NARRATE

Regenerative Resilient Smart Manufacturing Networks

D4.4 Intelligent logistics and warehousing modules (a)

2026/01/28

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D4.4 INTELLIGENT LOGISTICS AND WAREHOUSING MODULES

Work package	WP4
Task	T4.4
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Submission date	28/01/2026
Deliverable lead	DHL
Version	1.0
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Reviewers	Deike Ihnen (FhG), Dirk Busse (BUDATEC)
Abstract	This deliverable, D4.4, develops intelligent logistics and warehousing methods and tools to equip the Intelligent Manufacturing Custodian (IMC) to manage logistics and inventory operations in a Smart Manufacturing Network (SMN). It defines proactive and reactive operational models that translate planning and analytics into executable logistics actions, supported by a reference software architecture centred on the IMC and its Smart Manufacturing Module (SMM). A set of system workflow sequences specifies interactions between local industrial systems and central intelligence. The proposed approach enables data-driven buffering, disruption mitigation, and logistics optimisation, supporting resilient and efficient manufacturing network operations and preparing the ground for pilot validation.

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Keywords	Intelligent Logistics, Intelligent Warehousing, Intelligent Manufacturing Custodian, Smart Manufacturing Network, Supply Chain Resilience

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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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1	INSTITUTO TECNOLÓGICO METALMECÁNICO, MUEBLE, MADERA, EMBALAJE Y AFINES-AIDIMME	AID	ES
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Abbreviations

Abbreviation	Description
AI	Artificial Intelligence
API	Application Programming Interface
BO	Business Objective
BOM	Bill of Materials
DT	Digital Twin
DSS	Decision Support System
EC	European Commission
ERP	Enterprise Resource Planning
GPS	Global Positioning System
IMC	Intelligent Manufacturing Custodian
IoT	Internet of Things
IW	Intelligent Workflow
KPI	Key Performance Indicator
MES	Manufacturing Execution System
ML	Machine Learning
PoC	Proof of Concept
SC	Supply Chain
SO	Societal Impact
SMN	Smart Manufacturing Network
SMM	Smart Manufacturing Module
STO	Strategic Objective
TMS	Transport Management System
WMS	Warehouse Management System
WP	Work Package
XLS	Microsoft Excel Spreadsheet File

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EXECUTIVE SUMMARY

Deliverable D4.4 contributes to the NARRATE project by developing intelligent logistics and warehousing methods and tools that enable the Intelligent Manufacturing Custodian (IMC) to effectively manage logistics and inventory operations within a Smart Manufacturing Network (SMN). In line with NARRATE's overarching objective of strengthening supply-chain resilience, this deliverable addresses the critical challenge faced by manufacturing and logistics companies when unforeseen events disrupt material flows, increase costs, and jeopardise the ability to meet customer demand.

Building on NARRATE's AI-driven visibility, Digital Twin, and predictive analytics capabilities, D4.4 translates network-wide insights into actionable logistics and warehousing decisions. The work defines how the IMC leverages real-time data from production systems, warehouses, suppliers, and transport operations to anticipate risks, mitigate disruptions, and coordinate material flows across the value chain. Buffer-based strategies, combined with proactive and reactive decision logic, enable the SMN to absorb shocks and maintain production continuity under adverse conditions.

The methodology followed is model-driven and architecture-oriented. Proactive and reactive operational models for logistics and warehousing are defined and embedded into a reference software architecture centred on the IMC and its analytical core, the Smart Manufacturing Module (SMM). These models are operationalised through structured system workflows that connect local industrial systems with central intelligence, ensuring continuous feedback between execution, planning, and optimisation.

By integrating logistics and warehousing intelligence with the IMC and Digital Twin foundations of NARRATE, D4.4 strengthens the project's ability to deliver end-to-end visibility, predictive disruption management, and self-adapting supply-chain operations under human supervision. This deliverable lays the groundwork for pilot validation in real industrial environments, supporting NARRATE's goal of demonstrating resilient, efficient, and sustainable Smart Manufacturing Networks across diverse manufacturing sectors.

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1. INTRODUCTION

The present deliverable, D4.4 *Intelligent Logistics and Warehousing for the Intelligent Manufacturing Custodian*, builds on the results of D4.2[1] and D4.3[2]**¡Error! No se encuentra el origen de la referencia.** and extends them into the logistics and warehousing execution layer of the Smart Manufacturing Network. While previous deliverables focus on visibility and production planning, this work is grounded in the operational reality of manufacturers and logistics operators, where disruptions, delayed deliveries, and inventory imbalances have an immediate impact on production continuity and service levels.

Deliverable D4.2 established an end-to-end AI-driven visibility model and Decision Support System (DSS), enabling a lead manufacturer to gain real-time insights into material flows, inventory status, and key performance indicators across the SMN. Deliverable D4.3 focused on the development of production planning and process routing system algorithms, including predictive models for demand forecasting, production capacity, and resource utilisation, as well as mathematical models supporting production planning decisions. Together, D4.2 and D4.3 define what should be produced, when, and under which constraints, based on network-wide visibility and predictive analytics.

Deliverable D4.4 now extends these foundations by addressing how production planning decisions are operationally supported through intelligent logistics and warehousing. Its core objective is to develop intelligent methods and tools that equip the Intelligent Manufacturing Custodian to manage logistics and warehousing operations in a coordinated, resilient, and data-driven manner across an SMN. In this sense, D4.4 acts as the operational bridge between planning, visibility, and physical execution.

Intelligent logistics in this context relies on AI-powered analytics, IoT-enabled data acquisition, and real-time monitoring to assess transport operations and support timely mitigation decisions. Intelligent warehousing focuses on buffer inventory management, replenishment strategies, and predictive inventory positioning, enabling the SMN to absorb disruptions while maintaining production continuity.

This deliverable presents the proactive and reactive operational models, the supporting software architecture centred on the IMC and its Smart Manufacturing Module, and the system workflows required to translate high-level planning and visibility outputs into executable logistics and warehousing actions.

D4.9[3], the second part of D4.4, will build on this foundation by addressing implementation and validation aspects, including pilot-oriented deployment considerations and integration with industrial systems.

1.1 ARCHITECTURAL CONTEXT WITHIN NARRATE

This deliverable builds upon the core architectural foundations developed across the NARRATE project and consolidates them into a coherent framework for intelligent logistics and warehousing within a Smart Manufacturing Network (SMN). It focuses on the operationalization of logistics- and warehouse-related intelligence by equipping the Intelligent Manufacturing Custodian (IMC) with concrete methods, tools, and workflows that enable proactive and reactive decision-making under uncertainty.

At the centre of the NARRATE architecture, the IMC acts as the coordination and orchestration layer across production, logistics, warehousing, and external service

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providers. Previous deliverables established the IMC's conceptual role, data visibility capabilities, and decision-support logic. D4.4 extends these results by addressing the logistics and warehousing dimension, translating visibility and planning outputs into executable actions related to buffer inventory management, replenishment, transportation, and warehouse operations.

A key enabler of this integration is the Blueprint concept, which provides a structured, digital representation of components, suppliers, warehouses, logistics services, and operational constraints. Blueprints act as a shared semantic and data backbone across the SMN, allowing heterogeneous actors (manufacturers, suppliers, buffer warehouses, and logistics providers) to exchange consistent and machine-interpretable information. In D4.4, Blueprints are leveraged to support dynamic buffer sizing, inventory status monitoring, replenishment strategies, and logistics routing decisions, ensuring alignment between physical operations and digital decision models.

Within the IMC, the Smart Manufacturing Module (SMM) performs all data processing and analytical reasoning required to support logistics and warehousing decisions. The SMM consumes Blueprint data, real-time operational inputs, and contextual information (e.g. disruptions, transport availability, inventory levels), and applies intelligent methods to recommend or trigger actions such as buffer replenishment, component reallocation, or alternative supplier and transport selection. These capabilities are explicitly designed to operate in both proactive modes (anticipating disruptions and adjusting buffers in advance) and reactive modes (responding to realized disruptions with minimal recovery time).

Overall, D4.4 positions intelligent logistics and warehousing as a tightly integrated layer within the NARRATE reference architecture. Rather than operating as isolated optimisation functions, logistics and warehousing decisions are embedded into the IMC-centric control loop, ensuring consistency with production planning (D4.3), visibility and DSS functions (D4.2), and the Digital Twin-based representation of the SMN. This integration is a necessary step toward validating the IMC as an operational "nerve centre" for resilient, adaptive, and data-driven manufacturing networks, and prepares the ground for pilot implementation and validation in subsequent project phases.

1.2 DOCUMENT STRUCTURE

This deliverable is organised to progressively lead the reader from the context and objectives of intelligent logistics and warehousing to their architectural and operational implementation within a Smart Manufacturing Network.

Section 1 introduces the scope, objectives, and positioning of Deliverable D4.4 within the NARRATE project, including its relationship with previous deliverables on end-to-end visibility and production planning. Section 2 presents the conceptual framework for intelligent logistics and warehousing, defining the proactive and reactive operational models and describing the role of buffer warehouses and logistics optimisation in supporting resilience.

Section 3 details the functional and software architecture of the proposed solution, centred on the Intelligent Manufacturing Custodian and its Smart Manufacturing Module. This section also includes the definition of the system workflow sequences, which specify how data and decisions flow between local industrial systems and central intelligence for blueprint updates, buffer inventory management, replenishment, buffer usage, and production consumption tracking.

