NARRATE

Regenerative Resilient Smart Manufacturing Networks

D8.2 NARRATE TECHNOLOGY ROADMAP

21/02/2024

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Call: HORZON-CL4-2023-TWIN-TRANSITION-01 • Topic: HORIZON-CL4-2023-TWIN-TRANSITION-01-07 • Type of action: HORIZON Research and Innovation Actions

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

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

D8.2 NARRATE TECHNOLOGY ROADMAP

Work package	WP 8
Task	T8.2
Due date	29/02/2024
Submission date	29/02/2004
Deliverable lead	SERV
Version	0.3
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Abstract	This deliverable describes the NARRATE technology roadmap. It details the steps for creating the technology roadmap, relevant KPIs, and pilot digital maturity model.
Keywords	Technology roadmap, Supply Chain disruptions, Resilient supply chains, Manufacturing as a Service, sustainability, circularity, AI Platform, Digital Twins, Adaptive Supply Chains

Project co-funded by the European Commission in the H2020 Programme

Nature of the deliverable:	R
Nature of the deliverable:	SEN

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DOCUMENT REVISION HISTORY

Version	Date	Description of change	List of contributor(s)
0.1	0102/2024	First draft version.	SERV
0.2	14/02/2024	Comments and suggestions received by several project partners.	AID, INSA, NUNSYS, SAG, SERV
0.3	21/02/2024	Final version addressing reviewers comments & formatting issues	SERV

STATEMENT ON MAINSTREAMING GENDER

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

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ABBREVIATIONS

WP	Work Package
MSx	Milestone x
Mx	Month x
Tx.x	Task x.x
EC	European Commission
KPI	Key Performance Indicator
AI	Artificial Intelligence
DMM	Digital Maturity Model
IMC	Intelligent Manufacturing Custodian
IoT	Internet of Things
KPI	Key Performance Indicator
MaaS	Manufacturing as a Service
SC	Supply Chain
SMN	Smart Manufacturing Network

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EXECUTIVE SUMMARY

The digital technology roadmap presented herein outlines a transformative approach tailored specifically for ***NARRATE***, a ground-breaking multi-partner initiative in the realm of large-scale smart manufacturing. The roadmap is meticulously crafted to enhance supply chain resilience in response to unprecedented challenges while concurrently supporting the principles of circularity within manufacturing ecosystems. It meticulously navigates the project through the intricacies of technological integration and operational optimization. By aligning each technical component with overarching business and technical objectives, this roadmap ensures that every resource is utilized with precision and purpose. Moreover, it meticulously identifies and mitigates potential risks, safeguarding the project against unforeseen obstacles and setbacks. Crucially, it fosters transparency and communication, and a shared understanding of the project's trajectory. Ultimately, this roadmap not only guides ***NARRATE*** towards its envisioned success but also ensures that the project's impact resonates far beyond its inception.

Leveraging advanced technologies, particularly AI and big data analytics, the roadmap prioritizes real-time data acquisition and analysis to identify vulnerabilities and mitigate risks within the supply chain. By harnessing the power of digital twins, virtual representations of physical assets and processes, manufacturing entities can simulate various scenarios and optimize resource allocation in dynamic environments, thereby enhancing adaptability and responsiveness. Furthermore, the integration of IoT technologies enables seamless connectivity across the supply chain, facilitating real-time monitoring of inventory levels, production processes, and transportation logistics. Through predictive analytics and machine learning algorithms, the roadmap empowers manufacturing stakeholders to proactively identify potential disruptions and implement agile strategies to maintain operational continuity. In addition to bolstering supply chain resilience, this roadmap advances the principles of circularity to create sustainable and future-ready manufacturing ecosystems by optimizing resource utilization and minimizing waste generation.

A critical component of this roadmap involves the selection and implementation of an AI platform tailored to support the project's objectives and enhance supply chain resilience. The choice of an AI platform plays a pivotal role in enabling real-time data analysis, predictive modeling, and decision-making capabilities essential for mitigating supply chain disruptions and promoting circularity. Key considerations in selecting the AI platform for ***NARRATE*** include its support for interoperability fostering a cohesive ecosystem of interconnected functionalities, support for scalability to accommodate evolving project requirements, and, support for advanced analytics and machine learning algorithms. To ensure alignment with project goals, relevant key performance indicators (KPIs) that may include metrics such as inventory turnover rate, lead time variability, waste reduction percentage, are identified and utilized to evaluate the effectiveness of the chosen AI platform in enhancing supply chain resilience and promoting circularity.

Furthermore, the roadmap incorporates a digital maturity model to guide the implementation of pilot projects within the larger initiative. This model assesses the current state of digital capabilities across various aspects of the manufacturing process and defines a roadmap for advancing digital maturity over time. By conducting pilot projects guided by the digital maturity model, stakeholders can gain valuable insights into the feasibility and effectiveness of implementing AI-driven solutions to enhance supply chain resilience and support circularity.

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1. DIGITAL TECHNOLOGY ROADMAP

The technology roadmap in this section **produces the most effective technology development path to achieve smart, resilient and sustainable manufacturing networks**. It is a strategic guide that outlines the steps and milestones involved in integrating digital technologies into various aspects of the ***NARRATE*** manufacturing process. It **identifies the critical gaps** between technology capabilities and technology requirements to **achieve the growth and sustainability** required by the project [1].

The focus is on "how" to deliver innovation rather than on the "what", i.e., the detailed content of the innovation. This equates to a compelling transformative vision, with related activity engagement, timing, milestones and KPIs that will allow to meet the vision of ***NARRATE***.

1.1. GAPS

While significant progress has been made in enhancing supply chain resilience in response to challenges like COVID-19, there are still several gaps and areas that require attention and improvement. Below are some notable gaps in the current state of the art for supply chain resilience:

1. **End-to-End Visibility:**
    - Many supply chains still face challenges in achieving true end-to-end visibility. There are gaps in real-time monitoring and data sharing across the entire supply chain network, making it difficult to respond meaningfully and rapidly to disruptions.
2. **Supply Chain Mapping and Dependency Analysis:**
    - In some cases, organizations lack comprehensive view and mapping of their supply chain, including dependencies and vulnerabilities. Understanding the critical nodes in a supply chain ecosystem and dependencies is crucial for effective resilience planning.
3. **Proactive Risk Identification:**
    - While predictive analytics and AI are increasingly used for risk identification, there is room for improvement in proactively identifying emerging risks and external factors that may impact the supply chain.
4. **Collaboration and Communication:**
    - Communication and collaboration among supply chain partners, such as suppliers and logistics providers, remain challenging. Efficient information sharing and collaboration are essential during disruptions, but there are gaps in achieving seamless coordination across diverse stakeholders.
5. **SC Linearity and Lack of Flexibility:**
    - Supply chains traditionally are linear in nature, with a discrete progression of design, plan, source, make, and deliver. Today, however, supply chains must transform from a staid sequence to a dynamic, interconnected system that can more readily incorporate ecosystem partners and evolve to a more optimal state over time.
6. **Resilience Metrics and Measurement:**
    - The lack of standardized KPIs for measuring and benchmarking supply chain resilience makes it challenging to assess the effectiveness of resilience strategies across industries. Establishing common set of metrics could facilitate better comparison and improvement of efforts.
7. **Incorporation of Sustainability and Circularity:**
    - There is a pressing need for more integrated approaches that consider both sustainability and circularity factors in building resilient supply chains. This includes identifying patterns and trends minimising wasted material used during production and creating a closed-loop system in which waste and by-products are reused or recycled rather than discarded.
8. **Security Risks:**

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- With the increasing digitization of supply chains, there is a growing concern about security risks. Ensuring robust security measures to protect sensitive data and prevent disruptions due to security threats is an ongoing challenge.

