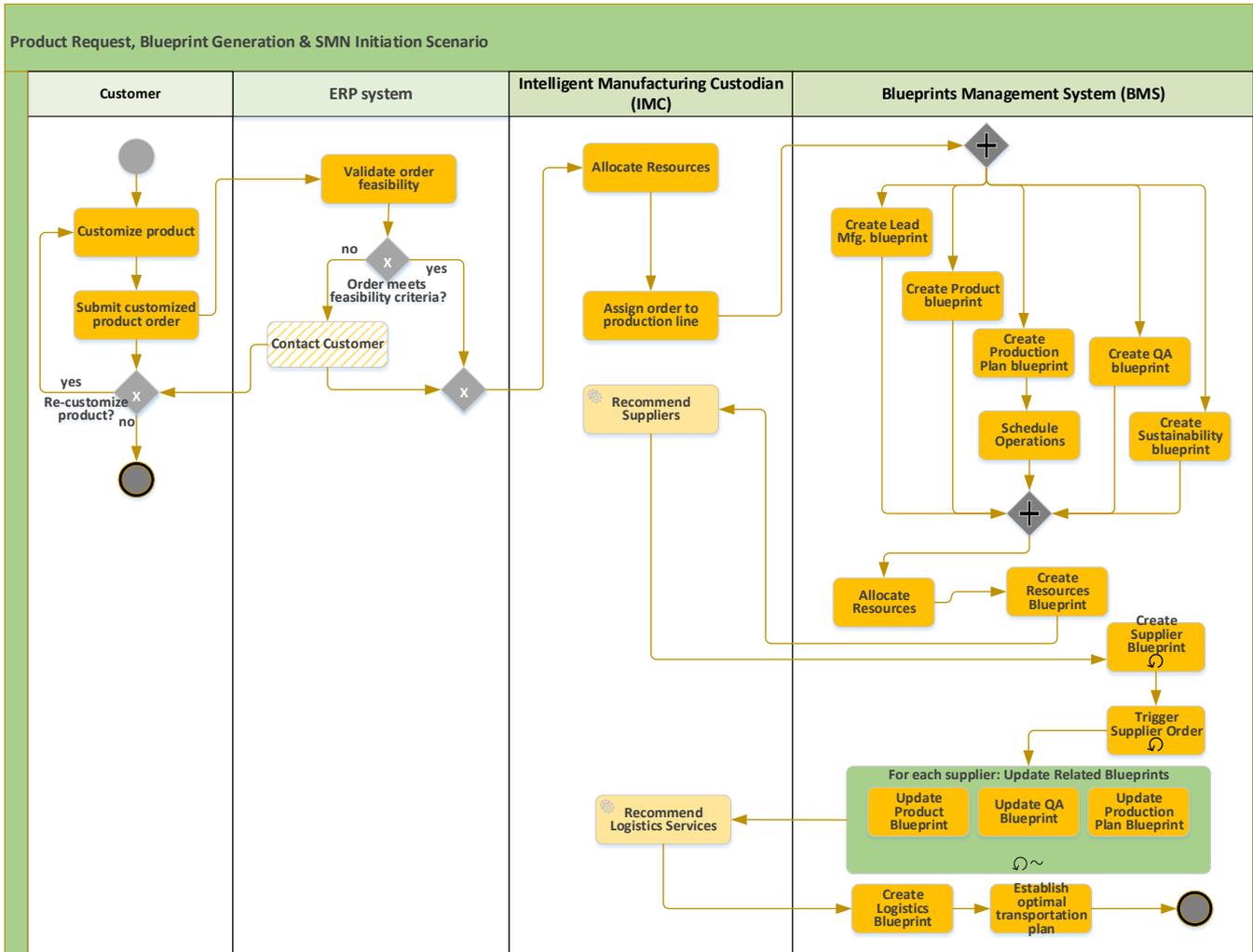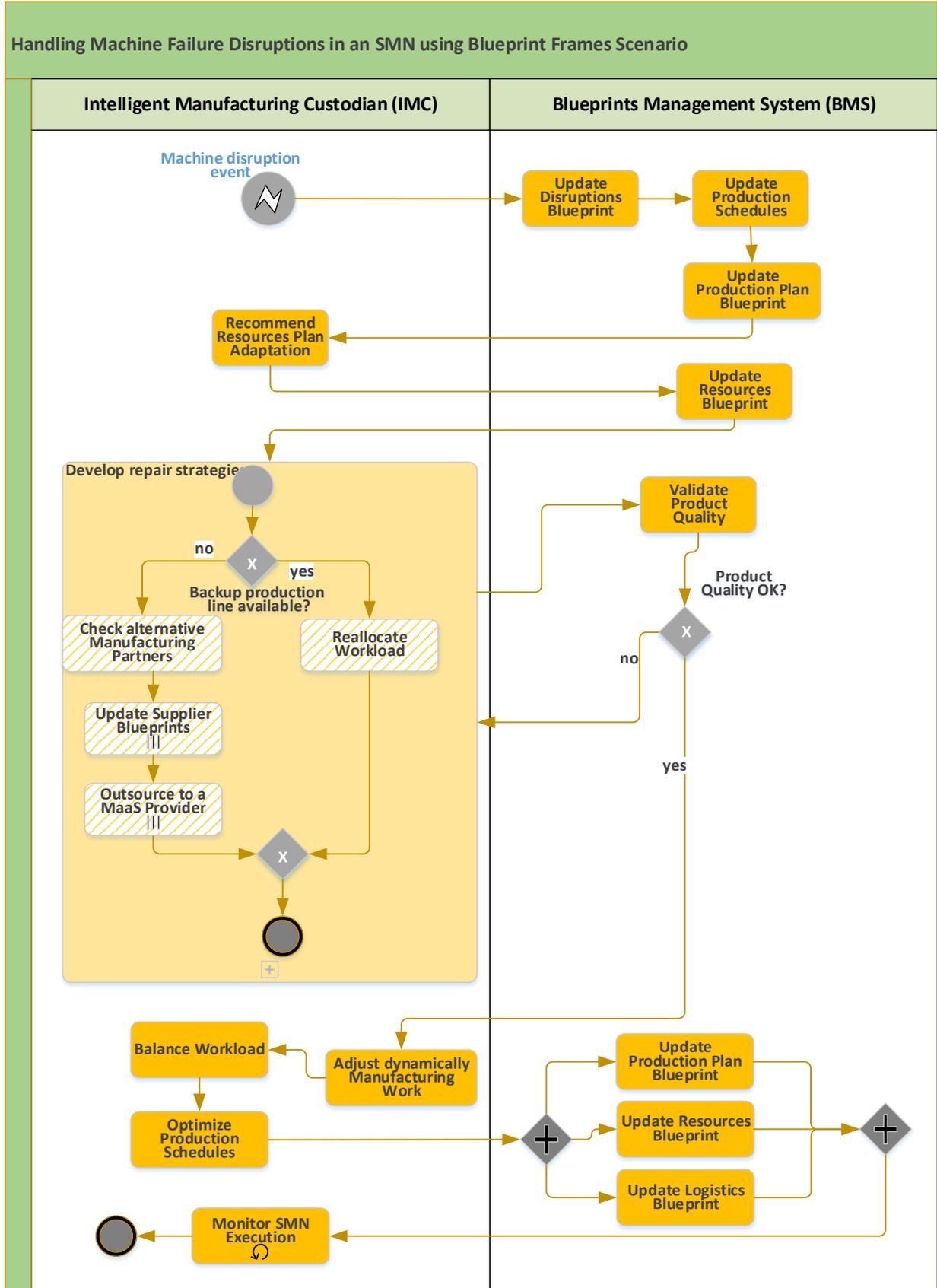### 4.3.1 Activity Diagrams for Bespoke Baby Cot Manufacturing Use Cases

