



NARRATE

Regenerative Resilient Smart Manufacturing Networks

D2.4 RESILIENCE STRATEGY & TOOL

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D2.4 RESILIENCE STRATEGY TOOL

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Abstract	<p>Manufacturing networks face significant Risk & Disruptions, making the selection of effective resilience strategies a critical but complex challenge for managers. Deliverable D2.4 introduces the Resilience Strategy Tool, a systematic framework. Resilience Strategy Tool designed to address this challenge by quantitatively evaluating resilience strategies. It models the manufacturing network as a network of nodes (e.g., suppliers, workspaces, customers) and edges (e.g., transport links), using an agent-based engine to track material flows and assess performance degradation across four key resilience loss indicators: loss of Quality, loss of Quantity, loss of Profit, and Delay (Q-Q-P-D). The RST analyses network vulnerability by modelling the impact of planned changes, inherent operational variability, and Risk & Disruption scenarios. This enables managers to identify critical vulnerabilities and make data-driven strategic decisions when implementing resilience strategies. Task T2.1 develops a Resilience Strategies Library including effective redundancy, diversification, and flexibility strategies. The Resilience Strategy Tool's</p>

effectiveness is validated through experiments on a synthetic manufacturing network, demonstrating its ability to pinpoint vulnerability and measure the benefits of resilience strategies.

Keywords Resilience Strategy Library, Resilience Strategy Tool, Manufacturing Network, Risk & Disruption

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ABBREVIATIONS

3PL	Third-party logistics
ABM	Agent-Based Model
BMS	Blueprint Management System
BOM	Bill of Materials
DES	Discrete-Event Simulation
IMC	Intelligent Manufacturing Custodian
LLM	Large Language Model
LSP	Logistics Service Provider
MaaS	Manufacturing as a Service
MTO	Make-to-Order
PL	Production Loss
Q-Q-P-D	Loss of Quality - Loss of Quantity - Loss of Profit - Delay
RST	Resilience Strategy Tool
TTR	Time to Recover
TTS	Time to Survive
TUT	Total Underproduction Time
WIP	Work-in-Process inventory

EXECUTIVE SUMMARY

Manufacturing networks face a constant threat of Risk & Disruption. Incidents like supplier failures, machine breakdowns, or logistics bottlenecks can cause significant losses. These unforeseen events lead to costly production delays, budget overruns, and reduced customer satisfaction. Without tools to proactively assess vulnerabilities, managers are often forced into reactive, expensive recovery tasks after disruptions have occurred.

Task T2.1 introduces the **Resilience Strategy Tool (RST)**, a strategic Decision-Support tool designed to shift manufacturers from reactive recovery to proactive resilience. The RST provides a quantitative, data-driven method for identifying critical vulnerabilities and selecting the most effective strategies before a disruption happens. It transforms complex strategic planning into a clear, analytical process.

The RST operates by creating a digital model of the manufacturing network. Its methodology includes Network Modelling: The network is modelled as a graph of Nodes (suppliers, workspaces, warehouses) and Edges (transport links) to map the manufacturing network, including flow of materials and critical interdependencies. It features a Simulation engine: An agent-based simulation engine models the flow of materials and operations throughout the network. Performance Analysis is another key component: The tool quantifies the impact of disruptions by measuring the "**Loss of Resilience**" across four key indicators: loss of **Quality**, loss of **Quantity**, loss of **Profit**, and **Delay** (Q-Q-P-D). This identifies exactly where and why performance degrades, showing the network's most vulnerable points.

Experimental validation of the **Resilience Strategy Tool** on a manufacturing network revealed the capability and advantages of the RST to explore specific, high-impact vulnerabilities that often go unmeasured. For example, a scenario of a two-day failure of a single-source supplier for inventory reduced the network performance significantly. Even this limited disruption caused delivery delays to more than double and increased costs for some customer orders. This demonstrates the importance of using the RST for enhancing the resilience capability of manufacturing networks.

The RST provides the foresight necessary for strategic planning. By translating risks & disruptions into clear operational metrics, the RST empowers managers to test and select the most efficient interventions from a **Library of Resilience Strategies**. To make this process highly effective, a comprehensive library of proactive strategies has been developed. Each solution is categorized by the network component it applies to (e.g., supplier, workspace), allowing managers to apply resilience strategies directly to their most critical vulnerable points. Ultimately, the RST is a data-driven decision support system that enables companies to 1) find critical vulnerabilities, 2) select a resilience strategy, and 3) assess its impact, justifying investments and building stronger, more competitive and resilient manufacturing networks.