Finally, Section 4 consolidates the outcomes of the deliverable by summarising the contribution of the proposed architecture to the NARRATE objectives and outlining the next steps towards implementation and pilot validation.

1.3 OBJECTIVES

Deliverable D4.4 provides the logistics and warehousing execution layer required to operationalise the resilience, visibility, planning, and intelligence objectives of the NARRATE project. It translates end-to-end visibility (STO-1)[4], production planning and predictive analytics (STO-3)[6], and Digital Twin–enabled contextualisation (STO-2)[5] into concrete, IMC-managed logistics and warehousing actions within a Smart Manufacturing Network. By defining methods, tools, and system workflows, D4.4 plays a central role in building and validating the Intelligent Manufacturing Custodian (STO-4)[7] and enabling its deployment in industrial pilots.

Contribution to STO-1: D4.4 extends the visibility capabilities developed in D4.2 by defining how real-time data on inventories, buffers, and logistics flows are used by the IMC to take operational decisions. It enables AI-driven mitigation actions directly supporting resilience and production efficiency.

Contribution to STO-2: D4.4 provides the logistics and warehousing behavioural models required to make SMN Digital Twins operationally meaningful. Buffer strategies, replenishment logic, and logistics workflows defined in D4.4 can be simulated within DT environments to analyse disruption scenarios and evaluate corrective actions.

Contribution to STO-3: Through the Smart Manufacturing Module (SMM), D4.4 applies predictive and prescriptive analytics to logistics and warehousing decisions. It enables proactive buffering, reactive mitigation, and continuous learning from execution data.

Contribution to STO-4: D4.4 is a core enabler of STO-4, as it assigns specific operational responsibilities to the IMC and defines executable workflows connecting local systems with central intelligence. These workflows form the basis for validation and demonstration in real industrial pilots.

Indirect contribution to SO-1 and BO-1: by optimising inventory levels, reducing emergency logistics, and improving coordination, D4.4 supports more resource efficient and resilient operations (SO-1)[8] and provides a clear architectural foundation for exploitation of IMC-based logistics and warehousing services (BO-1)[9].

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2. INTELLIGENT WAREHOUSING AND LOGISTICS COMMUNICATION FLOW DEFINITION

2.1 MANUFACTURING CAPACITY PLANNING

According to D4.3, with which this present deliverable is highly connected, the capacity planning may be approached from

1) a proactive model before an event or disruption occurs and
2) a reactive model once it has occurred.

Both models are essential to develop methods and tools to equip the IMC to better manage logistics and warehousing operations. As such, the first step has been to analyse the structure of both models (proactive and reactive) from the manufacturer-supplier-warehouse/buffer perspective. For that, we have considered the data ingestion required, the subjects involved, the critical information required by each of them and the responses expected to improve the operations and decision making using the IMC.

As a result, a set of general stages, that may be followed by any subject interested in using the Intelligent Manufacturing Custodian along the manufacturing supply chain, have been established. In this design, we have differentiated the set of methods to be followed by the stakeholders for data ingestion to the IMC and the tools to be developed to process that data to the IMC is able to provide answers for better decision making.

2.1.1 Proactive model setting

Step 1: Critical components definition and data processing

The process begins with METHOD 1 in Table 1, in which the manufacturer explicitly identifies a critical component whose availability has a direct impact on the continuity of the production process. For the selected component, the manufacturer ingests into the IMC a well-defined and standardised dataset, as detailed in Table 1, ensuring consistency and replicability across different industrial contexts. This dataset comprises static descriptive information, including the manufacturer´s own specific identification code, component type (e.g. raw material or pre-processed component), textual description, unit of measurement, physical characteristics such as weight and dimensions, supplier identification (name and code), unit cost, and origin–destination information. In addition, the manufacturer provides dynamic and historical operational data, specifically the total historical consumption of the component by the production line, the time horizon over which this consumption has been observed, and the number of production line calls during that period. These data elements constitute the minimum input required by the IMC to characterise component criticality and to compute reliable consumption and delivery-cycle estimations in subsequent steps.

Once the data are ingested, the Smart Manufacturing Module of the IMC processes the information to derive key performance indicators relevant for capacity planning. The Smart Manufacturing Module (SMM) estimates the average consumption per production line call (Tool 1), the frequency of production line calls over time (Tool 2), and the expected number of production line calls within one delivery cycle (Tool 3), based on the average supplier lead time. This processing step transforms raw historical data into actionable information for decision-making.

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Method 2 is also proactive and implies the ingestion of data from the different suppliers within the manufacturers operates.

	DATA to be ingested to the IMC by the manufacturer (processed by the SMM)	EXAMPLE	DATA received from the IMC by the manufacturer for DS
METHOD 1 CRITICAL COMPONENT IDENTIFICATION	Identification code (manufacturer criteria)	*MARTHA_C14739*	
	Type of component (raw material, pre-processed…)	*Raw material*	
	Units of measurement	*Un*	
	Weight	*0.08 kg*	
	Dimensions (volume)	*7.8 DIAM*	
	Historical consumption 1)production line consumption of the component 2) period 3) production line calls	*1) 6,176 units* *2) 10 months* *3) 11 production line calls*	
	Average Delivery time (delivery cycle)	*37 days*	
	Factor for delivery time	*1*	
	Period considered for historical data provided	*303 days*	
TOOL 1	Units/production line call		**561 Units/prod. line call 1.1 prod. line call/30 days**
TOOL 2	Production line calls/delivery cycle		**1.36 prod. line call/delivery cycle (37 days)**
TOOL 3	Units to be buffered		**561 (561*1) units to be buffered**
METHOD 2 SUPPLIER IDENTIFICATION	Supplier name	*INDAUX*	
	Supplier code	*00081*	
	Cost/unit	*1.72€*	
	Origin	*Italy*	
	Destination	*46430 Sollana, Valencia, Spain*	

Table 1. Data, methods and tools for critical components definition

Figure 1 illustrates the proactive model setting for capacity planning applied to critical components within the manufacturing supply chain. The graph represents the logical sequence of interactions between the manufacturer and the Intelligent Manufacturing Custodian from the identification of a critical component to the definition of the buffering strategy. Based on these calculations performed by the SMM, the IMC sends back to the manufacturer an estimation of the number of component units required to cover a full delivery cycle (2 in Fig. 1). This output represents the recommended quantity of components to be sent to the buffer warehouse. By setting the buffer stock at this level, the manufacturer ensures that production can continue uninterrupted, for a certain period, in the event of a disruption, while the next batch of components is being supplied.

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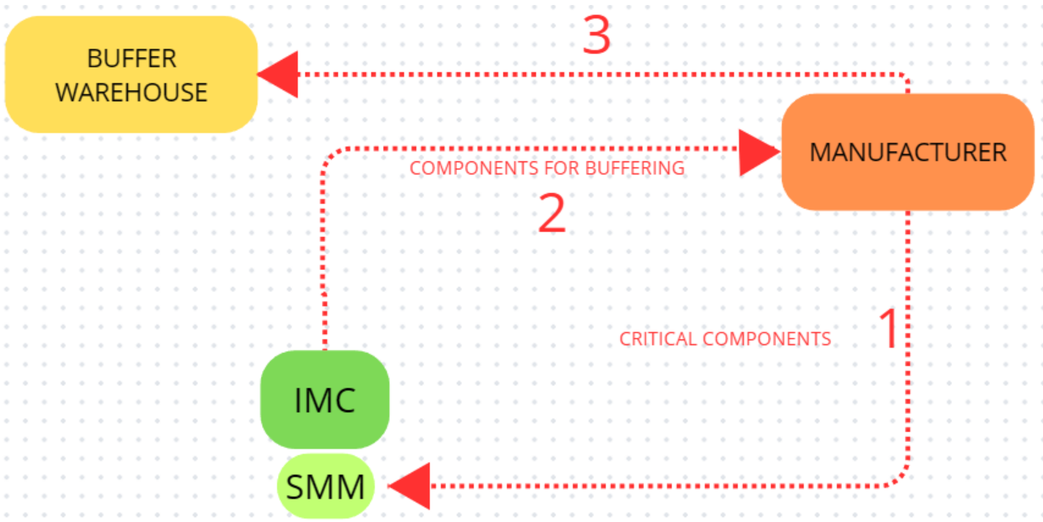

Figure 1. Stage 1 of critical component definition (proactive)

Figure 1 highlights the role of the IMC as critical for decision making support, clearly separating responsibilities between data provision by the manufacturer and data processing and estimation. This structured and replicable approach enables any manufacturer to proactively plan buffering capacity for critical components, independently of the specific supply chain configuration, provided that the required historical and operational data are available. Last, this process also comprises the acceptance and execution of the buffering estimation by the manufacturer (3), closing the proactive planning loop and operationalising the IMC recommendations received.