FIGURE 4 ACTIVITY DIAGRAM OF "PRODUCT REQUEST, BLUEPRINT GENERATION & SMN INITATION USE CASE"

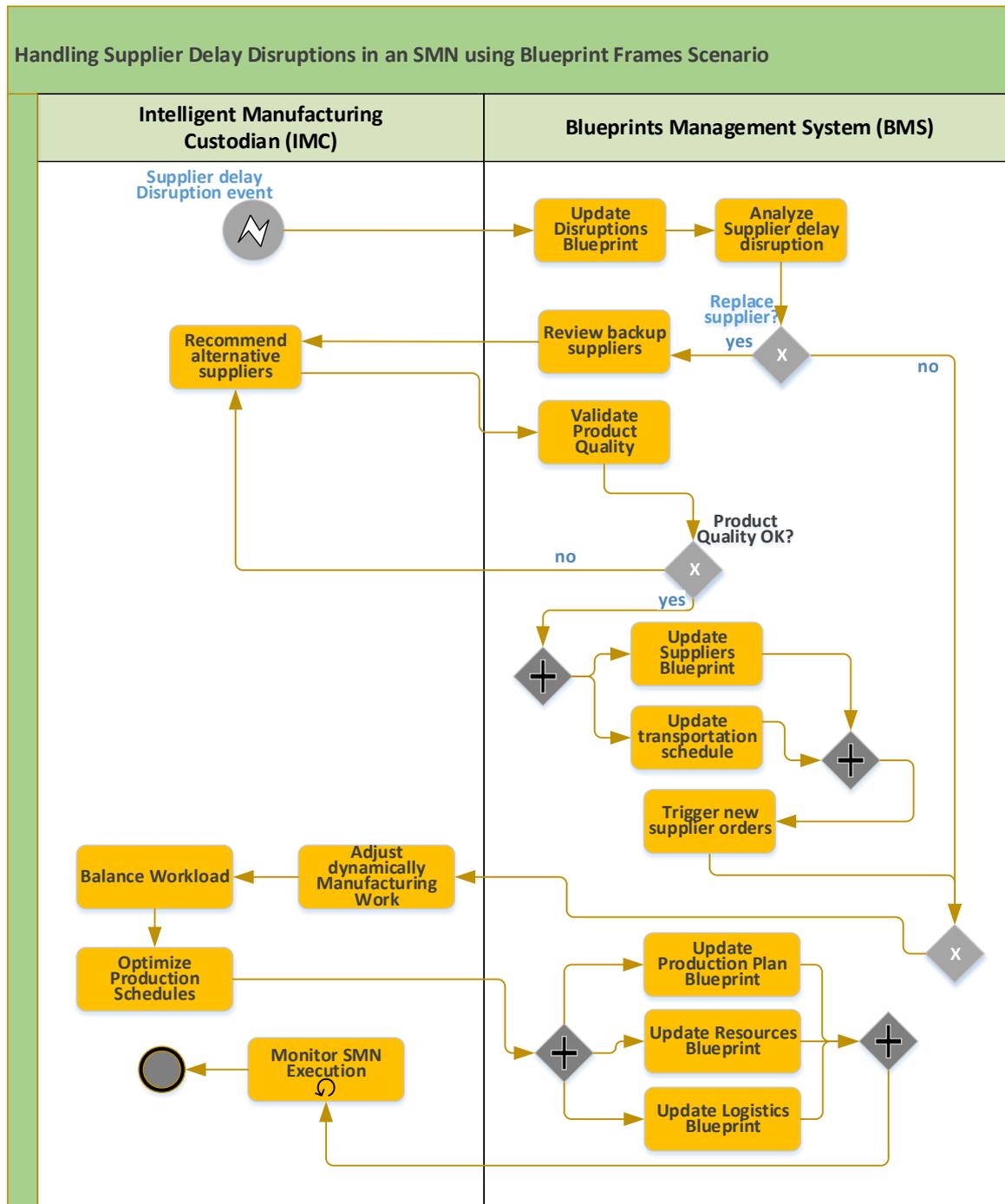FIGURE 5 ACTIVITY DIAGRAM OF "HANDLING MACHINE FAILURE DISRUPTION IN AN SMN USING BLUEPRINT FRAMES

FIGURE 6 ACTIVITY DIAGRAM OF "HANDLING SUPPLIER DISRUPTION IN AN SMN USING BLUEPRINT FRAMES"

4.3.2 Sequence Diagrams for Basic DTPL Operations

Sequence Diagrams for Use Case#1: Product Request, Blueprint Generation & SMN Initiation
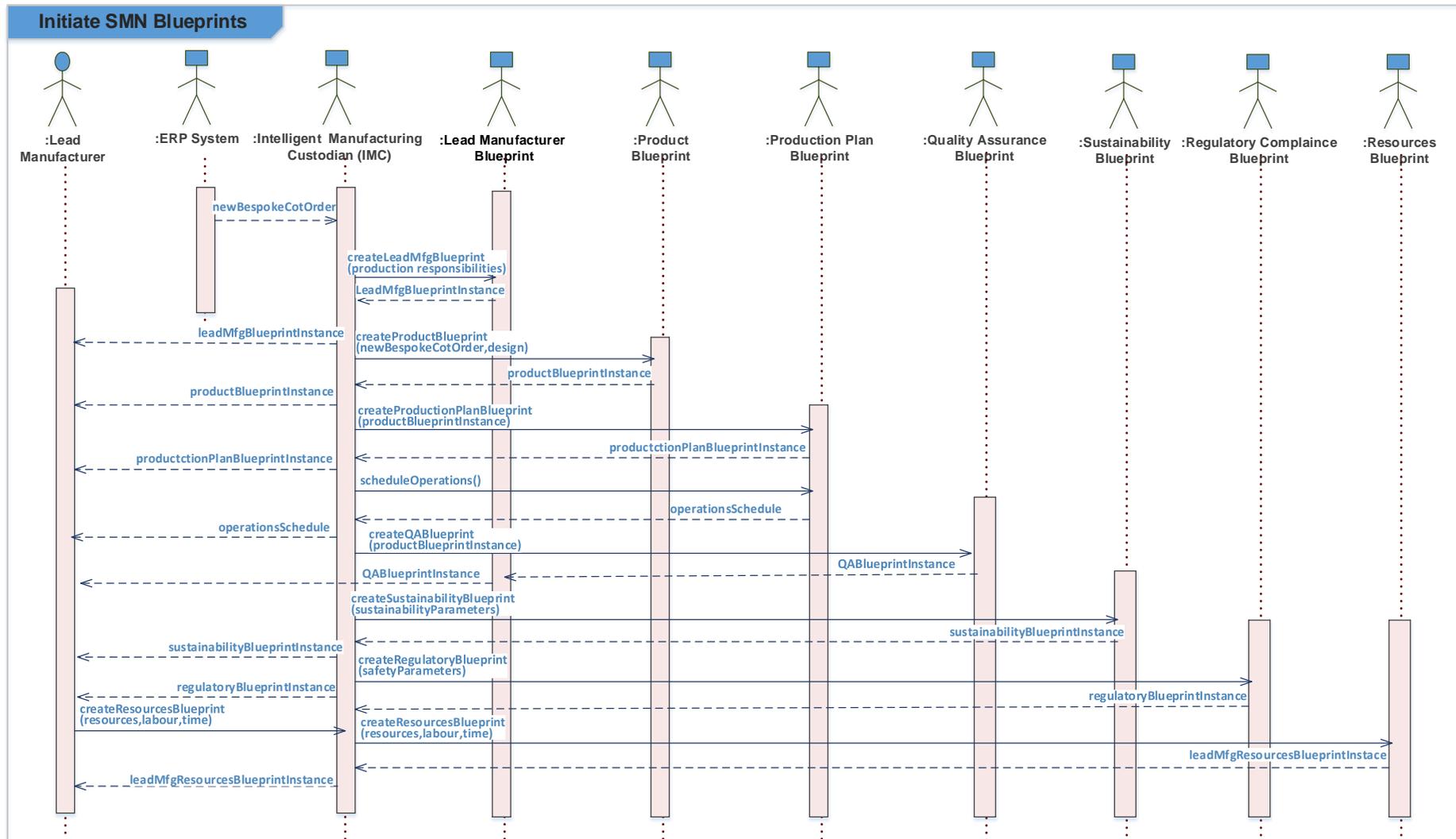
FIGURE 7 SEQUENCE DIAGRAM OF "INITIATE SMN BLUEPRINTS" USE CASE OF "PRODUCT REQUEST, BLUEPRINT GENERATION & SMN INITIATION"