1. INTRODUCTION

The selection of resilience strategies is a critical decision for manufacturing managers, who must navigate disruptions that impact performance across multiple dimensions. To analyse this complexity, this deliverable conceptualizes the manufacturing supply chain as a network model, or graph. In this representation, physical and logical entities (such as suppliers, production facilities, warehouses, and customers) are defined as nodes, while the flows of materials connecting them are represented as edges. Disruptions can degrade these nodes and edges partially or completely, leading to significant operational and financial losses.

This report addresses this challenge by developing a systematic framework and an accompanying algorithm to help managers select optimal resilience strategies. The core of our approach is to evaluate the impact of these strategies on four critical resilience indicators: Quality, Quantity, Profit, and Delay (Q-Q-P-D). Each potential strategy, such as adding a backup supplier or increasing buffer inventory, is modelled as a reconfiguration of the baseline network. Through simulation, we evaluate the performance of these alternative configurations under various disruption scenarios, providing a quantitative basis for decision-making.

The purpose of this framework is to empower manufacturing companies to move from reactive recovery to proactive resilience, enabling them to assess the trade-offs between cost, efficiency, and robustness.

2. RST WITHIN THE NARRATE ECOSYSTEM

The Resilience Strategy Tool operates as an integral component of the NARRATE platform ecosystem, establishing critical connections with other core platform services including the Intelligent Manufacturing Coordinator (IMC), LLM, Blueprint, and Risk Identification & monitoring Tool. Key connections include the Blueprint Management System (BMS) and the Large Language Model (LLM) facilities. During the early integration phase of the NARRATE project at M24, establishing these connections represents a critical architectural milestone. Early integration ensures that the RST can operate on harmonised, semantically rich data from the BMS and leverage LLM capabilities for enhanced reasoning and explainability. Building connections with other tools in NARRATE is essential because the RST's workflows, resilience strategies, and future automation capabilities depend directly on the quality, completeness, and timeliness of the data it receives. Together, these connections create the foundation for a fully interoperable and explainable resilience capability that will mature throughout the subsequent phases of the NARRATE project.

The RST maintains a connection with the IMC with other NARRATE tools (Figure 1), such as the LLM facilities and BMS, through a RESTful API that supports structured data exchange. The interaction follows a stateless architecture, where the RST receives input data for executing its algorithms and models, processes vulnerability analyses and resilience strategies, and returns the results to the IMC. This API-based integration ensures loose coupling, scalability, and maintainability while enabling the RST to function as an independent yet fully interoperable service within the NARRATE ecosystem.