Step 2: buffering estimation accepted and executed by the manufacturer

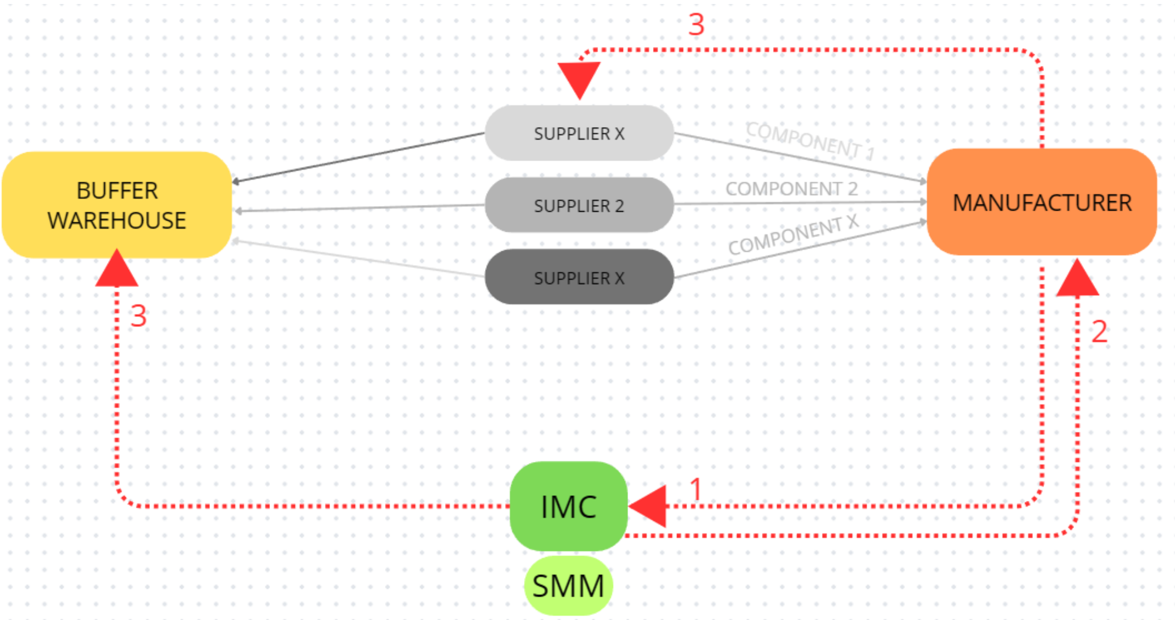

Figure 2. Stage 2 of critical component definition (proactive)

Figure 2 illustrates Stage 2 of the proactive capacity planning process in a multi-supplier, multi-component context. This stage is activated once the buffering estimations provided by the IMC in Stage 1 have been reviewed and accepted by the manufacturer and the corresponding execution decisions are taken.

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As shown in Step 1 of the graph, the manufacturer confirms to the IMC the set of critical components to be buffered, and the associated quantities previously calculated using the Intelligent Manufacturing Custodian analytical tools (Method 2). These estimations are component-specific and may originate from different suppliers, reflecting realistic manufacturing scenarios in which several suppliers provide distinct critical components (e.g. Component 1, Component 2, Component X). The IMC acts as the coordination layer, consolidating the accepted buffering requirements and ensuring their consistency across components and suppliers.

In Step 2, the manufacturer initiates the operational execution by placing orders for the buffered quantities to the corresponding suppliers. Each supplier receives an order aligned with the buffering quantity defined for the specific component it provides. This step represents the transition from decision support to execution, in which IMC recommendations are translated into specific procurement actions.

Step 3 represents the physical materialisation of the buffering strategy. Once produced and delivered by the suppliers, the components are routed to the buffer warehouse, where they are stored as dedicated buffer stock. This stock is dimensioned to cover at least one full delivery cycle per component, thereby reducing the manufacturer's exposure to upstream disruptions. The bidirectional links shown between suppliers, the buffer warehouse and the manufacturer highlight that buffered components can be accessed by the manufacturer when required, while replenishment continues to follow the proactive planning logic defined by the IMC.

Overall, Fig. 1 emphasises how Stage 2 operationalises IMC-based buffering decisions in a complex supply chain environment. It demonstrates the scalability of the approach, showing that the same execution logic applies regardless of the number of suppliers or critical components involved, while preserving the central role of the Intelligent Manufacturing Custodian in coordination and resilience-oriented capacity planning.

2.1.2 Reactive model setting for capacity and supply reconfiguration

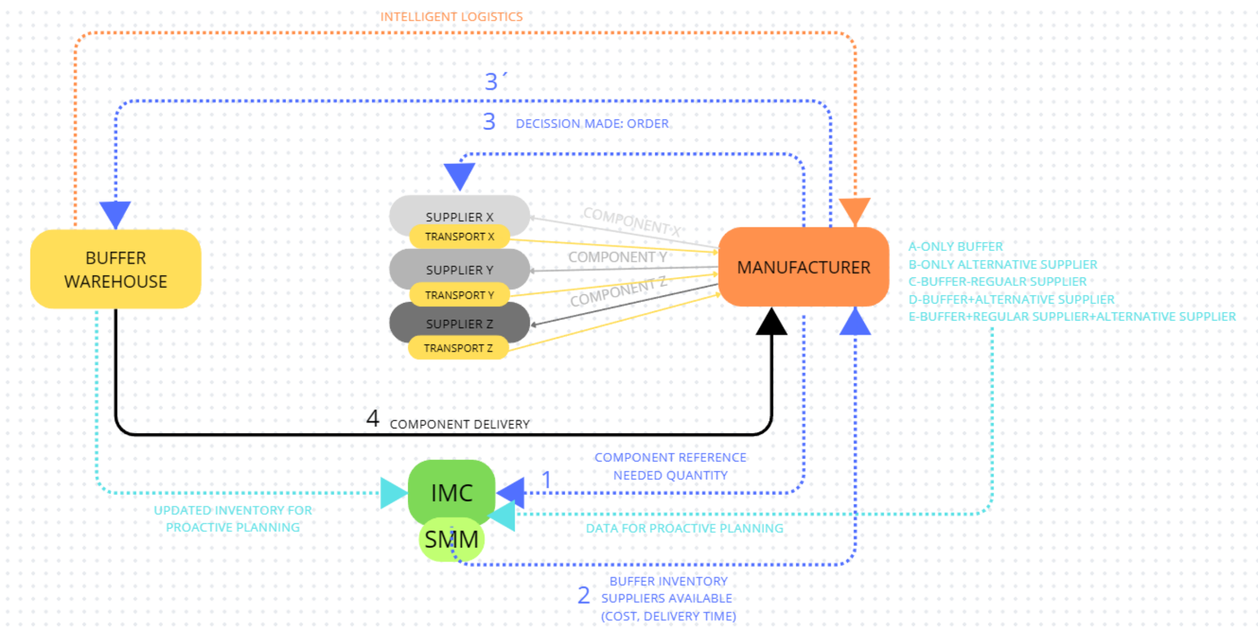

Figure 3. Reactive modelling setting

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Once proactive model settings (capacity planning, buffering definitions and supplier mappings) have already been established and a disruption occurs in the supply chain, the reactive model is activated. The reactive model here presented leverages the IMC, with the Smart Manufacturing Module (SMM) acting as its data processing and analytical engine, to support fast and informed mitigation decisions once a disruption takes place.

Manufacturer to IMC	IMC actions (through the SMM)	Answers by the IMC to the manufacturer
Reference of the article	INVENTORY FROM BUFFER SUPPLIER X SUPPLIER Y…	Units in buffer
Amount needed		Supplier X: cost, delivery time, origin, etc.
Date needed		Supplier Y: cost, delivery time, origin, etc.

OPTIONS	Answers by the IMC to the manufacturer	Data for DS
A	ONLY BUFFER	Units Cost Delivery time
B	ONLY ALTERNATIVE SUPPLIER	
C	BUFFER+REGUALR SUPPLIER	
D	BUFFER+ALTERNATIVE SUPPLIER	
E	BUFFER+REGULAR SUPPLIER+ALTERNATIVE SUPPLIER	

Table 2. Informative exchange IMC-Manufacturer for DS

Step 1: Reactive Input from the Manufacturer

As shown in Figure 3 and reflected in the first column of Table 2, the reactive process is initiated by the manufacturer following the detection of a disruption (e.g. supplier unavailability, transport delay or unexpected demand variation). The manufacturer provides the IMC with a concise but critical dataset, including:

- Reference of the affected component(s), and
- Required quantity needed to maintain or restore production continuity.

This information is ingested by the IMC and immediately processed by the SMM, which combines the reactive inputs with the data already available from the proactive phase.

Step 2: IMC Processing through the SMM

In Step 2 of the figure and the central column of Table 2, the SMM performs all analytical actions required for reactive decision-making. These actions include:

- Assessment of current buffer warehouse inventory levels.
- Identification of regular and alternative suppliers capable of supplying the affected components.
- Evaluation of available transport options, including delivery times and costs.
- Generation and comparison of feasible response scenarios.

At this stage, the SMM produces a structured decision space, ensuring that all relevant supply, inventory and logistics constraints are considered consistently.

Step 3: Decision Support Outputs and Configurations

The outputs of the Smart Manufacturing Module are returned to the manufacturer as decision support answers, shown in Step 3 of Figure 3 and detailed in the "Answers by the IMC to the manufacturer" columns of Table 2. These outputs are organised into five predefined reactive configurations:

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- **Option A – Only buffer**: immediate use of available buffered inventory to cover the required quantity.
- **Option B – Only alternative supplier**: sourcing the required quantity exclusively from an alternative supplier.
- **Option C – Buffer + regular supplier**: short-term reliance on buffer stock combined with replenishment from the regular supplier.
- **Option D – Buffer + alternative supplier**: immediate buffer usage with replenishment from an alternative supplier.
- **Option E – Buffer + regular supplier + alternative supplier**: a hybrid strategy combining buffer usage with parallel sourcing from both regular and alternative suppliers.