In this example and all the following examples blueprint frames need first to be created and then instantiated by consuming data from various data sources such as ERP, PLM, MES, and IoT.
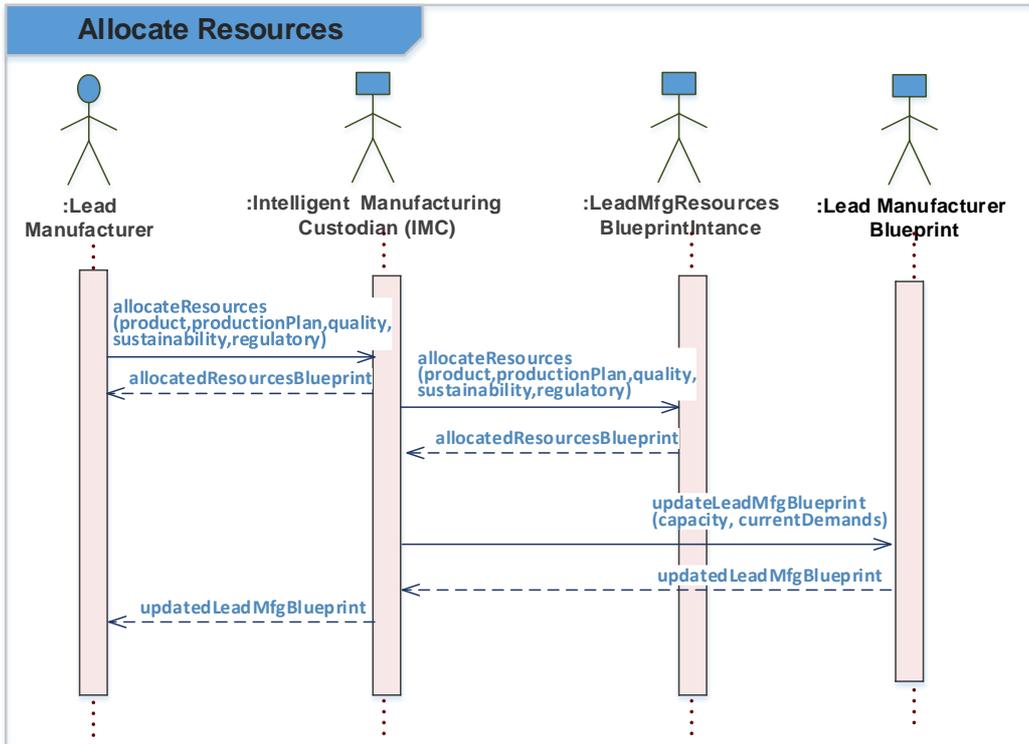
FIGURE 8 SEQUENCE DIAGRAM OF "ALLOCATE RESOURCES" USE CASE OF "PRODUCT REQUEST, BLUEPRINT GENERATION & SMN INITIATION"
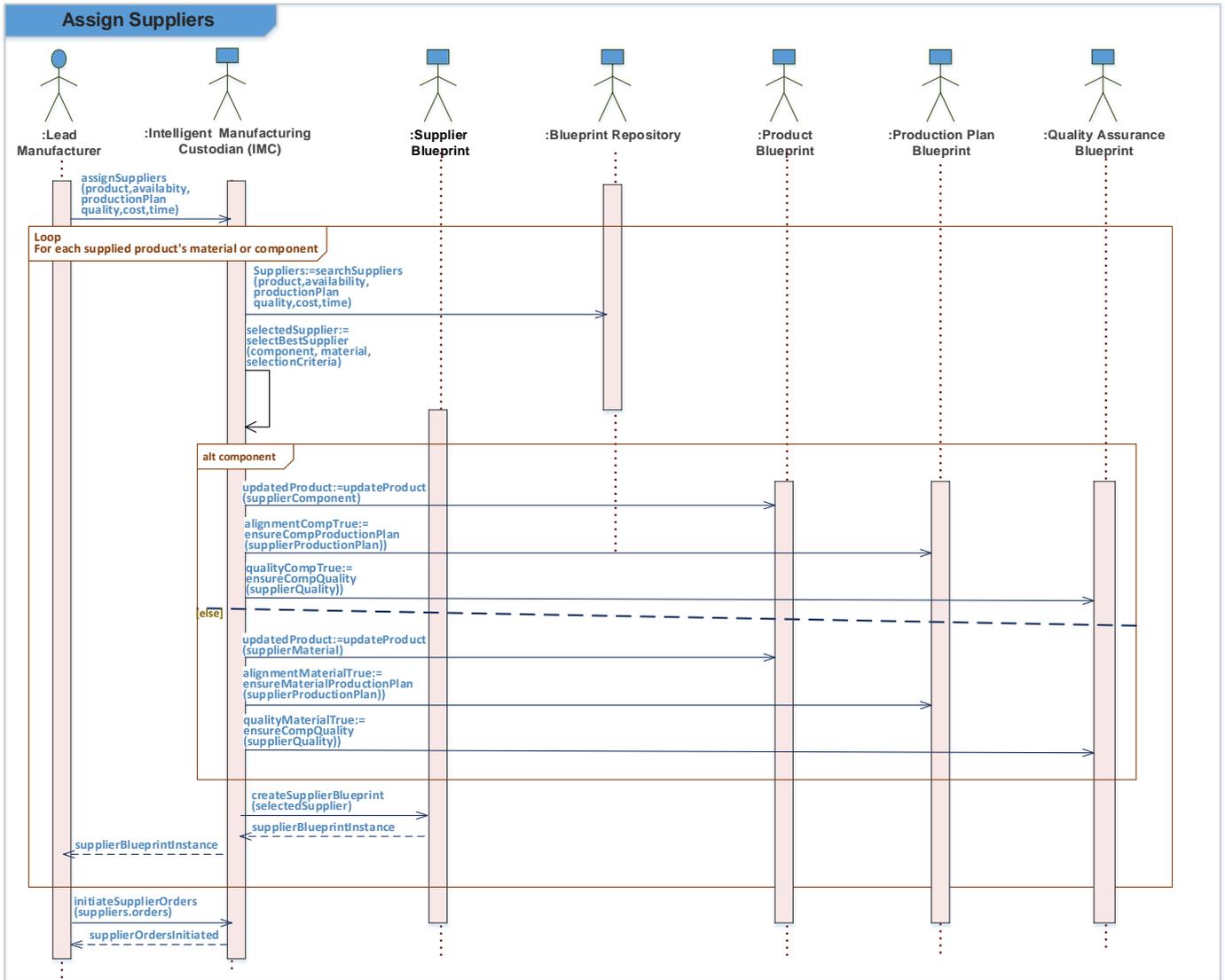
FIGURE 9 SEQUENCE DIAGRAM OF "ASSIGN SUPPLIERS" USE CASE OF "PRODUCT REQUEST, BLUEPRINT GENERATION & SMN INITIATION"
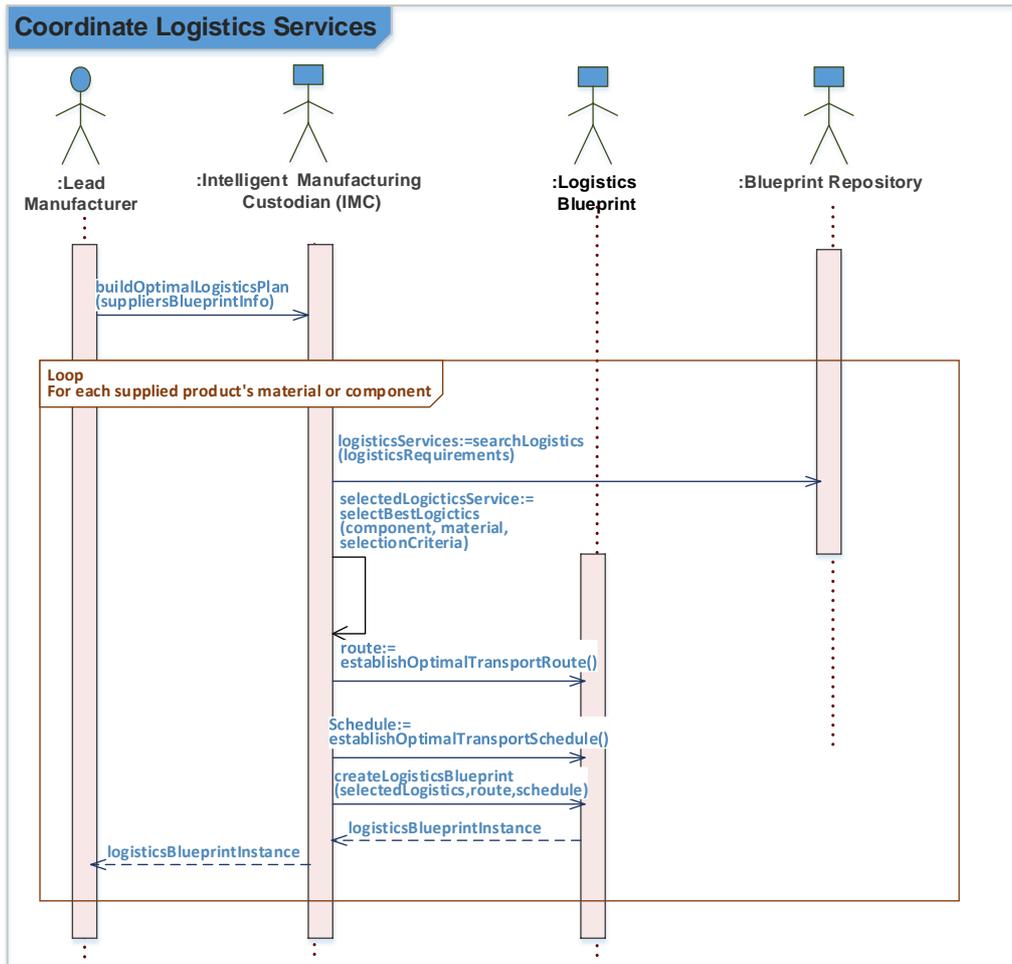
FIGURE 10 SEQUENCE DIAGRAM OF "COORDINATE LOGICTICS SERVICES" USE CASE OF "PRODUCT REQUEST, BLUEPRINT GENERATION & SMN INITIATION"