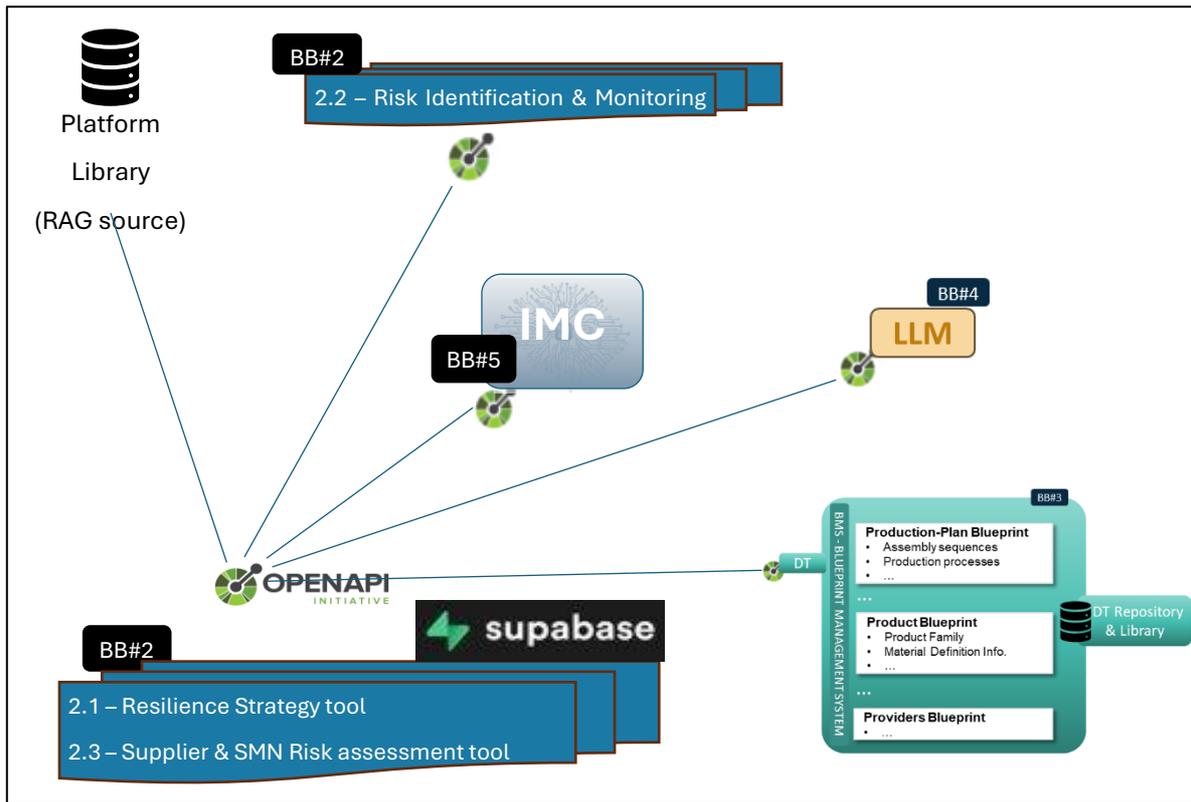


FIGURE 1. RST WITHIN THE NARRATE ECOSYSTEM

2.1 RST AND BLUEPRINT MANAGEMENT SYSTEM

The effectiveness of the solutions provided by the RST is tightly dependent on data quality. The Blueprint Management System leverages Blueprints as the primary source of harmonised, semantically enriched data covering suppliers (providers of inventories including raw materials, work-in-progress (WIP), and finished products), production facilities (workspaces including machines, human resources, and equipment), logistics (including transportation service providers and warehousing), and customers (orders of customers, order size, and due date). Blueprints provide the RST with a uniform, interoperable representation of all relevant Smart Manufacturing Network (SMN) entities (including nodes), their dependencies (including edges), constraints (operational assumptions), and behavioural characteristics. The RST consumes structured Blueprint data such as:

- **Supplier Blueprints:** Inventory lead times, inventory costs, supplier capacity, and inventory quality.
- **Production-Plan Blueprints:** Workspaces (machines, equipment, and human resources), production costs, production rate/time, production quality, and production capacity.
- **Logistics & Warehousing Blueprints:** Transport cost, transport time, transport capacity, transport quality (defect rate), warehouse operation (stacking, retrieving, and holding) costs, warehouse operation (stacking and retrieving) times, warehouse defect rate, and warehouse capacity.
- **Product & Bill of Materials (BoM) Blueprints:** Component dependencies, assembly constraints, and process plans.

The RST queries the structured data by API from Blueprints that are already harmonised, contextualised, and semantically structured, enabling automatic extraction of

dependencies, detection of critical paths across suppliers and production lines, identification of single points of failure, and access to standardised performance indicators.

Because each Blueprint encodes relationships, constraints, and behavioural characteristics, it provides both static data (data related to the configuration of the SMN that does not change on a daily basis, such as suppliers, manufacturing plants, and the list of products or materials) and real-time data (data that changes dynamically over time within the SMN, such as inventory levels in warehouses, WIP, production capacity, and availability of transportation service providers). The RST can generate scenarios to identify vulnerabilities within the SMN. For example, the RST analyses the effect of scenarios such as:

- **Supplier disruption:** Delay in supplying a raw material by a supplier and its impact on the loss of resilience (measured by Quality-Quantity-Price-Delivery metrics).
- **Production disruption:** Decrease in production rate due to machine failure leading to increased loss of resilience.
- **Logistics disruption:** Delay in a transportation edge resulting in delayed delivery of final products.

The RST examines these scenarios to identify the most critical vulnerabilities of the manufacturing network. The RST retrieves data from Blueprints through the IMC, tests scenarios and resilience strategies, and returns effective strategies to the IMC. These strategies are subsequently used by the BMS to create **Resilience Strategy Blueprints**, which formalize recommended actions such as supplier diversification, alternative routing, capacity adjustments, or sustainability-conscious mitigation measures. These **Resilience Strategy Blueprints** are:

- Stored in the BMS for future reference and orchestration.
- Available to the IMC for autonomous, data-driven resilience optimization.
- Linked to the original Supplier, Production, and Logistics Blueprints.
- Encoded in the same JSON-LD/graph-based format, ensuring semantic consistency.