For each configuration, the IMC provides data for decision support (DS), including expected delivery times, costs, quantities allocated to buffer usage versus supplier sourcing, and implications for buffer replenishment.

Step 4: Execution and Material Flow

Once the manufacturer selects the preferred configuration, the corresponding orders are executed, as shown in Step 4 of Fig. 3. Components are delivered either directly to the manufacturer or via the buffer warehouse, depending on the selected strategy. Buffered stock can be immediately released to ensure short-term continuity, while supplier deliveries restore medium-term stability.

Feedback Loop to Proactive Planning

Finally, the SMM updates the buffer inventory status and feeds this information back into the proactive planning processes within the IMC, as indicated Figure 3. This feedback loop ensures that future proactive buffering and capacity planning decisions are based on the most recent operational data.

2.2 LOGISTICS AND TRANSPORT OPTIMISATION

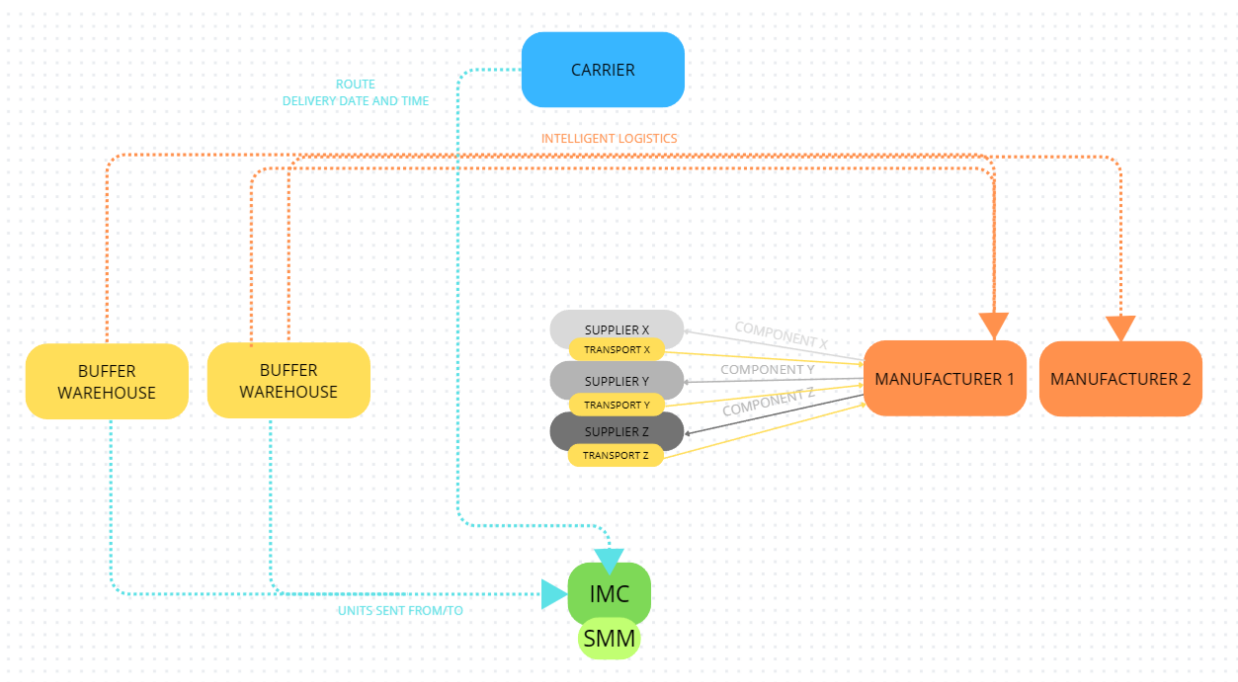

Figure 4. Intelligent logistics planning framework

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Figure 4 illustrates the integration of logistics and transport planning and optimisation within the overall framework previously defined by the proactive and reactive models. This layer represents the operational execution of capacity planning, buffering strategies, and disruption-response decisions, and is coordinated by the IMC with the SMM acting as its analytical and data-processing engine.

Continuity with the Proactive and Reactive Models

All information used in this phase originates from the outcomes of the earlier models:

- from the proactive model, the definition of critical components, buffering policies, target quantities, and buffer locations.
- from the reactive model, the selected mitigation configuration (use of buffer, regular supplier, alternative supplier, or combinations thereof) triggered by a disruption.

At this stage, the focus shifts from deciding *what* actions to take to determining *how* those actions can be executed in the most efficient and reliable way from a logistics and transport perspective.

Route Planning and Delivery Scheduling

As shown in Fig. 4, carriers provide the IMC with detailed information on routes, delivery dates, and time windows. The SMM processes this information to:

- Select the most appropriate transport mode and route for each logistics flow.
- Synchronise deliveries originating from multiple suppliers (X, Y, and Z).
- Coordinate shipments to one or multiple manufacturers, enabling multi-destination scenarios.
- Minimise transit times and logistics costs while respecting disruption-driven constraints.

In this way, the mitigation strategies defined in the reactive model are translated into concrete, optimised transport plans.

Management of Flows to and from Buffer Warehouses

Figure 4 explicitly includes multiple buffer warehouses as it is an extremely realistic scenario, expanding the logistics decision space. In this context, the SMM evaluates:

- Which buffer warehouse should supply components to the affected manufacturer.
- How and when buffer replenishment should be performed from suppliers.
- Whether shipments should be consolidated or split based on urgency and transport capacity.

All quantities sent to and from buffer warehouses are reported to the IMC, ensuring continuous inventory visibility and consistency with previously defined capacity and buffering strategies.

Execution and Feedback Loop

Once the optimal logistics plan is validated, transport orders are executed through the carriers. Execution data are returned to the IMC. The SMM then updates:

- Buffer and manufacturing inventory levels.
- Actual logistics performance indicators.
- Datasets feeding both the proactive and reactive models.

This closes a continuous feedback loop, enabling progressive improvement of planning accuracy and responsiveness.

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This step demonstrates how logistics and transport planning and optimisation are fully integrated with proactive capacity planning and reactive disruption management. The Intelligent Manufacturing Custodian, with the Smart Manufacturing Module as its analytical core, ensures that buffering, sourcing, and mitigation strategies are translated into efficient, coordinated, and resilient logistics flows, strengthening the overall performance and robustness of the manufacturing supply chain.

3. SOFTWARE ARCHITECTURE DESIGN

The functional architecture defined in this section 3 was developed through a progressive, experience-driven process, starting from the analysis of communication flow stages, described in the previous section, and evolving towards a structured architectural design. The initial baseline was the direct operational experience of manufacturers, logistics operators, suppliers, and buffer warehouse providers, reflecting how logistics and warehousing communicate and decisions are taken in real industrial environments. This stepwise transition ensures that the architecture remains rooted in industrial practice, while providing a scalable and implementable framework for intelligent logistics and warehousing management in a SMN.

3.1 FUNCTIONAL ARCHITECTURE

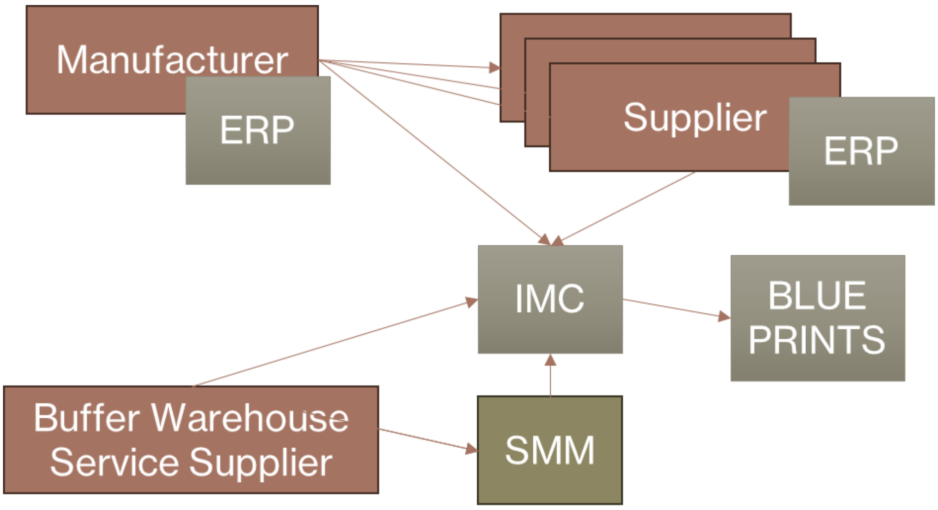

Figure 5. Data flows of functional architecture

Figure 5 presents the software architecture underpinning all communication flows and decision processes described in the previous sections. This architecture provides the digital implementation of the proactive and reactive models, as well as the logistics and transport optimisation mechanisms, by defining how data are exchanged between industrial actors and how analytical intelligence is applied in a coordinated manner.

The architecture is centred on the IMC, which acts as the central orchestration and coordination layer. The IMC acts as the central coordination layer of the proposed architecture. From an operational perspective, this means that the IMC does not replace existing enterprise systems, such as ERP or warehouse management systems, but instead consolidates selected data from these systems to support cross-network decision-making and coordination.