Sequence Diagrams for Use Case#2: Simple Retrieval
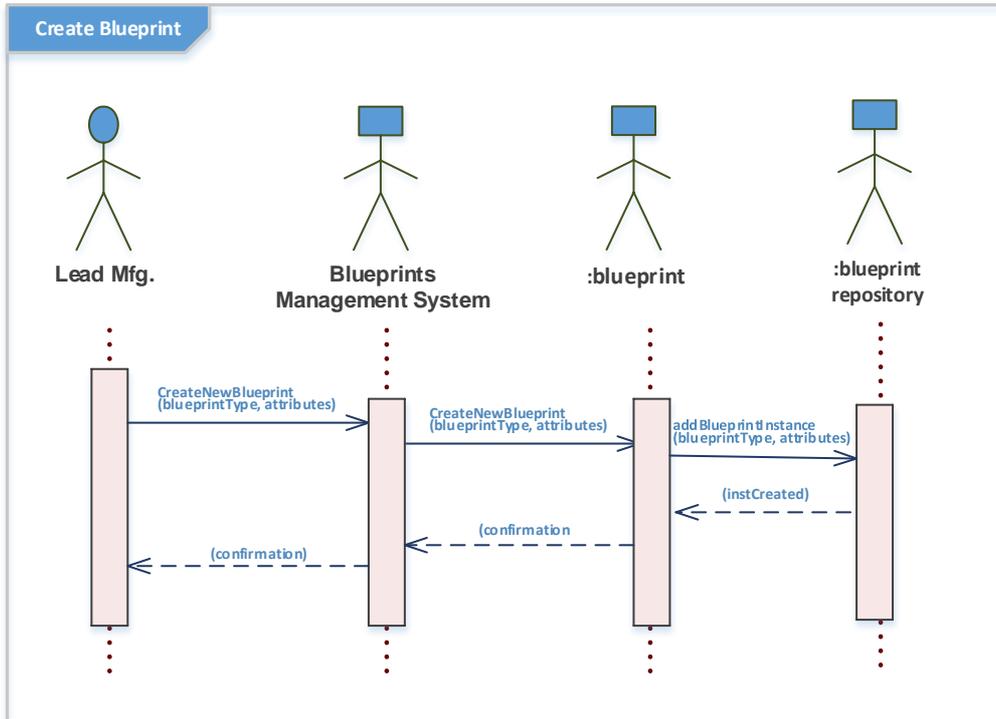
FIGURE 11 SEQUENCE DIAGRAM OF "CREATE BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"
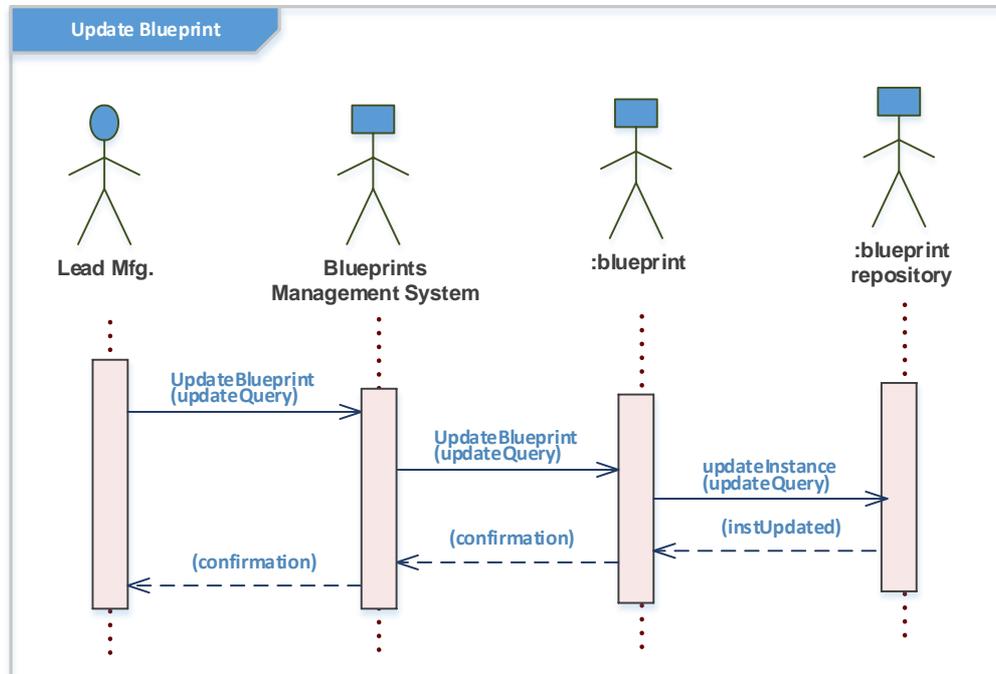
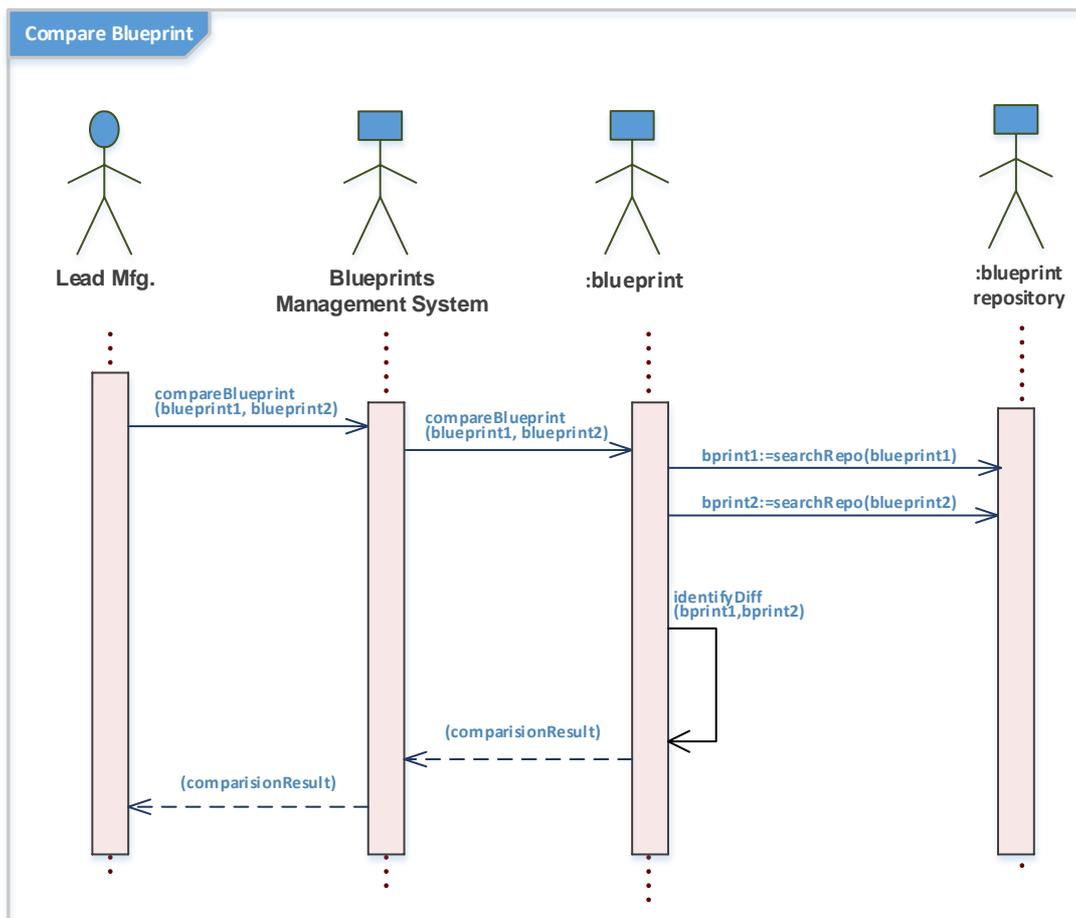