9. **Adoption of Emerging Technologies:**
    - While technologies like AI, Big Data, and Digital Twins offer great potential, the full-scale adoption and integration of these technologies into supply chain operations are still evolving. Overcoming implementation challenges and ensuring interoperability are key areas to address.

1.2. VALUE PROPOSITION: DRIVERS AND TRENDS

The COVID-19 pandemic and advancements in smart manufacturing technologies, including AI, Big Data, and Digital Twins, have significantly influenced the drivers and trends for supply chain resilience.

The drivers and trends for supply chain resilience involve a combination of technology adoption, risk management strategies, and a proactive approach to addressing disruptions, with a focus on building flexible and adaptive supply chain ecosystems.

1.2.1. Drivers for Supply Chain Resilience

The adoption of smart, resilient, and sustainable manufacturing networks is driven by various factors that contribute to improved efficiency, flexibility, and environmental responsibility [2]. The drivers described below are the forces or factors that push or encourage the development and implementation of resilient manufacturing networks.

1. **Supply Chain Disruption Preparedness:**
    - The experience of disruptions caused by the COVID-19 pandemic has highlighted the need for supply chain resilience. Organizations are now prioritizing preparedness for future global shocks.
2. **Risk Mitigation:**
    - Knowing which supplier, product lines, and routes are at risk empowers companies to be agile enough to respond to risks and potential disruptions by changing course at any given time with confidence.
    - Companies are increasingly aware of the risks associated with single-sourcing strategies and are diversifying their supplier base to mitigate the impact of disruptions.
3. **Emerging Technology Adoption:**
    - The integration of advanced technologies such as AI, Big Data, and Digital Twins into supply chain management enhances visibility, agility, and decision-making capabilities and provides the foundation for smart manufacturing networks, thus contributing to overall resilience. These technologies enable connectivity, real-time data analytics, and automation, fostering supply-chain efficiency and adaptability.
4. **Adaptive Manufacturing Capabilities:**
    - The need for rapid response to market changes and customer demands drives the adoption of agile manufacturing systems. Smart manufacturing networks allow for quick reconfiguration of production lines, easy scalability, and adaptability to changing production requirements.
5. **Supply Chain Visibility and Integration:**
    - End-to-end visibility of supply chain performance is a crucial element for resilience purposes. Technologies like IoT and advanced analytics contribute to improved tracking and monitoring. With the right key performance indicators companies, measure, and analyse the results so they can identify bottlenecks, eliminate manual errors, analyze

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risks, and predict outcomes to increase resilience during uncertain times to orchestrate their entire supply chain with ease.
    - End-to-End Supply Chain Integration: Smart manufacturing networks leverage technologies for end-to-end visibility and integration across the supply chain. This facilitates better demand forecasting, inventory management, and coordination with suppliers and distributors, leading to increased resilience and responsiveness to market changes.
6. **Energy Efficiency and Sustainability:**
    - **Green Manufacturing Practices:** Smart manufacturing networks must incorporate energy-efficient technologies, waste reduction strategies, and environmentally conscious processes to minimize the ecological footprint of manufacturing operations.
7. **Collaborative Supply Chain Ecosystems:**
    - Collaboration among manufacturers, suppliers, and other stakeholders within a supply-chain ecosystem promotes seamless information sharing enabling better decision-making and responsiveness to market dynamics.

1.2.2. Trends in Supply Chain Resilience

Trends represent the directions in which smart, resilient and sustainable manufacturing networks are evolving. These are often influenced by technological advancements, market demands, and societal changes. Key trends include [3]:

1. **Digital Twins:**
    - Digital Twins, virtual representations of physical objects or systems, enable companies to simulate and optimize supply chain processes. This technology aids in predicting and mitigating disruptions.
2. **AI and Machine Learning:**
    - AI and machine learning algorithms enhance forecasting accuracy, demand planning, and risk assessment. These technologies enable quicker and more informed decision-making in the face of uncertainties.
3. **Big Data:**
    - Big Data analytics allows organizations to analyze vast amounts of data for patterns, trends, and insights. This is crucial for identifying potential risks and opportunities for optimization within the supply chain.
4. **Automation and Advanced Logistics:**
    - Increased adoption of automation in smart manufacturing and advanced logistics reduces dependence on human labour, making supply chains more adaptable and less susceptible to disruptions.
5. **Synergy of Predictive/Prescriptive/Adaptive Analytics:**
    - The synergy of predictive, prescriptive, and adaptive analytics enables a holistic approach to decision-making. By combining these analytics types, manufacturers can not only predict and optimize potential disruptions but also respond dynamically to changing conditions, creating a more resilient and agile manufacturing ecosystem.
6. **Sustainability & Circularity Considerations:**
    - Sustainable and environmentally conscious supply chain practices are gaining prominence. Companies are integrating sustainability into their resilience strategies, considering both economic and environmental factors.
7. **Supplier Diversity** enables companies to widen their pool of suppliers, which gives them more choices during the procurement process, drives competition and provides potential links to new perspectives and ideas.

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1.3. CLOSING THE GAPS

Today, supply chain performance can be disrupted by a variety factors. Some of the most common causes include natural disasters, pandemics and health crises, weather risks, geopolitical events, supplier issues, machine failures and transportation delays. Such disruptions can impact manufacturing facilities, transportation infrastructure, and supply chain routes, causing factory closures, and disrupting transportation.

To navigate rapid unexpected effects and manage supply network interactions, manufacturers need to adapt the supply chain to frequent changes and respond with sets of correlated solutions that can be adjusted as conditions evolve. More agile and resilient supply chains - *which possess the ability to deal with adversity, recover quickly from unexpected events, withstand shocks and continuously adapt and accelerate as disruptions arise overtime* - play a crucial role in closing these gaps and building more robust and adaptive supply chains by developing innovative strategies and technologies.