As shown in Fig. 5, manufacturers and suppliers interact with the architecture primarily through their existing ERP systems. This design choice ensures non-intrusive integration, allowing organisations to participate in the IMC ecosystem without modifying their internal enterprise systems. Manufacturers provide production needs, component requirements, and disruption signals via their ERP, while suppliers expose availability, lead times, and fulfilment information in the same manner.

The Buffer Warehouse Service Supplier represents a specialised external actor responsible for physical buffering operations. Inventory levels, release requests, and replenishment information are exchanged between the buffer warehouse systems and the IMC, enabling the buffering strategies defined in the proactive model and mobilised in the reactive model.

Within the architecture, the SMM feeds processed results into the IMC, which then disseminates validated information, recommendations, and execution directives to the relevant stakeholders. This separation ensures a clear distinction between data ingestion and orchestration (IMC), and analytical reasoning and optimisation (SMM).

The presence of the Blueprints component highlights the role of shared data models, rules, and reference configurations. These blueprints ensure semantic interoperability across actors, providing a common understanding of components, processes, and decision logic throughout the system.

Overall, this architecture establishes a hub-and-spoke model in which the IMC serves as the trusted custodian of manufacturing relevant information, while external actors remain autonomous and loosely coupled. The design supports scalability, interoperability, and resilience, and provides the software foundation required to operationalise the communication flows, decision loops, and optimisation processes described in the previous sections.

3.2 SEQUENCE CHARTS OF SYSTEM WORKFLOW

3.2.1 Blueprint update

This section describes the Blueprint Update workflow, which constitutes the first sequence of system interactions in the overall software architecture. This workflow establishes the shared reference layer on which all subsequent proactive planning, reactive decision-making, and logistics optimisation processes depend.

The workflow is organised around a clear separation between Local Systems and Central Systems, reflecting both governance and architectural principles. Local systems remain fully owned and operated by each stakeholder, while central systems provide shared custodianship, processing, and semantic alignment.

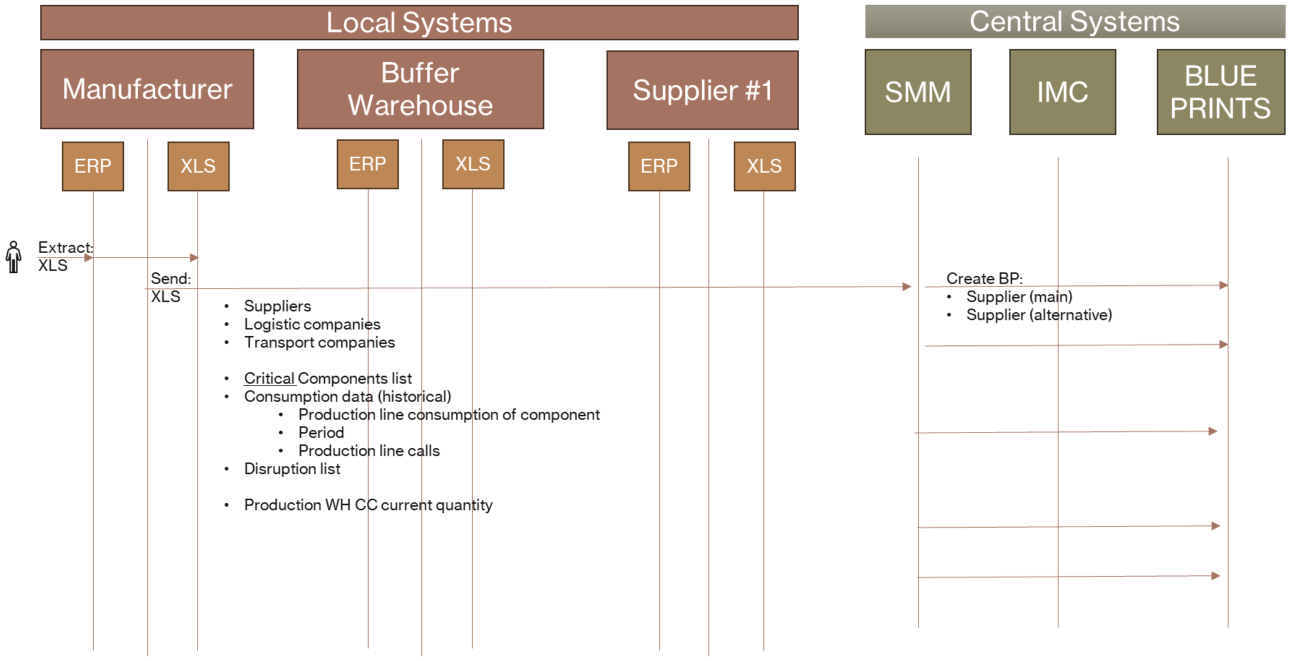

Figure 6. Blueprint update system workflow

Local Systems: Reference Data Provisioning

On the local side, the Manufacturer, Buffer Warehouse Service Supplier, and Supplier each rely on their existing information systems to manage master and reference data. These systems may include:

- Structured ERP platforms.
- Semi-structured XLS files, enabling participation regardless of digital maturity.

During the Blueprint Update workflow, stakeholders extract and share non-transactional, structural data. Typical datasets include:

- Identification of suppliers (regular and alternative).
- Logistics and transport company references.
- Critical components lists.
- Historical consumption descriptors (cycles, production line calls).
- Known disruption categories.
- Current reference quantities relevant for planning.

The extraction process is intentionally lightweight and non-intrusive, ensuring that no changes are required to internal ERP logic or data models.

Central Systems: Custodianship and Harmonisation

Once transmitted, the reference data are received by the IMC, which acts as the trusted central custodian of the manufacturing ecosystem. The IMC governs access, versioning, and ownership of shared references, ensuring that contributions from different actors remain traceable and controlled.

All data processing, validation, and harmonisation activities are performed by the SMM. The SMM applies predefined mappings and rules to:

- Normalise heterogeneous inputs.
- Resolve structural inconsistencies.

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- Align local terminologies with shared definitions.

In parallel, the Blueprints component is created or updated. This repository represents the authoritative reference layer of the system, capturing the agreed structure of actors, components, roles, and relationships across the supply chain.

Outcome and Role in the Overall Architecture

The outcome of this workflow is a consistent and shared blueprint that can be reused by all subsequent system workflows. By stabilising the reference layer at an early stage, the Blueprint Update workflow ensures that:

- Proactive capacity planning is based on coherent component and actor definitions.
- Reactive disruption handling operates on aligned supplier and buffer references.
- Logistics and transport optimisation rely on consistent structural assumptions.

This first sequence therefore marks the transition from isolated local data silos to a federated but semantically aligned digital ecosystem, providing the foundation for all higher-level intelligence and optimisation capabilities described in the following sections.

3.2.2 Buffer inventory

This section describes the second system workflow sequence, dedicated to Buffer Inventory Management. This workflow builds directly on the Blueprint Update sequence and represents the first operational data exchange required to enable both proactive capacity planning and reactive disruption management.

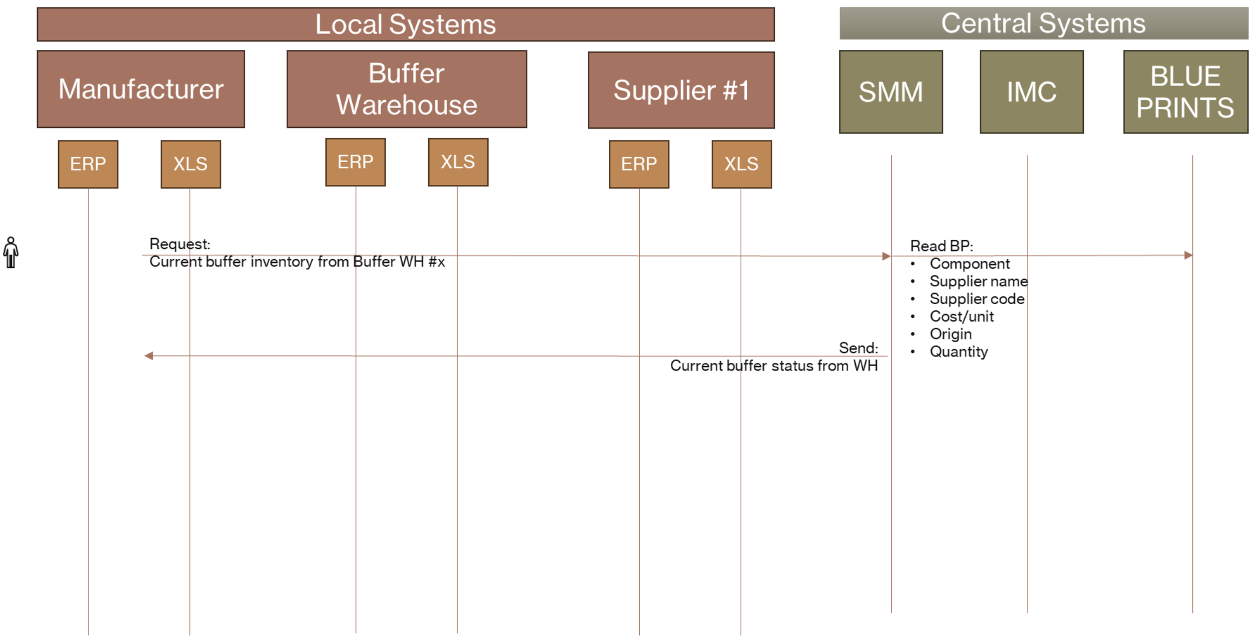

Figure 7. Buffer inventory management system workflow

The objective of this workflow is to establish and maintain an accurate and updated view of buffer warehouse inventory within the central system, ensuring that buffering strategies defined in earlier stages can be reliably monitored and executed.