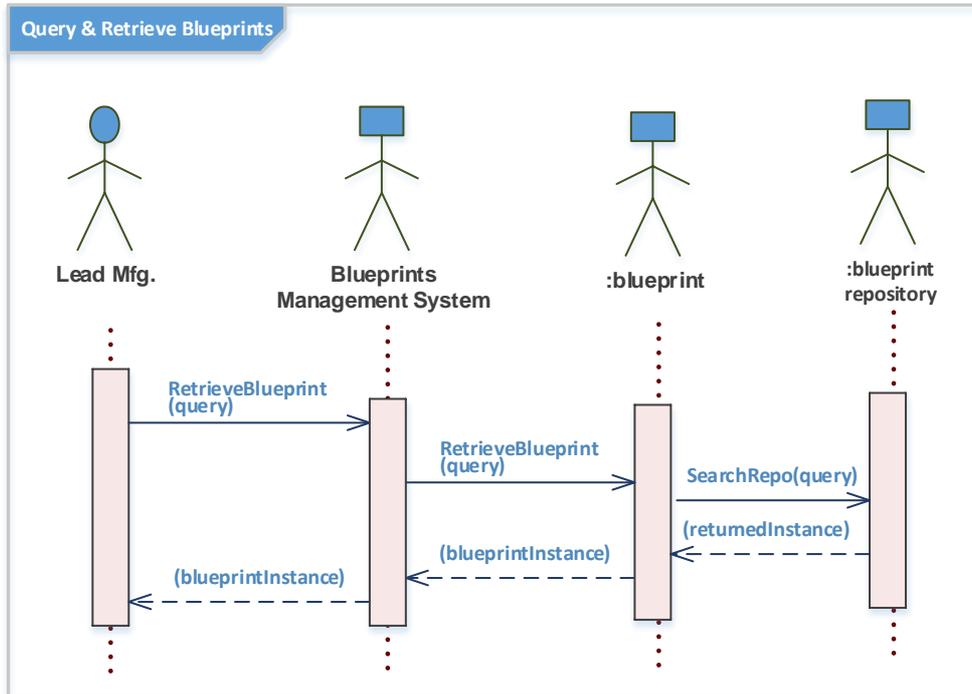FIGURE 12 SEQUENCE DIAGRAM OF "UPDATE BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"
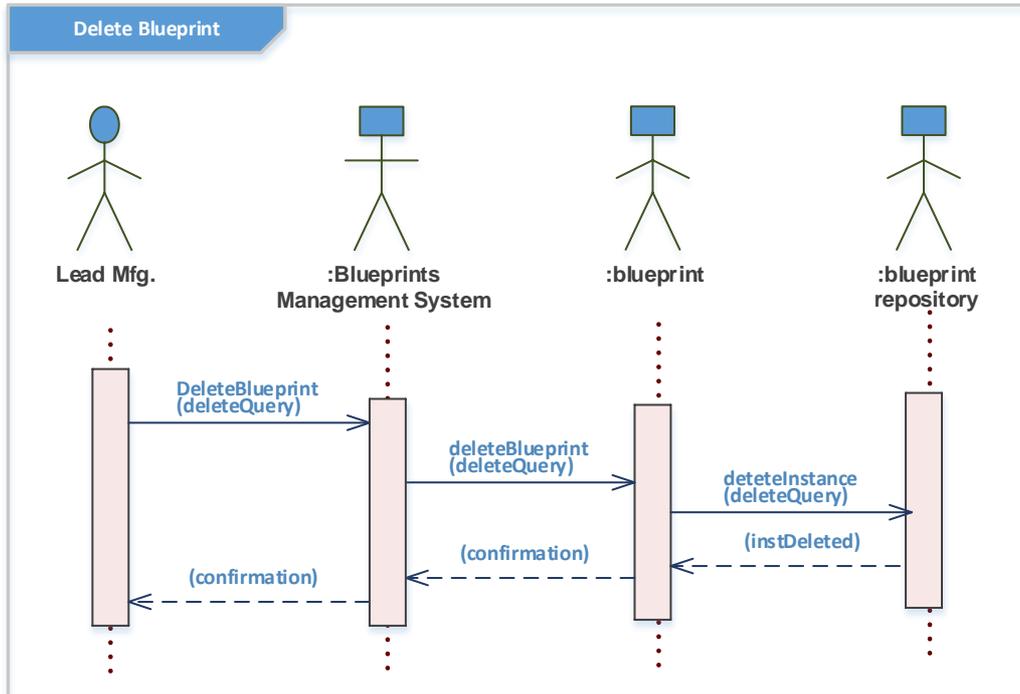
FIGURE 13 SEQUENCE DIAGRAM OF "DELETE BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"