1.3.1. Vision

In the imminent future, supply chains are poised to transform into seamlessly connected, autonomously orchestrated ecosystems. These next-level supply chains will not only achieve end-to-end connectivity but will also prioritize resilience and sustainability. All relevant functions, including procurement through manufacturing and logistics, will be intricately connected using a unified data network. This interconnected landscape will extend beyond organizational boundaries to include key supply chain partners, logistics service providers, and customers. This comprehensive integration is designed not only to enhance supply chain efficiency but also to fortify the supply chain against disruptions, embodying a resilient and adaptive approach to the challenges of tomorrow.

A smart, resilient and sustainable manufacturing network initiative as proposed by ***NARRATE***, is one of the major challenges for the future. This approach includes concepts like advanced data analysis capabilities to fine-tune planning, speed up design cycles, and gain better visibility into supply chain and manufacturing processes evaluate the entire supply chain and seek opportunities to reduce waste, increase supplier diversity, and prioritize the use of sustainability and circularity.

1.3.2. Operational Framework

To address the multifaceted challenges outlined above, the ***NARRATE*** project aims to spearhead cutting-edge research, seamlessly amalgamating recent strides in foundational digital technologies, including Artificial Intelligence (AI) and Machine Learning (ML), Big Data, IoT, and Digital Twins (DT). The project's focal point involves the creation of a strategically centralized hub known as an *Intelligent Manufacturing Custodian* (IMC). This IMC serves as an avant-garde solution, facilitating end-to-end visibility and control across supply chain operations monitoring, managing, and optimizing various aspects of the supply chain to enhance resilience responsiveness and sustainability.

The IMC harnesses sophisticated AI capabilities in tandem with robust models, simulators, digital twins, decision-making and planning. Drawing insights from diverse data sources, encompassing product details, production metrics, and pertinent supply chain data, as well as information from machines, sensors, and IoT devices, the IMC takes on the role of a proactive decision-making nerve center. It acts as a pivotal entity within the smart, resilient and sustainable supply-chain network, offering real-time monitoring and coordination of intelligent production processes and logistics, thereby fostering a harmonized and responsive ecosystem.

By integrating an IMC into a supply-chain network, supply chain operations will evolve into a Smart Manufacturing Network (SMN): a *connected and self-orchestrated ecosystem linked end-to-end* with programmable *Manufacturing-as-a-Service* (MaaS) capabilities that can withstand disruptions. The

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hallmark of these new supply chain ecosystems lies in their ability to *self-orchestrate*. Companies will leverage autonomous capabilities to make dynamic 'course corrections' that align with the company's priorities and AI-driven decision parameters. This autonomy empowers the supply chain ecosystems to be not only self-orchestrated but also self-learn, adapting and evolving based on real-time insights and changing circumstances.

Figure 1 intricately details the Smart Manufacturing Network (SMN), spotlighting the Intelligent Manufacturing Custodian (IMC) as the central intelligence hub orchestrating production dynamics. The SMN's star-shaped structure, with the IMC and its AI Platform overseen by a lead manufacturer, exemplifies a holistic approach to sophisticated supply chain management. The AI Platform manages IoT devices, sensors, supply chain assets, end-to-end workflows, and ensures security and privacy services. This symbiotic relationship epitomizes a holistic approach to sophisticated supply chain management in the digital era. Ongoing efforts focus on innovative strategies, integrating the IMC on a robust AI platform, leveraging industry standards, and diverse datasets for rapid and secure functionality at scale.

In this next-level modular and resilient supply chain ecosystem, partners like suppliers, logistics service providers, and customers will be seamlessly integrated, leveraging distributed and programmable resources enabled by Digital Twin Technology, see Figure 1. Digital twins meticulously replicate products and their individual components, conducting intricate simulations to optimize product designs. Furthermore, they offer a holistic and real-time depiction of the entire Smart Manufacturing Network and manufacturing processes, encompassing production and logistics with unparalleled detail and accuracy.

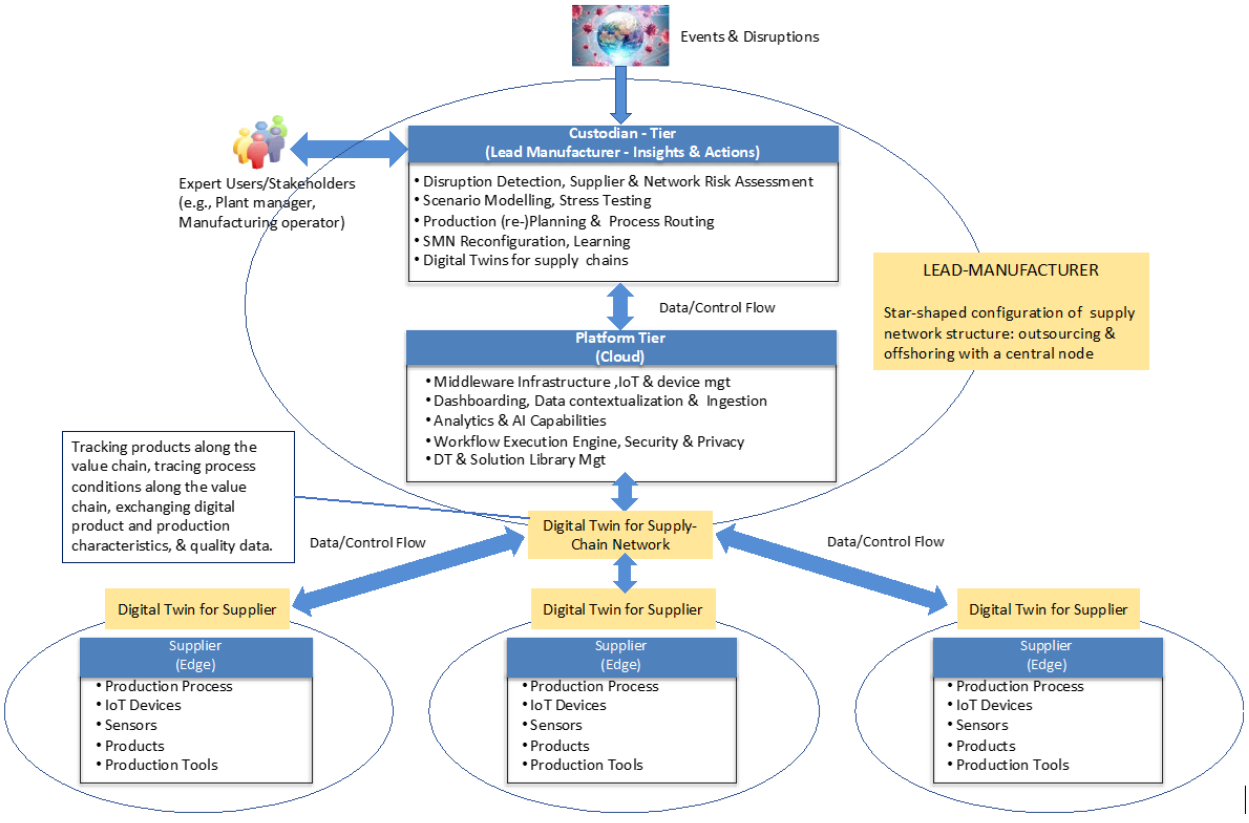

FIGURE 1 OVERVIEW OF A CONNECTED AND AUTONOMOUS RESILIENT SUPPLY CHAIN ECOSYSTEM

Lead manufacturers within Smart Manufacturing Networks (SMNs) in Figure 1 establish seamless links connecting order reception, raw material sourcing, production, and delivery to reverse flow handling. In this evolved landscape, manufacturers autonomously orchestrate intricate supply chain ecosystems, optimizing performance through close collaboration with suppliers, logistics providers, and customers in the edge [4]. The overarching objective is "end-to-end orchestration," seamlessly integrating planning and

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execution in near-real-time through comprehensive automation, both internally and with external partners. The ultimate aspiration is a cohesive and agile supply chain framework rapidly adapting to market dynamics for a harmonized and responsive approach to evolving demands and challenges.