The Buffer Inventory workflow enables the system to:

- Retrieve the current inventory status of a specific buffer warehouse.

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- Associate inventory data with the correct components and suppliers using the previously defined blueprints.
- Make this information available to the Smart Manufacturing Module for analytical and decision-support purposes.

This workflow is a prerequisite for buffering estimation validation, buffer utilisation during disruptions, and logistics planning.

Local Systems: Inventory Data Exposure

At the local level, the Buffer Warehouse Service Supplier manages inventory information through its own systems, typically an ERP or XLS records. These systems remain authoritative for physical stock data.

When a buffer inventory update is required, a request is initiate, either manually or automatically, to extract the current buffer inventory status from the buffer warehouse system. This includes, for each buffered component:

- Component reference.
- Associated supplier.
- Available quantity.
- Cost and origin information, if relevant.

No transactional control is transferred; the workflow strictly concerns visibility and synchronisation of inventory data.

Central Systems: Interpretation and Alignment

Once transmitted, the buffer inventory data are received by the Intelligent Manufacturing Custodian, which governs the ingestion process and ensures that the information is correctly contextualised. The Smart Manufacturing Module performs all processing activities, including:

- Validation of component references against the existing blueprints.
- Alignment of inventory records with supplier and warehouse identifiers.
- Structuring of quantities so they can be directly used in planning and optimisation models.

To perform these tasks, the Smart Manufacturing Module consults the Blueprints repository, retrieving the reference definitions required to correctly interpret the incoming data (e.g. component attributes, supplier codes, and contractual roles).

Data Consolidation and Feedback

After processing, the consolidated current buffer inventory status is stored within the central system and becomes immediately available for:

- Proactive buffering level verification.
- Reactive decision-making (e.g. assessing whether buffer-only or hybrid mitigation strategies are feasible).
- Logistics and transport planning activities.

Where required, confirmation or feedback can be sent back to local systems, ensuring traceability and consistency between local and central views of inventory.

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Role in the Overall Workflow Chain

This second workflow sequence acts as a bridge between static reference alignment and dynamic operational intelligence. While the Blueprint Update establishes *what* exists in the ecosystem, the Buffer Inventory workflow establishes *what is currently available*.

By ensuring a reliable and shared understanding of buffer stock levels, this workflow enables the IMC to support resilient manufacturing operations, accurate planning decisions, and timely responses to disruptions in the subsequent workflow sequences.

3.2.3 Buffer inventory replenishment (reactive)

This section describes the third system workflow sequence, dedicated to Buffer Inventory Replenishment in a reactive context. This workflow is activated once a disruption has occurred and follows the execution of the Buffer Inventory update workflow. Its purpose is to restore buffer stock levels after partial or full buffer utilisation, in alignment with the mitigation strategy selected during the reactive decision-making process.

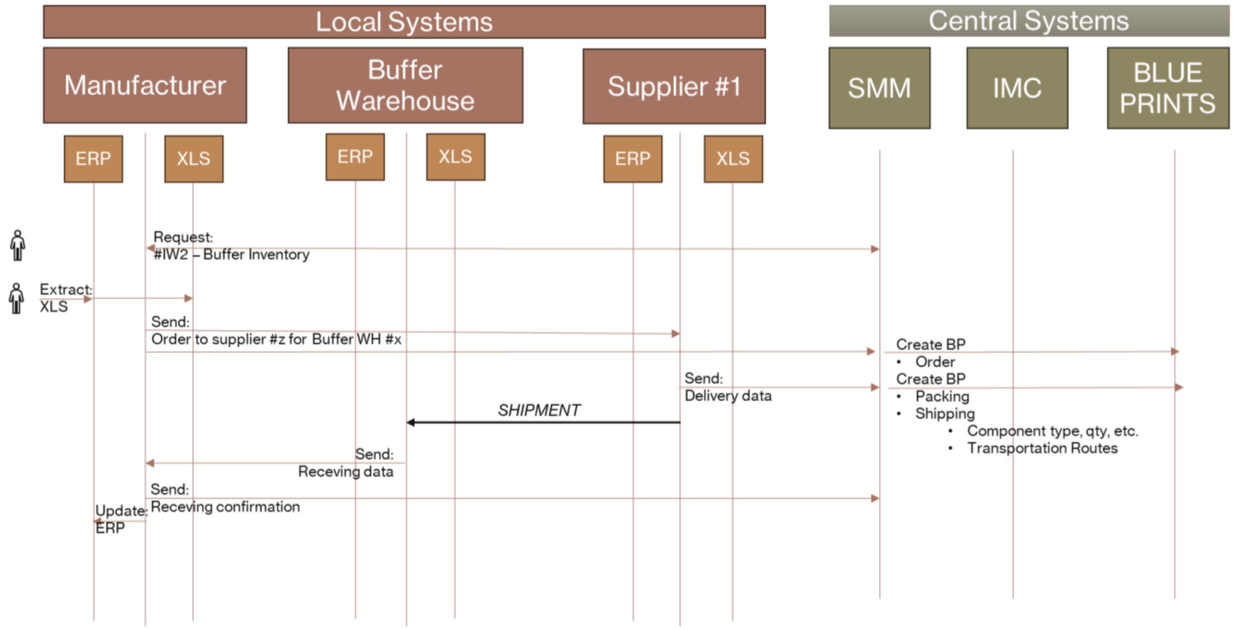

Figure 8. Buffer inventory replenishment (reactive) system workflow

The workflow operationalises the transition from reactive decision support to procurement, shipment, and inventory confirmation, ensuring continuity between analytical recommendations and physical execution.

Trigger and Context

The workflow is triggered when the Smart Manufacturing Module based on updated buffer inventory data and disruption analysis, determines that buffer replenishment is required. This may occur, for example, after buffer stock has been released to support production continuity, or when projected demand indicates that buffer levels will fall below acceptable thresholds.

At this stage, all reference information required to interpret components, suppliers, and buffer locations is already available through the previously established Blueprints and the latest Buffer Inventory data.

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Local Systems: Order Initiation and Supplier Interaction

From the local systems perspective, the Manufacturer initiates the replenishment process by issuing an order to the selected supplier (regular or alternative), using its existing ERP system or, where necessary, an XLS-based mechanism. The order explicitly targets the buffer warehouse as the delivery destination and specifies:

- Component to be replenished,
- Required quantities,
- Buffer warehouse identifier.

This step reflects the execution of a reactive decision previously supported by the Intelligent Manufacturing Custodian, without altering existing procurement practices at the local level.

Central Systems: Custodianship and Processing

In parallel, order-related information is transmitted to the IMC, which acts as the central coordination and traceability layer. The Intelligent Manufacturing Custodian delegates all processing activities to the SMM, which performs the following actions:

- Creation or update of order-related records aligned with the shared blueprints.
- Association of the replenishment order with the correct buffer warehouse and supplier.
- Preparation of downstream logistics and tracking information.

Where required, the SMM consults the Blueprints repository to ensure that component identifiers, supplier roles, and logistics attributes are interpreted consistently.

Shipment, Delivery, and Confirmation

Once the supplier processes the order, shipment data are communicated to the central system. This information is captured and structured by the SMM, enabling end-to-end visibility of the replenishment process.

Upon physical delivery of the components to the buffer warehouse, receiving data and confirmation are generated by the buffer warehouse local systems and transmitted back to the IMC. The Smart Manufacturing Module processes this confirmation to:

- Update the central view of buffer inventory levels.
- Validate completion of the replenishment cycle.
- Close the reactive replenishment workflow.

In parallel, confirmation data may be propagated back to the manufacturer's ERP system, ensuring consistency between local and central records.

Outcome and Role in the Overall Workflow Chain

The outcome of this workflow is the restoration of buffer inventory to levels consistent with the buffering strategy defined in the proactive model, adjusted where necessary based on the disruption context. By closing the loop between buffer utilisation and replenishment, this workflow ensures that the system remains ready for future disruptions.

This third workflow sequence therefore represents a critical element of the reactive execution layer, linking decision support, procurement actions, logistics execution, and

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inventory synchronisation into a single, coherent process managed under the custodianship of the IMC.

3.2.4 Buffer replenishment (Proactive)

The fourth system workflow sequence is dedicated to Buffer Replenishment in a proactive context. Unlike the reactive replenishment workflow, which is triggered by an actual disruption or buffer consumption event, this workflow is initiated in anticipation of potential disruptions or expected demand evolution, based on predictive inputs and proactive planning logic.