FIGURE 14 SEQUENCE DIAGRAM OF "COMPARE" USE CASE OF "SIMPLE RETRIEVAL"

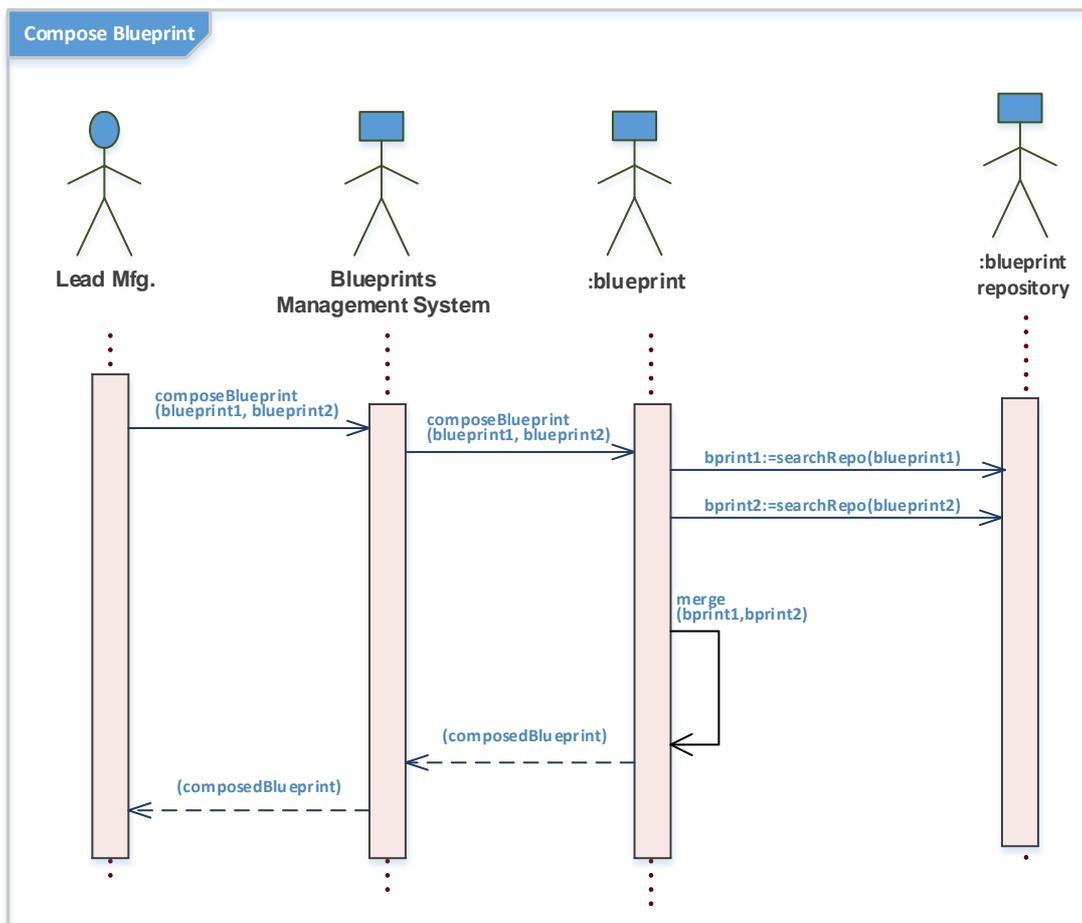FIGURE 15 SEQUENCE DIAGRAM OF "QUERY & RETRIEVE" USE CASE OF "SIMPLE RETRIEVAL"

FIGURE 16 SEQUENCE DIAGRAM OF "COMPOSE BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"
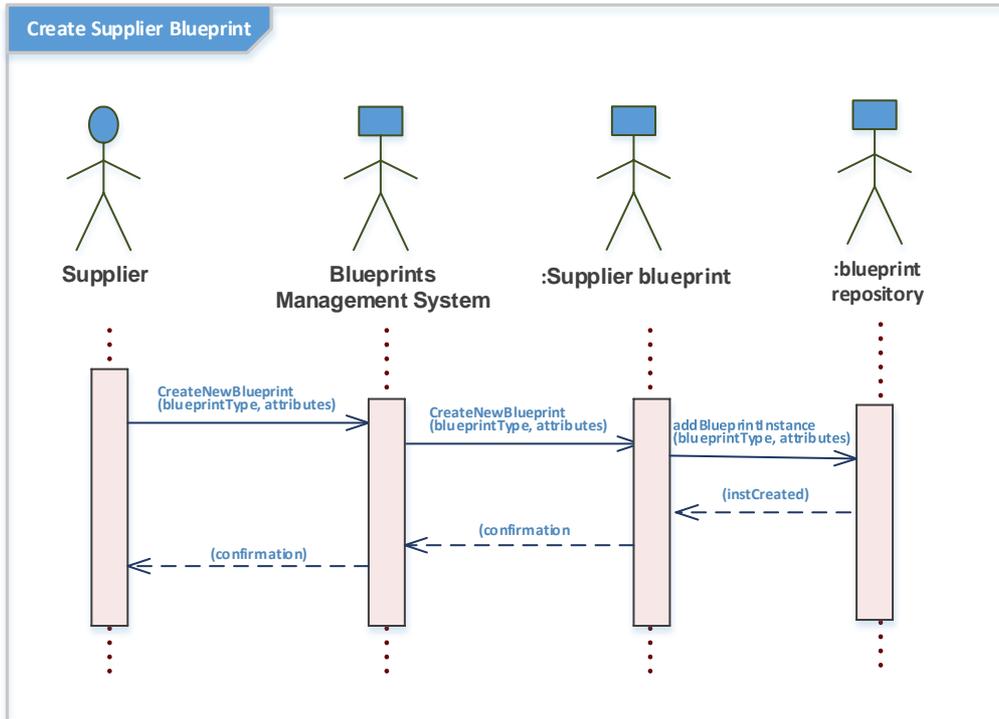
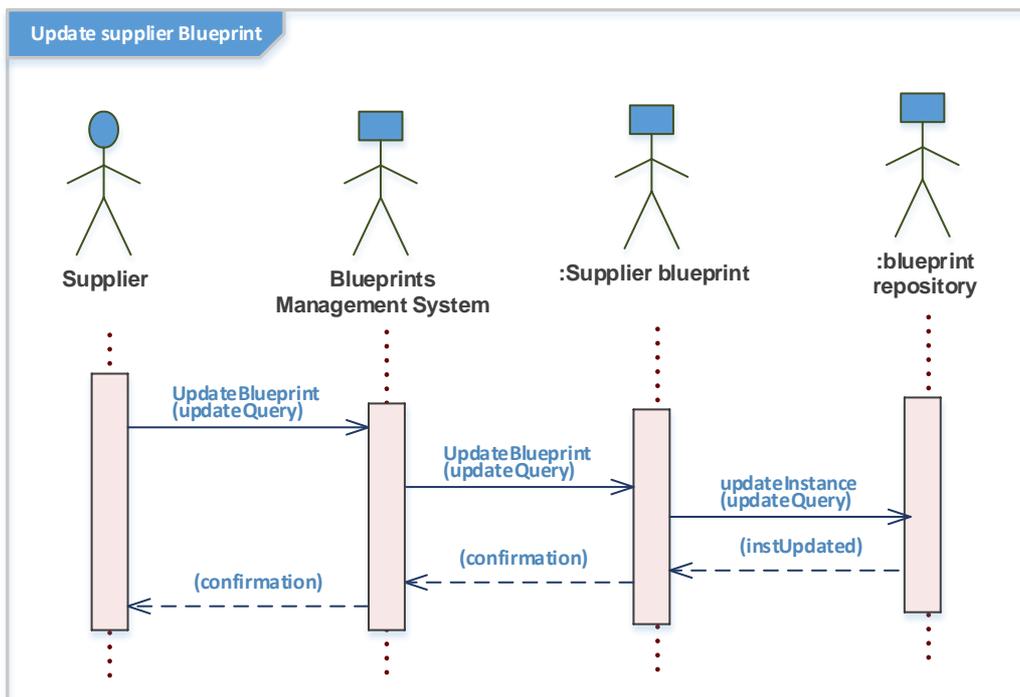FIGURE 17 SEQUENCE DIAGRAM OF "CREATE SUPPLIER BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"