The interplay of downstream and upstream linkages within the production process facilitates the metamorphosis of raw materials into refined products, fostering seamless information flows between collaborating firms in an SMN. To scrutinize disruptions in terms of category, type, impact, geographical reach, and duration of effects, the IMC leverages a Digital Twin framework. This involves creating a Digital Twin for both the lead manufacturer's supply chain and each direct supplier, establishing a collaborative environment for supply chain comprising interconnected Digital Twins, as illustrated in Figure 1.

The above advanced capabilities are designed to empower firms within a Smart Manufacturing Network to converge around a shared resilience framework for the next generation of supply chains. This convergence fosters a market-driven momentum, creating a compelling incentive for a collective "race to the top" among participating entities facilitating the transition from the conventional 'smart factory' model to the more evolved and interconnected 'smart value network.'

1.3.2.1. The Advanced Capabilities

The advanced capabilities that follow not only align seamlessly with but also extend beyond the activities and insights carried out by leading industry experts in the field [5]. This illustrates a clear and robust correlation between ***NARRATE*** functionalities and the expertise of industry leaders.

- **Supply Chain Visibility and Transparency as the Foundational Catalysts Setting the Stage for Elevated Sustainability:** The project aims to enhance visibility, model scenarios, identify hidden risks, and automate a significant portion of supply chain processes, both internally and externally, with the ultimate goal of achieving a dynamic and responsive supply chain that adapts in near-real-time to evolving market demands and disruptions. By fostering collaborative external engagement with suppliers, logistics service providers, and customers within a broader ecosystem, transparency becomes foundational for building more robust and adaptive supply chains.
- **Digital Twins Intricately Model and Simulate the Entire Smart Manufacturing Network, Offering a Centralized 'One-Stop-Shop' for Holistic Insights**: A Digital Twin serves as a comprehensive model providing a reliable framework to reproduce and simulate the intricate workings of an entire SMN. The foundation of the Digital Twin acts as a centralized 'one-stop-shop,' offering holistic and precise insights into production dynamics to significantly enhance decision-making processes. Expanding from a product configurator to an intricate representation of the entire SMN, each element within, including product, quality, service, and production processes, is dynamically linked to SMN operational data. This interconnectivity unlocks deeper operational intelligence, supporting proactive resilience management and providing an unparalleled view for strategic decision-making. The Digital Twin is invaluable in analysing challenges such as the complexity of physical flows, disruptions, supplier concentrations, and supply bottlenecks through the assessment of diverse disruption scenarios.
- **AI-driven Ecosystems Redefine Supply Chain Resilience and Sustainability, Navigating Disruptions with Adaptability:** An AI-driven ecosystem has emerged as a beacon of resilience and sustainability transforming traditional supply chains into dynamic, adaptive networks capable of navigating unforeseen disruptions and optimizing for sustainability. Through predictive analytics, machine learning algorithms, and real-time data processing, the AI-driven ecosystem anticipates potential challenges, adjusts strategies on the fly, and ensures continuity in the face of uncertainties. The fusion of AI and sustainability principles creates a powerful synergy that not only enhances operational resilience but also contributes to sustainable practices by optimizing

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resource utilization, minimizing waste, and fostering responsible decision-making throughout the supply chain.

- **Manufacturing as a Service (MaaS) offers on-demand manufacturing, providing flexible access to diverse capabilities, reducing upfront machinery investments, and facilitating collaboration within Smart Manufacturing Networks**: MaaS offers on-demand manufacturing services via the internet, eliminating the need for local installations and maintenance. Companies can access manufacturing capabilities like 3D printing and CNC machining without owning the physical equipment. In smart manufacturing networks (SMNs), MaaS integrates as a flexible and scalable solution, allowing easy access to manufacturing resources. By providing diverse manufacturing services through the cloud, MaaS enables manufacturers to adjust production levels in real-time, reducing the necessity for substantial upfront machinery investments. SMNs involve collaboration among stakeholders, and MaaS supports global collaboration by creating a centralized platform for entities to access and share manufacturing resources.
- **Strategic Planning Seamlessly Integrating Supply Chain Partners to Foster Uninterrupted Optimization.:** Advancing to the next level of planning involves seamless synchronization in near-real-time with execution, fostering integration across supply chain partners and facilitating continuous optimization. Achieving a pinnacle of precision and responsiveness in planning necessitates implementing comprehensive approaches that span the entirety of the end-to-end supply chain, encompassing suppliers, logistics service providers, and customers.
- **Intelligent Logistics and Warehousing Take Centre Stage in the Interwoven Supply Chain Landscape:** Smart logistics and warehousing emerge as the pivotal driver of savings and a catalyst for growth within the interconnected supply chain ecosystem. Managing the physical flow of goods, from origin to consumption, is an indispensable facet of the supply chain. Elevating this coordination to the next level, smart logistics intertwines the physical shipment and information flow interactively and in near-real-time among suppliers, manufacturers, and customers while smart warehousing utilizes advanced technologies such as IoT devices and automation to optimize inventory management, order fulfilment, and overall warehouse operations. This evolution builds upon the foundation of supply chain transparency and integrated planning, laying the groundwork for heightened efficiency and responsiveness.
- **Dynamic Supply Chain Segmentation Optimizes Customer Centricity while Maintaining a Continuous Balance among Service Levels:** Dynamic supply chain segmentation is a strategy in which companies categorize customers and products based on specific criteria, adapting in real time. This approach embraces flexibility and requirement-driven configurations by aligning supply chain strategies with individual customer needs, allowing transactions to be dynamically allocated to supply chain segments. Smart algorithms are leveraged for superior customer centricity and heightened throughput. Dynamic segmentation facilitates continuous balancing of trade-offs, such as costs versus service level, demand versus supply, and product portfolio options. This holistic perspective guides optimization decisions, leading to significant improvements in overall supply chain performance.