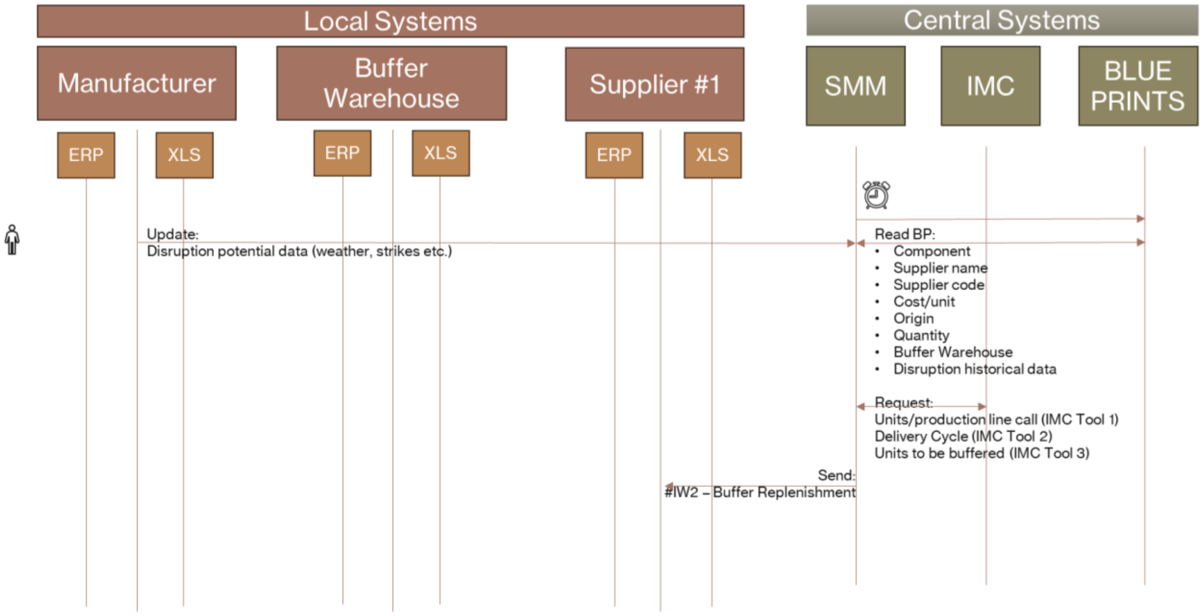

Figure 9. Buffer replenishment (proactive) system workflow

The objective of this workflow is to maintain buffer inventory at target levels defined by the proactive capacity planning model, thereby reducing the likelihood that emergency replenishment actions will be required.

Trigger and Context

The proactive Buffer Replenishment workflow is triggered by forecast-driven or risk-driven signals, such as:

- Early indicators of potential disruptions (e.g. adverse weather conditions, strikes, geopolitical events).
- Trends observed in historical disruption data.
- Deviations between current buffer inventory levels and the target buffering quantities defined during proactive planning.

These signals are periodically or event-driven transmitted from local systems to the central platform and initiate a proactive evaluation cycle.

Central Systems: Proactive Analysis and Replenishment Planning

Upon receiving updated disruption-related or contextual data, the IMC coordinates the analysis, while the SMM performs all data processing and analytical tasks. The Smart Manufacturing Module retrieves the relevant reference information from the Blueprints repository, including:

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- Component definitions.
- Supplier identities and roles.
- Cost and origin data.
- Buffer warehouse identifiers,
- Historical disruption records.

Using this information, the Smart Manufacturing Module applies the proactive IMC tools previously defined:

- Tool 1 to determine units consumed per production line call,
- Tool 2 to estimate the number of production line calls within a delivery cycle,
- Tool 3 to calculate the target number of units to be buffered.

The outcome of this analysis is an updated buffer replenishment requirement, computed before any buffer shortage occurs.

Execution via Local Systems

Once the proactive replenishment quantities are validated, the replenishment request is transmitted to the local systems for execution. The Manufacturer initiates the replenishment order using its ERP or XLS-based mechanisms, targeting the designated buffer warehouse and selected supplier.

This step closely mirrors standard procurement processes, ensuring that proactive replenishment can be executed without introducing additional operational complexity at the local level.

Link to Reactive Workflows

The proactive replenishment workflow may directly invoke or schedule a buffer replenishment execution sequence like the reactive workflow, but without the urgency imposed by an active disruption. In this sense, it acts as a preventive layer, reducing reliance on reactive replenishment and increasing overall supply chain stability.

Outcome and Role in the Overall Workflow Chain

The outcome of this workflow is the continuous alignment of buffer inventory with proactively defined targets, based on predictive insights rather than emergency response. By systematically replenishing buffers ahead of time, the system strengthens resilience and reduces the operational impact of future disruptions.

This fourth workflow sequence completes the buffering lifecycle by closing the loop between proactive planning, inventory monitoring, and execution, ensuring that buffer management remains both anticipatory and adaptive within the IMC-driven architecture.

3.2.5 Component buffer pull

The Component Buffer Pull workflow represents the operational consumption of buffer stock by the manufacturer and constitutes a key execution step linking buffer management with both reactive and proactive replenishment mechanisms.

The objective of this workflow is to enable the manufacturer to pull critical components from a buffer warehouse in a controlled and traceable manner, while ensuring that buffer inventory changes are immediately reflected in the central system and used to trigger subsequent planning actions.

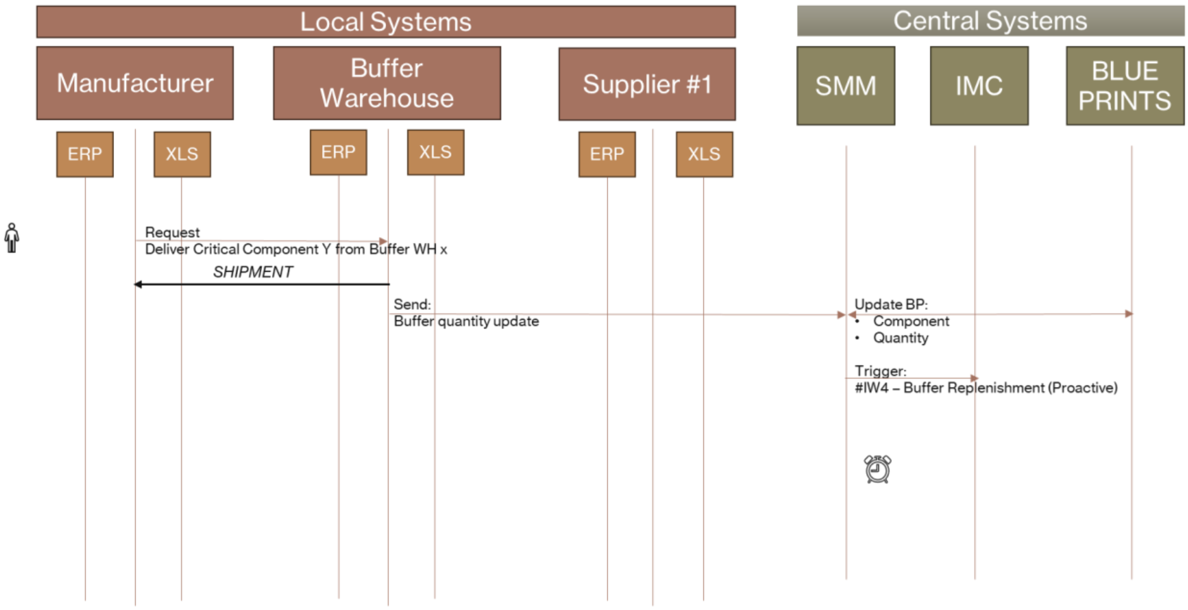

Figure 10. Component buffer pull system workflow

Trigger and Context

The Component Buffer Pull workflow is triggered when the manufacturer requires immediate access to buffered components, typically:

- to maintain production continuity during a disruption,
- to compensate for delayed supplier deliveries,
- or to smooth short-term demand fluctuations.

At this point, buffer availability has already been confirmed through previous workflows, and the manufacturer initiates the pull based on operational needs rather than planning calculations.

Local Systems: Request and Physical Shipment

From the local systems perspective, the Manufacturer issues a request to the Buffer Warehouse to deliver a specific critical component and quantity. This request is executed using existing local tools, such as the manufacturer's ERP system or an XLS-based request mechanism.

Upon receiving the request, the buffer warehouse prepares and executes the physical shipment of the requested components to the manufacturer. This shipment represents the actual consumption of buffer stock and is treated as a standard logistics operation at the local level.

Central Systems: Inventory Update and Custodianship

In parallel with the physical shipment, the Buffer Warehouse transmits an updated buffer inventory status to the IMC. This update includes:

- Component reference,
- Quantity withdrawn,
- Resulting buffer stock level.

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The SMM updates the central inventory view and aligns the new buffer status with the corresponding component definitions by consulting the Blueprints repository. As part of this workflow, the blueprints are updated to reflect the new buffer quantity, ensuring that all subsequent analytical and decision-support processes operate on current data.

Triggering Proactive Replenishment

A key feature of this workflow is its automatic linkage to proactive replenishment logic. Once the buffer quantity update is processed, the SMM evaluates whether the remaining buffer level falls below the proactively defined target threshold.

If this condition is met, the workflow triggers the Proactive Buffer Replenishment sequence. This ensures that buffer consumption is systematically followed by anticipatory replenishment actions, reducing the risk of buffer depletion over time.

Outcome and Role in the Overall Workflow Chain

The outcome of the Component Buffer Pull workflow is twofold:

1. Immediate production support, through timely delivery of critical components from the buffer warehouse to the manufacturer.
2. System-wide synchronisation, ensuring that buffer inventory changes are centrally recorded and used to drive further planning actions.