This closed-loop knowledge architecture of the NARRATE platform enables the IMC to apply strategies programmatically, recompute the digital twin state, test implementation feasibility, and deploy resilience actions within the Manufacturing-as-a-Service (MaaS)/SMN orchestration environment.

2.2 RST AND LLM FACILITIES

The RST integrates with the LLM facilities developed in WP3 and WP4 to augment resilience analysis with advanced reasoning, explainability, and natural-language interaction. The LLM does not replace the RST's quantitative optimization capabilities; instead, it enriches and supports RST workflows through four complementary mechanisms.

2.2.1 Candidate Resilience Option Generation

While the RST computes quantitative vulnerabilities of the SMN and provides resilience strategies through its Resilience Strategy Library using analytics modules and algorithms, the LLM expands the range of qualitative or hybrid resilience strategies by refining and developing options such as:

- Generating alternative supplier diversification strategies informed by other tools within the NARRATE platform.
- Identifying alternative logistics pathways sourced from descriptive metadata.
- Proposing resilience strategies that consider sustainability or circularity recommendations based on descriptive annotations from other tools in the NARRATE platform.

This allows the RST to consider strategies not purely derived from numeric optimization models, thereby broadening the solution space for resilience planning.

2.2.2 Human-Readable Explanations and Decision Rationales

Outputs from the RST, including vulnerability analyses of manufacturing network elements (suppliers, warehouses, production facilities, and transportation service providers), can be complex and multi-dimensional. The LLM converts these outputs into executive summaries, human-readable explanations, decision rationale narratives, and what-if scenario descriptions. This supports explainability, stakeholder communication, and decision auditing, ensuring that resilience strategies are transparent and justifiable to both technical and non-technical users of the NARRATE platform.

2.2.3 Interactive Decision Support

Through the NARRATE dashboard and user interfaces, human operators can pose natural-language questions such as:

- "Why is Supplier S3 recommended?"
- "What alternatives do we have if production site P1 also becomes unavailable?"

The LLM acts as an intermediary between the human operator and the RST through the IMC, interpreting questions, retrieving relevant strategy information from the RST and Blueprint data, and generating contextual answers for users. This transforms the RST into an interactive, conversational resilience assistant, lowering the barrier to entry for decision-makers and enabling more intuitive exploration of resilience options.

2.2.4 Continuous Knowledge Enrichment

Beyond immediate decision support, the LLM contributes to the ongoing enrichment and evolution of the Blueprint ecosystem by facilitating feedback loops and knowledge capture. This continuous process improves the data quality and semantic richness available to the RST, ensuring that resilience strategies become progressively more informed and contextually relevant over time.

3. BACKGROUND OF RESILIENCE MANUFACTURING NETWORK

Manufacturing networks operate in dynamic and often unpredictable environments where disruptive events (such as machine failures, material shortages, or external disturbances) can interrupt production flows. These disruptions lead to production losses, reduced throughput, and operational inefficiencies. Consequently, designing manufacturing networks with inherent resilience has become an essential priority for ensuring continuity, stability, and competitiveness. A resilient manufacturing network

must be capable of minimizing operational (production, transportation, and warehousing) losses during disruptions and rapidly recovering to a normal operation once they are resolved [1].

Modelling the manufacturing company and its supply chain as an integrated network (see Figure 2) is critical for understanding complex interdependencies and improving resilience. As supply chains have become more global and interconnected, this analysis has shifted from a theoretical exercise to a practical necessity [2]. In WP2, BUL has explored several approaches to capture this complexity:

- **Network Theory** is a widely adopted method that represents manufacturing networks as graphs. This approach excels at identifying critical nodes and links, analysing vulnerability patterns, and revealing how disruptions propagate through interconnected networks [3].
- **Agent-Based Modelling (ABM)** offers a more detailed perspective by simulating the behaviours and interactions of individual agents (e.g., suppliers, machines, customers, transportation service providers). While network theory provides a structural overview, ABM models this structure by capturing dynamic, adaptive behaviours, making it valuable for exploring "what-if" scenarios [4].
- **Bayesian Networks** introduce a probabilistic dimension by accounting for the uncertainty inherent in manufacturing environments. These networks use probability distributions to represent stochastic variables (such as order sizes, transport times, disruption impact and likelihood, or production quality) enabling an evaluation of how uncertainty propagates and impacts manufacturing network [5].