1.3.2.2. The Digital Building Blocks

The core building blocks that ***NARRATE*** will research and develop for a resilient connected and autonomous resilient supply chain ecosystem include:

1. **Real-time Visibility:**
    - Enhance end-to-end supply chain real-time visibility into the entire supply chain, including suppliers, manufacturers, distributors, and logistics partners.
    - Monitor the movement of goods, inventory levels, and other relevant data points.
    - Empower companies to model and evaluate various scenarios, uncover hidden risks, identify potential failure points, and pinpoint supply chain nodes, particularly suppliers, sensitive to disruptions.
2. **Data Contextualization:**

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- Embed meta-data, relevant background information and actions within the manufacturing context, enabling a deeper understanding of data and enhancing decision-making.
- Enable a more precise interpretation of data, leading to improved efficiency in various processes within the smart manufacturing network and optimal utilization of resources. This includes better utilization of machinery, human resources, and materials, leading to improved overall productivity.

3. **Data Integration and Analytics:**
   - Integrate data from various sources, such as IoT devices, sensors, ERP systems, and external data feeds, to create a comprehensive and unified view of the supply chain.
   - Utilize advanced analytics and machine learning algorithms to extract actionable insights from the integrated data.
4. **Risk Management:**
   - Identify potential risks and disruptions in the supply chain, such as natural disasters, geopolitical events, or disruptions in the transportation network.
   - Implement risk mitigation strategies and provide early warning alerts to allow proactive decision-making. The risk management strategy will involve end-to-end supply chain planning, scenario planning and predictive analysis, all of which increase the organization's change management capability.
5. **Predictive Modelling:**
   - Use predictive modelling to forecast demand, supply chain disruptions, and potential bottlenecks.
   - Enable scenario planning to assess the impact of various factors on the supply chain and make informed decisions.
6. **Collaboration and Communication:**
   - Facilitate collaboration and communication among different stakeholders in the supply chain, including suppliers, manufacturers, logistics providers, and customers.
   - Improve coordination and information sharing to enhance overall supply chain efficiency.
7. **Automated Decision Support:**
   - Implement automated decision support systems that leverage artificial intelligence (AI) and machine learning (ML) to make real-time decisions based on the current state of the supply chain.
   - Automate routine and repetitive tasks to improve operational efficiency.
8. **Continuous Improvement:**
   - Monitor key performance indicators and performance metrics to identify areas for improvement.
   - Facilitate continuous improvement initiatives by analyzing data and implementing changes to optimize the supply chain.
9. **Adaptive Planning and Execution:**
   - Enable adaptive planning and execution strategies to quickly respond to unexpected events and changes in market conditions.
   - Support dynamic re-routing of shipments, inventory repositioning, and other agile supply chain practices.
10. **Compliance and Regulatory Management:**
    - Ensure compliance with regulatory requirements and industry standards.
11. **Customer Experience:**
    - Enhance the overall customer experience through better visibility and communication.

By integrating these building block functions, an IMC aims to create a more resilient and agile supply chain that can adapt to disruptions and optimize performance in real time.

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1.4. STEPS FOR CREATING A DIGITAL TECHNOLOGY ROADMAP

Creating a technology roadmap for an advanced project aimed at building agile and resilient supply chains involves integrating AI, IoT, Big Data, and Digital Twins. Table 1 illustrates the ***NARRATE*** technology roadmap. The technology roadmap is divided into several phases with respective activities, determines key milestones, deliverables, and timelines for each phase and assigns responsibilities and establishes cross-functional implementation teams. The implementation team here comprises the deliverable leaders associated with a particular phase and activity.

A clear roadmap as shown in Table 1 is defined by its activities, timing, and milestones. These milestones should be ambitious, pushing the project forward to reach its full potential. By setting targets, we can measure progress, prevent setbacks, and ensure they are on the right path to achieving the project vision and objectives.

Provided below is a comprehensive step-by-step guide that outlines the process of developing and implementing the essential technologies required for the distinct phases of the technology roadmap. The roadmap phases naturally evolve from the project tasks and the corresponding deliverables associated with each specific roadmap stage. This guide serves as a navigational tool, offering detailed insights and procedural clarity to progress through the intricacies of technology development and implementation, ensuring alignment with the overarching goals and objectives of the project.

TABLE 1 NARRATE TECHNOLOGY ROADMAP

PHASE	TIME PERIOD	DELIVERABLES	MILESTONE	ACTIVITY	IMPLEMENTATION
1	[M1-M9]	**M6:** D1.1,D1.2	M#1	Foundation Establishment: Pilot & Architectural Requirements Analysis	AID, FhG, SERV
		M9: D1.3	M#2		
2	[M10-M15]	**M15:** D2.1, D3.1, D3.2, D4.1, D4.2	M#3	Design of Building Blocks	BUL, NUN, SAG, SERV,
3	[M16-M24]	**M24:** D2.4, D3.3, D3.4, D3.6, D4.3, D4.4, D5.1, D6.1	M#4	Demonstration of Building Blocks	AID, BUL, DHL, FhG, INSA, NUN, SERV, SYN
4	[M25-M30]	**M27:** D5.4	M#5	System Integration, Testing & Verification	AID, BUL, FhG, NUN, SAG, SERV
		M30: D2.2, D2.3, D3.7, D3.8, D3.9, D4.6, D4.7,	M#6		
5	[M31-36]	**M33:** D3.5, D4.5, D4.8, D4.9, D5.2, D6.2	M#7	Final Platform & IMC Release & Rollout	AID, DHL, INSA, NUN
		M36: D5.3, D6.3	M#8		

The roadmap is periodically reviewed and updated to reflect changes in technology trends, market demands, and business priorities.

1. **Phase 1: Foundation Establishment [M1-M9]**
   - **Define Project Vision, Objectives and Key Performance Indicators (KPIs):**
     - Clearly outline the goals of the agile and resilient supply chain.
     - Identify measurable KPIs to evaluate progress and success.
   - **Assess Current State:**
     - Conduct a thorough assessment of existing supply chain processes, technologies, and data infrastructure.

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- **Identify Key Digital Technologies and Solutions:**
  - Evaluates relevant digital technologies, such as IoT, AI, big data analytics, and Digital Twins to improve supply-chain resilience.
  - Assess the feasibility and potential impact of each technology on SMN manufacturing operations.
  - Prioritize technologies based on their alignment with defined objectives and overall business strategy.
- **System Architecture Design:**
  - Develop a high-level architecture for the smart manufacturing network.
  - Define communication protocols, data formats, and interoperability standards.
- **Pilot Analysis and Setup:**
  - Definition of pilot requirements based in user stories and validation criteria assessing as well process circularity.
  - Develop a detailed planning and setting up of the pilots and scenarios guiding the pilot´s implementation.