This workflow therefore closes the operational loop between buffer usage and buffer management, acting as the pivot point between reactive execution and proactive resilience. By tightly coupling physical buffer consumption with central inventory updates and automated replenishment triggers, the system maintains continuous alignment between execution and planning within the IMC-driven architecture.

3.2.6 Production line consumption update

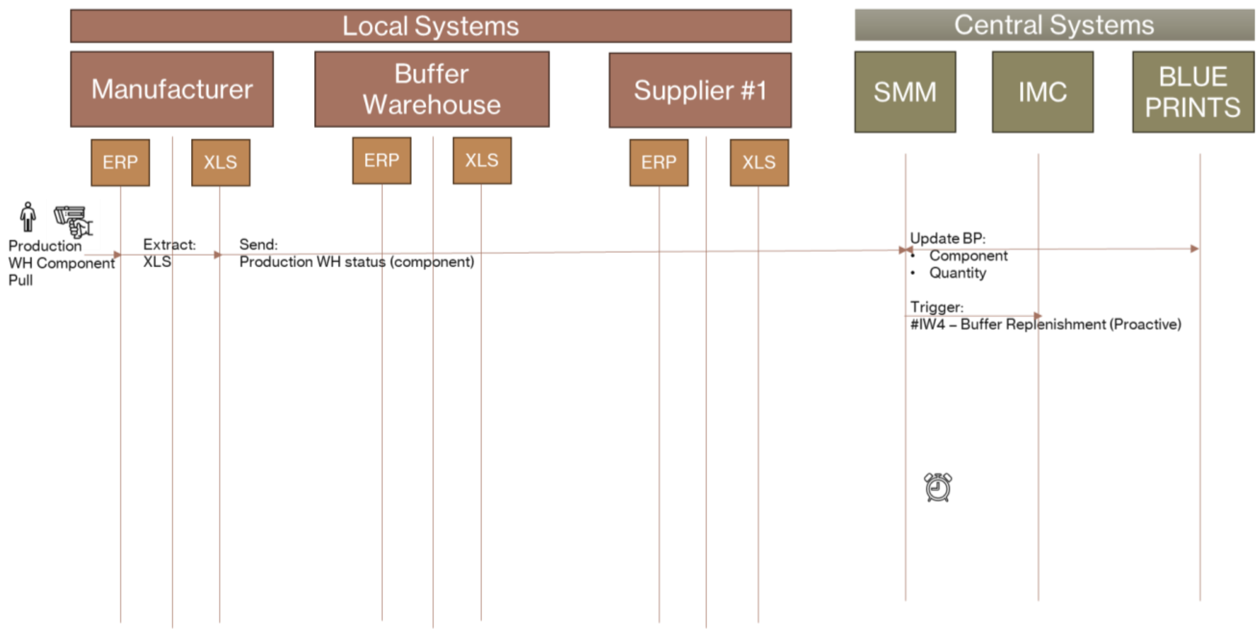

Figure 11. Production line consumption update system workflow

This section describes the sixth system workflow sequence, dedicated to the Production Line Consumption Update. This workflow captures the actual consumption of

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components at the production line level and ensures that real operational usage is continuously reflected in the central system. It plays a critical role in keeping proactive planning, buffer management, and replenishment logic aligned with real production behaviour.

Purpose and Context

The Production Line Consumption Update workflow is triggered by component consumption at the manufacturer's production line, independently of whether components originate from regular suppliers or buffer warehouses. Its primary objective is to:

- Provide an accurate and timely view of component usage.
- Update production warehouse inventory levels.
- Feed real consumption data back into the analytical models managed by the IMC.

This workflow is essential for maintaining the validity of historical consumption data used in proactive capacity planning and buffering calculations.

Local Systems: Consumption Recording and Data Extraction

At the local level, the Manufacturer records component consumption through its existing systems, typically an ERP or XLS-based tracking mechanism. Consumption events occur as part of normal production operations, such as a production warehouse component pull or a production line call.

Periodically or event-driven, the manufacturer extracts updated production warehouse status information, including:

- Component references.
- Quantities consumed.
- Remaining quantities at the production warehouse.

This extraction step ensures that operational data remain under the manufacturer's control while still being made available for central analysis.

Central Systems: Custodianship and Processing

The Smart Manufacturing Module performs these activities:

- Validates component references against the Blueprints repository.
- Updates the central view of production warehouse inventory and consumption.
- Aligns the new data with existing historical consumption records.

As part of this process, the Blueprints are updated to reflect revised component quantities where required, ensuring consistency between reference data and operational status.

Triggering Proactive Replenishment and Planning Updates

A key outcome of this workflow is its interaction with proactive buffer replenishment logic. Once updated consumption data are processed, the SMM evaluates whether observed usage patterns or current inventory levels deviate from planned assumptions.

If thresholds are reached or trends indicate increased risk, the workflow may trigger the Proactive Buffer Replenishment sequence or inform updated buffering and capacity planning calculations. In this way, real production behaviour directly influences future planning decisions.

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Outcome and Role in the Overall Workflow Chain

The outcome of the Production Line Consumption Update workflow is a continuously synchronised view of component usage across local and central systems. By closing the loop between production execution and planning intelligence, this workflow ensures that:

- Buffering strategies remain grounded in actual consumption.
- Replenishment actions are triggered based on real needs.
- Proactive and reactive models evolve with the operational reality of the factory.

This sixth workflow sequence therefore acts as the feedback backbone of the system, anchoring all higher-level planning and resilience mechanisms in accurate, real-world production data.

4. CONCLUSIONS AND NEXT STEPS

This deliverable has defined a coherent and end-to-end architectural framework for resilient manufacturing operations, integrating proactive capacity planning, reactive disruption management, buffer-based mitigation strategies, and logistics and transport optimisation under a unified software architecture. The approach is centred on the Intelligent Manufacturing Custodian, with the Smart Manufacturing Module as its analytical core and is designed to interoperate with existing industrial systems without imposing intrusive changes.

Across the different sections, the work has progressively moved from conceptual models to executable system workflows. The proactive model establishes buffering strategies and capacity planning based on historical consumption and delivery cycles. The reactive model enables rapid and structured decision-making when disruptions occur, leveraging buffer availability and alternative sourcing options. These models are operationalised through a set of clearly defined workflow sequences, covering blueprint alignment, buffer inventory visibility, reactive and proactive buffer replenishment, buffer consumption, and production line consumption updates. Together, these workflows form a closed-loop system in which planning, execution, and feedback are continuously aligned.

From a software perspective, the architecture introduces a clear separation between local systems such as ERP and spreadsheet-based tools operated by manufacturers, suppliers, and buffer warehouse service providers and central systems, which host shared custodianship, analytics, and reference management. This separation ensures scalability, interoperability, and respect for data ownership, while enabling cross-actor coordination through shared blueprints and structured data flows.

Overall, the proposed architecture demonstrates how resilience-oriented manufacturing concepts can be translated into practical, implementable software interactions, capable of supporting both long-term planning and short-term operational response in complex supply chain environments.

Next steps towards Architecture finalisation and Pilot implementation

To move from architectural design to full implementation and validation in a pilot environment, the following next steps are required:

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1. **Architecture Consolidation and technical specification**

   Finalise the logical architecture by defining concrete technical components, interfaces, and data models. This includes specifying APIs, data formats, security mechanisms, and integration patterns for ERP, WMS, and logistics systems, in alignment with the workflow sequences described.

2. **Blueprint Model Finalisation**

   Complete the definition of the Blueprint data models, including entity schemas, versioning rules, and governance processes. This step is critical to ensure semantic consistency and long-term maintainability across all participating stakeholders.

3. **SMM Algorithm Implementation and Validation**

   Implement the analytical and optimisation logic within the Smart Manufacturing Module, covering proactive buffering calculations, reactive scenario evaluation, and replenishment triggering. These algorithms should be validated using historical and synthetic datasets prior to pilot deployment.

4. **Pilot System Integration**

   Select pilot partners (manufacturer, supplier(s), and buffer warehouse service provider) and integrate their local systems with the IMC using the defined interfaces. Particular attention should be paid to accommodating different levels of digital maturity and ensuring minimal disruption to existing operations.

5. **End-to-End Workflow Testing**

   Execute end-to-end tests covering all defined workflows (IW1 to IW6), validating data consistency, timing, and correctness across proactive, reactive, and execution phases. This includes testing both normal operations and disruption scenarios.

6. **Operational Monitoring and Feedback Collection**

   During the pilot, monitor system performance, data quality, and decision outcomes. Collect qualitative and quantitative feedback from all stakeholders to assess usability, effectiveness, and integration effort.

7. **Refinement and Scaling Preparation**

   Use the results of the pilot to refine the architecture, workflows, and algorithms. Prepare guidelines and deployment templates to support scaling the solution to additional sites, partners, and industrial contexts.

By following these steps, the architecture described in this deliverable can be transitioned from design to validated operational implementation, demonstrating its value in real manufacturing environments and providing a solid foundation for future industrial adoption.

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[5] STO-2 Contextualization of SMNs using advanced digital twins technologies

[6] STO-3 Advanced analytics tools for more accurate predictions and mitigation of risks and disruptions

[7] STO-4 Building and validating smart manufacturing networks and intelligent manufacturing custodian

[8] SO-1 Societal Impact

[9] BO-1 Innovation management, economic objectives: commercialization and exploitation.

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