FIGURE 18 SEQUENCE DIAGRAM OF "UPDATE SUPPLIER BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"
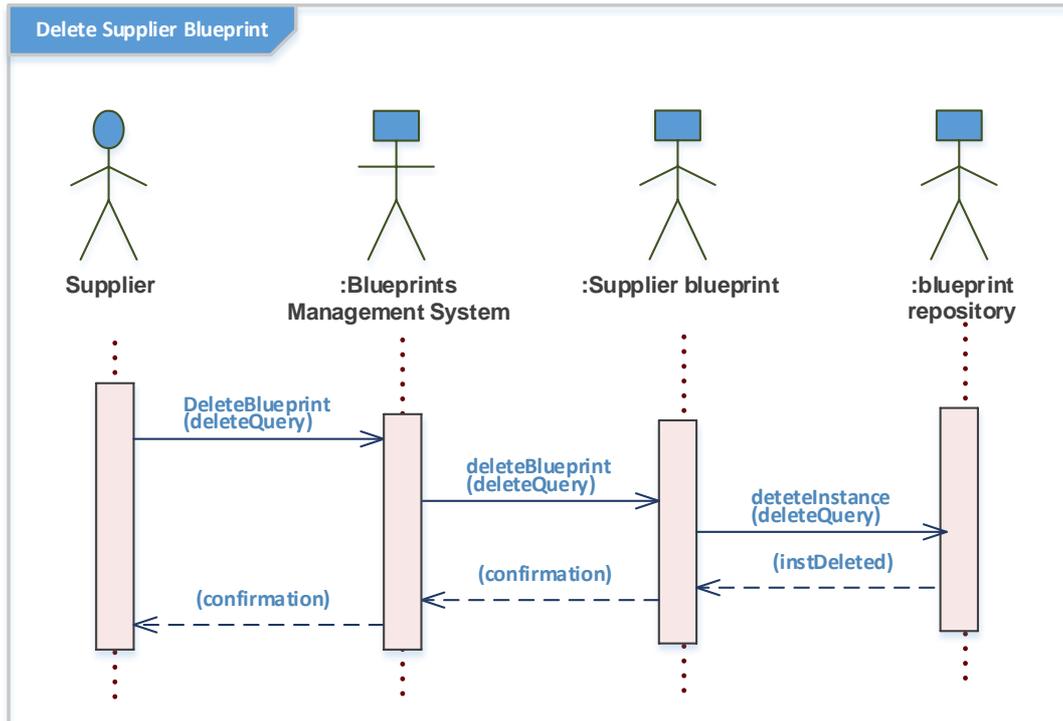
FIGURE 19 SEQUENCE DIAGRAM OF "DELETE SUPPLIER BLUEPRINT" USE CASE OF "SIMPLE RETRIEVAL"

Sequence Diagrams for Use Case#3: Handling Disruptions in an SMN Using Blueprint Frames
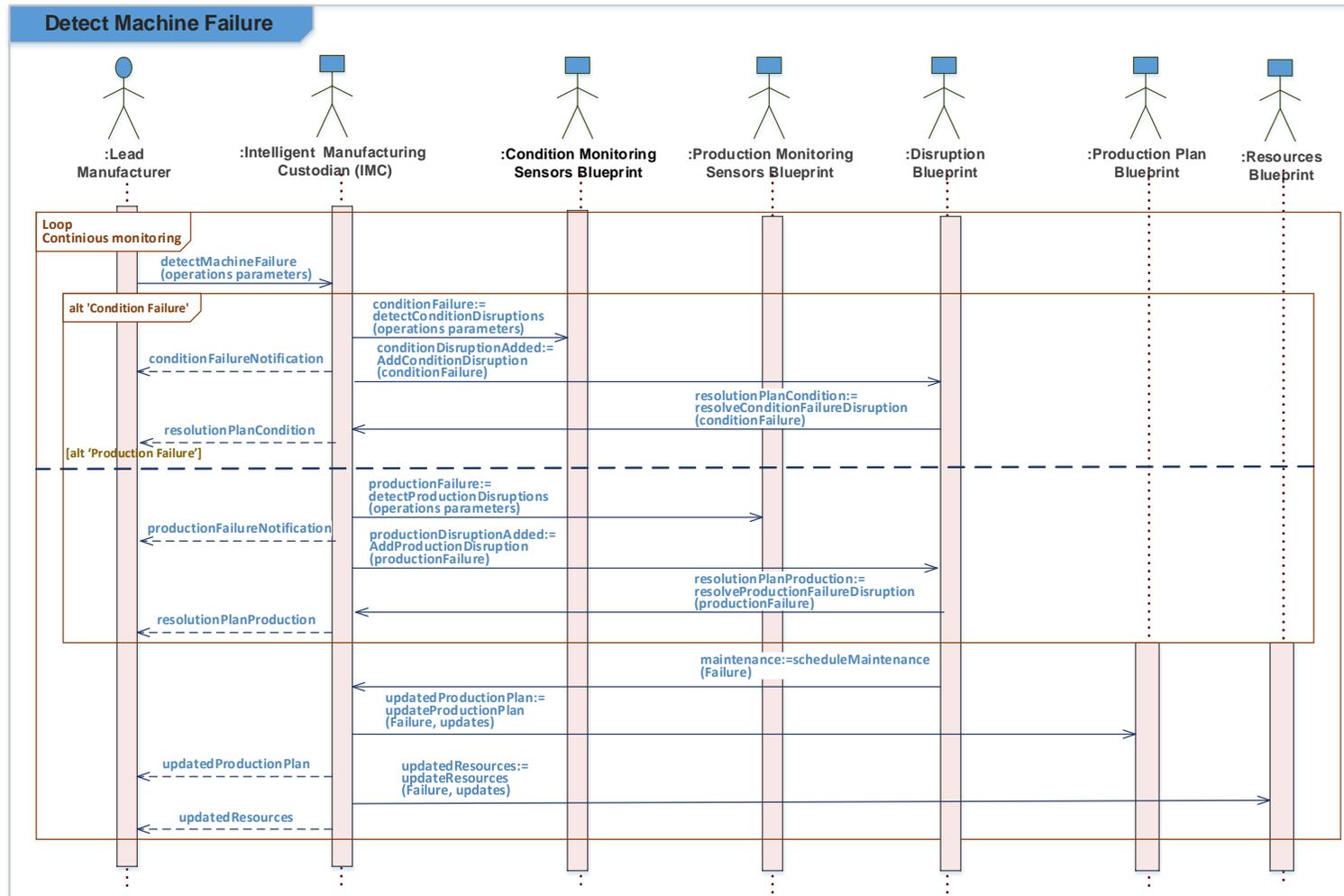