2. **Phase 2: Design of Digital Building Blocks [M10-M15]**
   - **Analysis & Design of Disruption Resilience Strategies**
     - Classify disruptive events, analyse and assess potential operational impacts of each disruption.
     - Design response plans that outline actions that need to be taken in case of a disruption.
   - **Design of Production Contextualization & Interoperability**
     - Annotate relevant production data and operational events spread across different production sites using data categorisation and metadata tagging.
   - **Digital Twin Design**
     - Design a Digital Twin model as a virtual replica of an SMN eco-system providing visibility into SMN interdependencies to help identify vulnerabilities and areas of risk and stress test multiple disruptive scenarios.
   - **Design of Knowledge Model using Digital Twin Technology**
     - Design a Digital Twin model as a virtual replica of an entire SMN eco-system providing visibility into SMN interdependencies.
   - **Design of Resilience, Sustainability & Circularity Stress Testing Scenarios**
     - Analyse and design dynamic simulation in the IMC to stress test SMN & analyze its behaviour in response to various disruptions.
   - **Design of End-to-end AI-driven Visibility Model & Decision Support System**
     - Design models to provide a comprehensive view of the entire SMN, including suppliers, manufacturers, logistics providers, and customers, and the flow of materials, goods, information to help a lead manufacturer gain a deeper understanding and optimize end-to-end supply chain operations.
3. **Phase 3: Development & Early Demonstration of Building Blocks [M16-M24]**
   - **Disruption Resilience Strategy & Tool**
     - Develop response plans that outline actions that need to be taken in case of a disruption, which will include alternative sourcing options, logistics and inventory management strategies and backup options.
   - **Early SMN Knowledge Model using a Neuro-symbolic Decision Support System**
     - Implement an early prototype version of a simple Neuro-Symbolic Question Answering Decision Support System Using Digital Twin Expert Knowledge and Facts.
   - **Early Automated Workflows & Process Orchestration**
     - Implement a preliminary orchestration of multiple individual Digital Twins into one fully connected digital process from the order confirmation up to the delivery of the product to replicate each element of operation and assets across an entire SMN.

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- **Development of Production Contextualization Services**
  - Annotate relevant production data and operational events spread across different production sites to allow the various assets to communicate and exchange information in a standardized format.
  - Create a digital communication framework that enables seamless real-time data exchange between different machines, and production lines in an SMN.
- **Early Production Planning & Process Routing System & Algorithms**
  - Implement a preliminary AI-driven production planning & process routing system that covers the scope of the SMN ecosystem to optimize production schedules, and enhance the ability of an SMN to incorporate and resolve disruptions from the confirmation of the order up to the delivery of the product.
- **Early Intelligent Logistics and Warehousing System**
  - Implement a preliminary intelligent logistics version of prototype that uses AI-powered algorithms and IoT to gather data about transportation activities, analyze, and improve efficiency.
  - Implement a preliminary intelligent warehousing system to optimize warehouse operations.
- **Early Pilot Demonstration**
  - Elaborate a mapping between pilots, NARRATE tools, and User Requirements/KPIs for the validation assessment.
  - Formalize the evaluation steps for testing, assessing and validating the industrial use cases.
  - Perform a fine-tuning of the Intelligent Manufacturing Custodian (IMC) and Artificial Intelligence (AI) platform, detecting the opportunities for improvements and the corresponding implementation plan.
  - Propose an early demonstrator for a selected pilot in release R1.
- **Early Integration of Intelligent Manufacturing Custodian & AI Platform**
  - Provide an early demonstrator in the platform release R1 partially integrating the SMN main innovative building blocks, such as the contextualized mechanisms, Digital Twin and NSQA Intelligent Digital Tools, AI-driven sensing, panning and production tools.

4. **Phase 4: System Integration, Testing & Verification [M25-M30]**
   - **Risk Identification & Monitoring Tool**
     - Develop a real-time risk identification & monitoring system to provide SMN analysts with a proactive tool and real-time dashboard to identify and respond to potential disruptions quickly and effectively.
   - **Supplier & SMN Risk Assessment Tool**
     - Develop an SMN Risk Assessment analytics tool to help identify patterns & anomalies that could signal potential disruptions by assessing supplier risk, mapping out the entire SC network using digital twins and identifying the critical nodes and dependencies, and monitoring industry trends.
   - **Design of Knowledge Model using Digital Twin Technology**
     - Implement a Digital Twin model of an entire SMN eco-system providing visibility into SMN interdependencies on thebasis of phase-3.
   - **SMN Knowledge Model using a Neuro-symbolic Decision Support System**
     - Develop a simple Neuro-Symbolic Question Answering Decision Support System using Digital Twin Expert Knowledge and Facts on the basis of phase-3 using a range of scenarios and test cases to identify bottlenecks, inefficiencies, or areas of suboptimal performance, and make the necessary adjustments.
   - **Resilience, Sustainability & Circularity Stress Testing Scenarios**

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- Develop a tool to stress test SMN & analyze its behaviour in response to various disruptions and development of preliminary resilience mitigation plans on the basis of design results obtained in phase-2.

- **Development of end-to-end AI-driven visibility model & support DSS**
  - Develop knowledge models – on the basis of design results obtained in phase-2 - to provide a comprehensive view of the entire SMN supporting visibility and transparency by providing real-time insights into the movement of materials, goods, and other key performance metrics based on appropriate extensions of the neuro-symbolic DSS in phase-3.
- **Continuous Pilot Experimentation**
  - Enhance the ongoing exploration through pilot trials and early demonstrator in release R1 by incorporating findings from the suite of tools developed throughout phase-4, thereby enriching pilot functionality and advancing the project's trajectory.

5. **Phase 5: Final Release & Rollout of Platform & Intelligent Manufacturing Custodian [M31-M36]**
   - **Security & Privacy services**
     - Develop a security and privacy tool that provides a digital signature framework and cryptographic hashing functionality for data and meta data integrity and includes service categories such as governance, risk management, asset management, access control, and incident response.
   - **Reconfiguration of Production**
     - Develop a tool that re-orchestrates SMNs after considering potential risks, identifying vulnerabilities, and final contingency plans and after streamlining logistics operations in in phase-3
     - Enable analysis, and response to changes in demand, supply, and logistics and embed self-adjusting and self-configuring capacities in the Intelligent Manufacturing Custodian.
   - **Production Planning & Process Routing System & Algorithms**
     - Develop an AI-driven production planning & process routing system that covers the scope of the entire SMN ecosystem to optimize production schedules, and enhance the ability of an SMN to incorporate and resolve disruptions from the confirmation of the order up to the delivery of the product employing Digital Twins.
   - **Intelligent Logistics and Warehousing System**
     - Develop an intelligent logistics and warehousing tool as part of the IMC that uses AI-powered algorithms Digital Twins, IoT and data-driven approaches to optimize the movement, storage, and management of goods within the supply chain.
     - Incorporate resilience within logistics and warehousing operations to mitigate the impact of disruptions.
     - Develop AI-driven algorithms to optimize the selection of routes based on real-time conditions, while minimizing fuel consumption, transportation costs, and environmental impact.
   - **Intelligent MfG Custodian & AI Platform Full Prototype (Release R2)**
     - Develop an operative Platform (R2) that includes the core IMC's functionalities including AI-driven production, root cause analysis and tools to predict and remediate asset failures proactively together with advanced AI-driven services to support informed decision making and communication with human operators.
   - **Pilot Implementation with Final Modules in Release R2**
     - Define activities to be performed for the execution of each pilot trial in release R2 and monitor progress with experimentation conducted in conjunction with technical implementations that will be gradually available to the pilot trial users.
     - Prioritize the implementations required by the pilots to optimize effort while getting the soundness expected by the industrial pilots and use cases.
   - **Intelligent MfG Custodian & AI Platform Testing, Evaluation and Rollout**

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- Continuously test, evaluate, and enhance all fundamental and innovative features within Release R2.
- Elevate the AI Platform to a fully operational state by integrating extended functionalities along with asset management tools and production planning and scheduling capabilities.
- Conduct quality assurance, quality control, and ongoing software testing activities to offer continual feedback for refining the final release. This feedback guides users during pilot phases, indicating necessary adjustments.

- **Final Pilot Evaluation with Platform Rollout**
  - Roll out successful pilot projects across the SMN and IMC operation once the platform testing is finished in the previous activity.
  - Provide in-depth analysis of interviews and other data gathered from the users' experiences and feedback.
  - Evaluate the performance and soundness of the IMC & Platform and their operational effectiveness and performance for each pilot.
  - Use key performance indicators to measure success and impact and refine the roadmap based on feedback, new technologies, and evolving business needs.

2. CHOOSING A PLATFORM TO SUPPORT THE SMART MANUFACTURING NETWORK

An AI platform designed to support Intelligent Manufacturing Custodian and Smart Manufacturing Network operations serves as a centralized and integrated hub for managing and optimizing various facets of the manufacturing ecosystem. The strategic selection of the platform involves a meticulously orchestrated series of successive steps described below, each intricately performed to ensure optimal alignment with the overarching goals and requirements of the ***NARRATE*** manufacturing ecosystem.

1. **Define Requirements:**
   - Clearly outline the specific requirements of the smart manufacturing pilots and applications based on user stories.
   - Identify key features needed for supply chain resilience, such as real-time monitoring, predictive analytics, and scalability.
2. **Understand Use Cases & Scenarios:**
   - Analyze different smart manufacturing use cases within the SMN and prioritize them based on their impact on supply chain resilience.
3. **Interoperability and Integration:**
   - Ensure that the AI platform supports interoperability with a variety of devices, sensors, and equipment from different manufacturers.
   - Assess the platform's ability to integrate with existing systems in the project for seamless data exchange.
4. **Scalability:**
   - Consider the scalability of the AI platform to accommodate the growing volume of devices and data.
   - Evaluate how easily the platform can scale to support additional manufacturing sites or expanded functionalities.
5. **Data Security and Privacy:**
   - Prioritize a platform with robust security features, including data encryption, access controls, and secure communication protocols.
   - Ensure compliance with relevant data privacy regulations, especially when dealing with sensitive supply chain information held in Digital Twins and the IMC.

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6. **Analytics and Predictive Maintenance:**
   - Assess the platform's analytics capabilities for real-time data analysis and predictive services, or ability to accommodate those facilities.
   - Look for features like anomaly detection and machine learning algorithms that can help predict and prevent disruptions in the supply chain.
7. **Reliability and Uptime:**
   - Evaluate the reliability and uptime of the AI platform to ensure continuous operation.
   - Check for redundancy and failover mechanisms to minimize downtime during unexpected events.
8. **Flexibility and Customization:**
   - Choose a platform that offers flexibility in terms of customization to meet the unique requirements of the ***NARRATE*** pilot and smart manufacturing applications at large.
   - Assess the ease of adapting the platform to changing business needs.
9. **User Interface and Ease of Use:**
   - Consider the user interface of the AI platform and assess its user-friendliness.
   - Ensure that relevant stakeholders can easily navigate and use the platform without extensive training.
10. **Cost and ROI:**
    - Evaluate the total cost of ownership, including licensing, implementation, and maintenance costs.
    - Estimate the potential return on investment (ROI) based on the platform's ability to enhance supply chain resilience.
11. **Pilot and Proof of Concept:**
    - Run pilots or proof of concept to validate the AI platform's capabilities in a real-world setting.
    - Gather feedback from key stakeholders and end-users during the pilot phase.
12. **Continuous Evaluation and Improvement:**
    - Establish a process for continuous evaluation of the AI platform's performance.
    - Stay informed about updates and new features to ensure that the platform remains aligned with evolving needs of the project.

By following these steps, we can systematically evaluate and select an AI platform [6] that best suits the project's goals for smart manufacturing applications targeting supply chain resilience and sustainability.

3. KPIS

The purpose and value of KPIs in a technology roadmap for smart, resilient, and sustainable manufacturing networks lie in their ability to guide strategic alignment, measure performance, assess environmental impact, and support a holistic approach to creating a manufacturing ecosystem that is both technologically advanced and environmentally responsible. KPIs serve as critical tools in achieving the broader goals of resilience, sustainability, and intelligence in manufacturing networks.

3.1. PURPOSE OF KPIS

An exploration of the purpose and value of typical KPIs that will be used in the context of technology roadmap follows.

1. **Strategic Alignment:**
   - **Purpose:** Ensure that technology initiatives align with the overarching goals of creating smart, resilient, and sustainable manufacturing networks.
   - **Value:** This KPI can help assess the extent to which technology investments contribute to the strategic objectives of visibility, resilience, sustainability, on-time delivery and intelligence in the manufacturing network.

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2. **Performance Measurement:**
    - **Purpose:** Quantify the performance improvements resulting from the implementation of smart and sustainable technologies.
    - **Value:** This KPI provides tangible metrics for evaluating the impact of technology on key areas such as energy efficiency, waste reduction, and overall operational resilience.
3. **Sustainability & Circularity Metrics:**
    - **Purpose:** Measure and monitor the environmental impact, sustainability and circularity practices within the manufacturing network.
    - **Value:** This KPI is related to carbon footprint, energy consumption, amount of recycled content and waste reduction help organizations track progress toward sustainable manufacturing practices.
4. **Supply Chain Resilience:**
    - **Purpose:** KPIs contribute to the identification of vulnerabilities, risks and disruptions within the manufacturing network, supporting proactive measures for risk mitigation and enhancing overall adaptability.
    - **Value:** This KPI can measure the network's ability to adapt to changes, recover from disruptions, and maintain operational continuity.
5. **Improving On-Time Delivery:**
    - **Purpose:** Track the percentage of deliveries that are made on or before the scheduled delivery date.
    - **Value:** Ensure that products reach customers on time, reducing the risk of disruptions enhancing the reliability of the supply chain, and reducing environmental impact of delivering products from manufacturing facilities to end-users.

Table 2 presents select KPIs from above list that relate to operational and cost improvements and proposes improvements stipulated by the project

TABLE 2 OPERATIONAL & COST IMPROVEMENT KPIS.