FIGURE 20 SEQUENCE DIAGRAM OF "DETECT MACHINE FAILURE" USE CASE OF "HANDLING DISRUPTIONS IN AN SMN USING BLUEPRINT FRAMES"
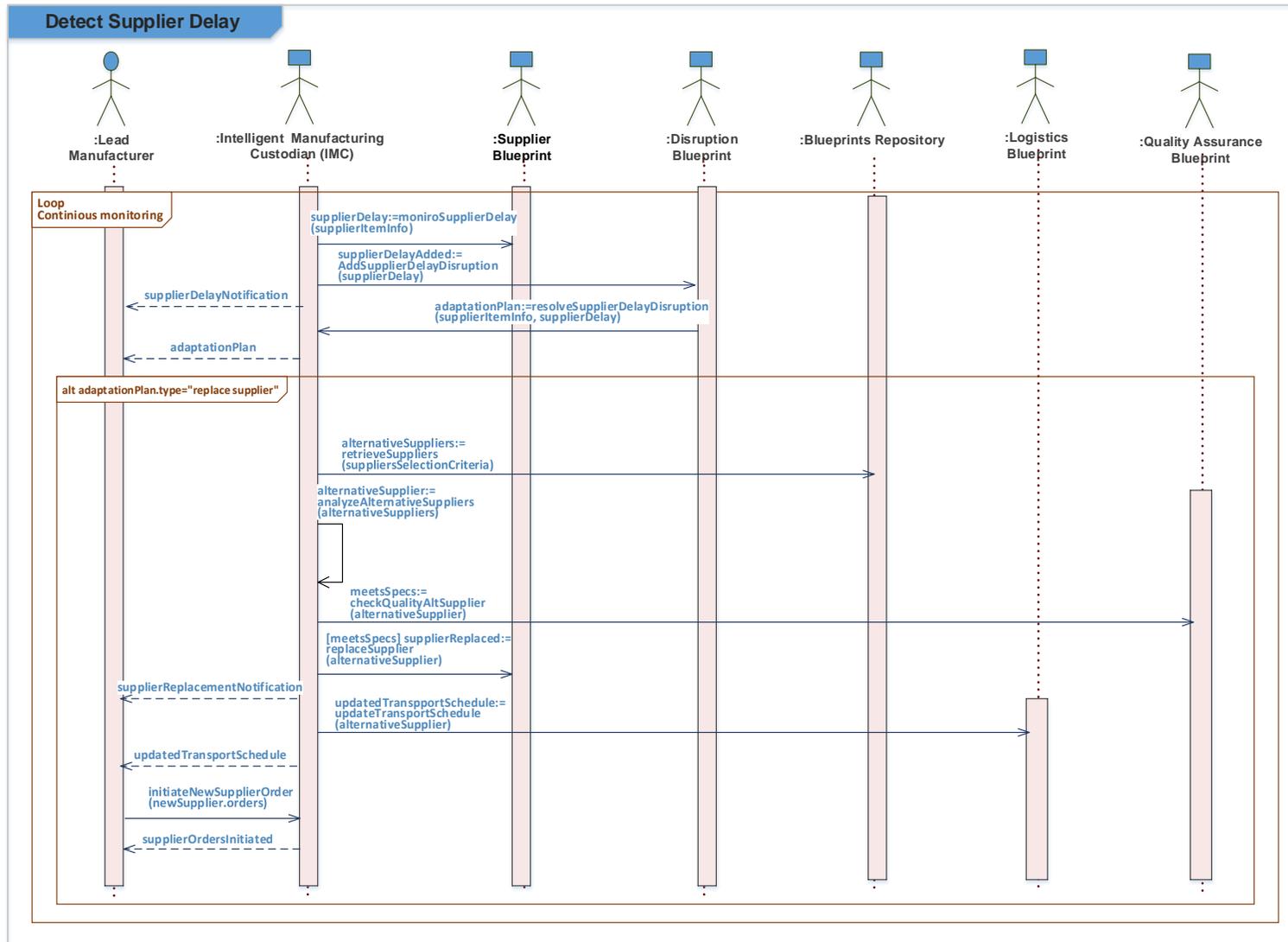
FIGURE 21 SEQUENCE DIAGRAM OF "DETECT SUPPLIER" USE CASE OF "HANDLING DISRUPTIONS IN AN SMN USING BLUEPRINT FRAMES"

5.   FUTURE WORK

To ensure the robustness, practicality, and industrial viability of the Blueprint Frames and the Digital Twin Processing Language, the NARRATE project will undertake a comprehensive, multi-phase evaluation in real-world pilot settings. These pilots will serve as testbeds for validation, allowing stakeholders to assess the effectiveness, scalability, and interoperability of the Blueprint approach within a Smart Manufacturing Network.

Key areas of assessment will include:

- o   **Modular Digital Twin Orchestration** — Evaluating how Blueprint Frames facilitate the structured management of **digital twins across various domains**, including products, production processes, logistics, and machinery.
- o   **Real-Time Adaptability** — Assessing the DTPL's ability to *dynamically respond* to operational changes, ensuring manufacturing resilience and supply chain agility.
- o   **Automated Decision-Making** — Validating the integration of *AI-driven analytics and rule-based reasoning* to enhance predictive insights and autonomous system responses.
- o   **Interoperability with the Intelligent Manufacturing Custodian (IMC)** — Ensuring that the Blueprint Frames and DTPL seamlessly interface with the IMC's decision-support mechanisms, enabling *intelligent coordination, data harmonization, and optimized decision workflows* within the SMN.

Guiding Refinements and Future Enhancements

The insights gained from these pilot evaluations will drive *iterative refinements* to the Blueprint and DTPL frameworks, ensuring that their final versions:

- o   Align with **industry standards** and **best practices** in smart manufacturing.
- o   Address **technical feasibility** challenges, ensuring practical and scalable deployment.
- o   Deliver tangible **business value**, supporting cost-effective, resilient, and adaptive manufacturing ecosystems.

Additionally, findings from the pilot phase will shape the *long-term roadmap* for the NARRATE project, potentially leading to:

- o   The extension of DTPL capabilities, incorporating advanced event processing (via ESPER) for real-time monitoring and response.
- o   The enhancement of OWL/SPARQL implementations, ensuring seamless integration with imperative programming models.
- o   The exploration of broader industry applications in all project pilots, to validate the Blueprint approach across diverse sectors.

Through this structured and iterative validation process, the NARRATE project aims to deliver a next-generation Digital Twin framework that is scalable, intelligent, and industry-ready, setting a new standard for Smart Manufacturing Networks.

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