Key Performance Indicators (on average)
• improvement in identification of potential risks & disruptions by 30%. • improvement of 20% of time to recover to full functionality after a disruption. • Improvement of 15% of on-time delivery rate • 10% reduction of greenhouse gas emissions & energy consumption in production. • 10% reduction of amount of waste generate by lead supplier or tier-1company in SC.

In addition to the above KPIs, the project has identified KPIs specific to its three pilots which include:

- improvement in stock reduction: 5 - 10%,
- increase in customer satisfaction (quality preservation/JIT delivery and information on environmental performance): 5 - 10%
- extension of machine lifespan by about 10%.

4. DIGITAL TECHNOLOGY ROADMAP & PILOT DIGITAL MATURITY MODEL

A pilot digital maturity model (PDMM) can help assess the level of technological advancement in the project pilots and guide them toward higher levels of digital integration and innovation. Below is a digital maturity model tailored specifically for the ***NARRATE*** smart manufacturing network, encompassing five maturity levels in Figure 2 that are associated with the five roadmap stages. These PDMM levels are Pre-

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Digitization, Basic-Digitization, Connected Supply Chain, Predictive & Prescriptive Supply Chain, and Adaptive Supply Chain.

The PDMM in Figure 2 is an effective means of identifying a pilot's maturity and offers an exploration of the different levels of pilot development. Detailed instructions on how to move between the different levels of maturity are provided by the Digital Technology Roadmap as shown in Figure 2. The implementation of each pilot level of maturity is aligned with factors such as industry requirements of its respective pilot, its technological capabilities, and resource availability as specified in WP-6

PHASE	TIME PERIOD	DELIVERABLES	MILESTONE	ACTIVITY
1	[M1-M9]	M6: D1.1,D1.2	M#1	Foundation Establishment: Pilot & Architectural Requirements Analysis
		M9: D1.3	M#2	
2	[M10-M15]	M15: D2.1, D3.1, D3.2, D4.1, D4.2	M#3	Design of Building Blocks
3	[M16-M24]	M24: D2.4, D3.3, D3.4, D3.6, D4.3, D4.4, D5.1, D6.1	M#4	Demonstration of Building Blocks
4	[M25-M30]	M27: D5.4	M#5	System Integration, Testing & Verification
		M30: D2.2, D2.3, D3.7, D3.8, D3.9, D4.6, D4.7,	M#6	
5	[M31-36]	M33: D3.5, D4.5, D4.8, D4.9, D5.2, D6.2	M#7	Final Platform & IMC Release & Rollout
		M36: D5.3, D6.3	M#8	

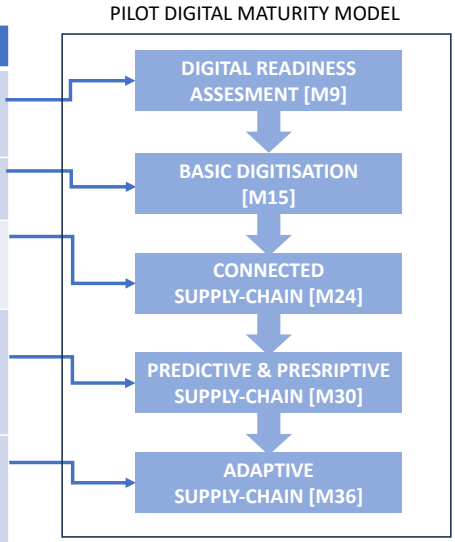

FIGURE 2 THE PILOT MATURITY MODEL.

The PDMM is being used to baseline and track the maturity of different facilities and identifies the key capabilities for different levels of maturity as follows.

1. **Digital Readiness Assessment:**
   - **Characteristics:**
     - Steps toward designing and building a robust and adaptive supply chain that can withstand disruptions and challenges.
   - **Focus Areas:**
     - Planning the integration and optimization of technology across the Supply Chain.
     - Planning and setting up of project pilots and scenarios.
     - Enhancing visibility and transparency.
     - Plans for achieving supply-chain wide interoperation.
     - Plans for designing and implementing AI-platform and tools.
   - **Key Goals:**
     - Improve efficiency through automation.
     - Lay the foundation for more advanced digital capabilities.
2. **Basic Digitization:**
   - **Characteristics:**
     - Design and basic automation and computerization of manual processes.
     - Limited use of sensors and basic data collection.
     - Design of connectivity between supply-chain systems and machines.
   - **Focus Areas:**
     - Process automation and optimization.
     - Data connectivity and correlation via Digital Twins.
   - **Key Goals:**

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- Improve efficiency through automation.
- Lay the foundation for more advanced digital capabilities.

3. **Connected Supply-Chain:**
   - **Characteristics:**
     - Connectivity between SC partner facilities.
     - Implementation of IoT devices and sensors for data collection.
     - Integration of data from various sources into a logically centralized facility using Digital Twins.
   - **Focus Areas:**
     - Enhance data visibility and accessibility.
     - Partial integration of Smart Manufacturing System.
   - **Key Goals:**
     - Achieve SC-wide data access, visibility, and interoperability.
     - Enable better decision-making through data correlation.
4. **Predictive & Prescriptive Supply-Chain**
   - **Characteristics:**
     - Supplementing data visibility and transparency with AI predictive and prescriptive capabilities will improve operation-wide efficiency, identify disruptions & inefficiencies, predict & reduce failures, & improve automation.
     - Enhanced supply chain resilience, visibility and coordination.
   - **Focus Areas:**
     - Advanced analytics and improved quality control.
     - Integration of supply chain processes with suppliers and customers.
   - **Key Goals:**
     - Minimize disruptions through predictive and prescriptive AI models.
     - Optimize production and logistics schedules based on predictive and prescriptive analytics.
5. **Adaptive Supply-Chain:**
   - **Characteristics:**
     - Dynamic and agile Supply Chain that anticipates and responds to external disruptions.
     - Continuous learning and reshaping of the Supply Chain through adaptive analytics.
   - **Focus Areas:**
     - Implementation of adaptive analytics for real-time decision-making.
     - Integration of AI and machine learning for autonomous operations.
     - Collaboration with external partners in a digitally connected supply chain ecosystem.
   - **Key Goals:**
     - Achieve a high level of agility and responsiveness.
     - Enable autonomous decision-making based on real-time data.
     - Establish a collaborative and adaptive supply chain ecosystem and achieve KPIs stipulated in the project proposal.

5. CONCLUSIONS

The technology roadmap serves as an intricate and high-level guide, acknowledging that the specific activities and timelines may require nuanced adjustments to accommodate the unique requirements and challenges inherent to the project. In achieving successful execution, the pivotal factors lie in fostering a culture of regular communication and collaboration among partners, stakeholders, and project teams. This dynamic interplay ensures not only the adaptability of the roadmap but also the alignment of efforts and insights essential for navigating the evolving landscape of the project with precision and cohesion.

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