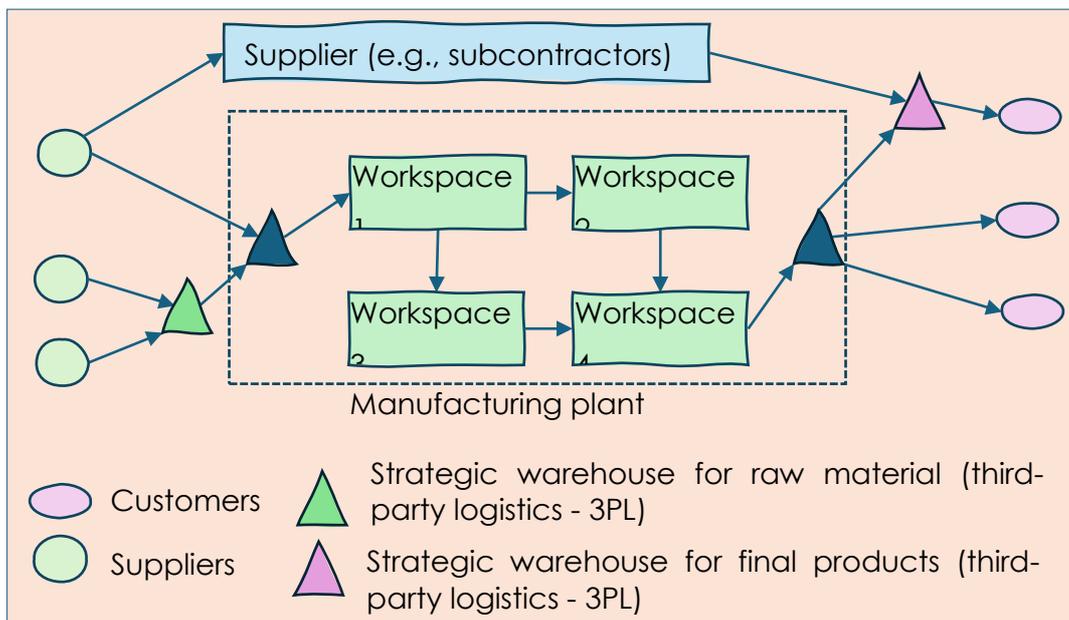


Figure 2. Manufacturing Network

Despite their advantages, developing network models for real-world problems presents several challenges. A primary difficulty is data availability and quality, as detailed information on supplier and internal processes is often fragmented or proprietary [6]. Second, as models grow in detail to capture realistic behaviours, their computational complexity can increase, creating a tension between model reliability and practical usability. Finally, manufacturing networks are not static; they evolve as supplier relationships, production schedules, and customer demands fluctuate. This dynamic nature demands models capable of adapting to changing structures.

Within the NARRATE platform, these data challenges are addressed by using **Blueprints** to ensure that data is supplied with reasonable care and handled accurately. This approach provides the consistent, high-quality data required to model the supply chain network for strategic analysis, ensuring the reliability of the resilience tool and its outputs.

Beyond the complexities of modelling, quantitatively measuring network resilience presents another significant challenge [7]. The selection of appropriate metrics is essential for evaluation. Practitioners and academics employ a portfolio of indicators to capture different dimensions of performance. Common metrics include Production Loss (PL), Time to Recover (TTR), Time to Survive (TTS), and Total Underproduction Time (TUT), which quantify how a system continues and recovers from a disruption (e.g., [8] and [9]).

Additionally, economic-focused metrics are crucial for quantifying the financial consequences of disruptions [10]. To maintain operational continuity, a company need to make decisions that result in a loss of profit. In WP2, BUL analyses trade-offs between cost and resilience across four losses:

1. **Sourcing:** Selecting more expensive, reliable suppliers or paying higher prices for materials to prevent shortages.
2. **Logistics:** Using more expensive transportation options after incident rather than normal situation, such as air freight, to accelerate deliveries and avoid delays.
3. **Production:** Investing in redundant assets and resources, such as backup machinery or secondary production plants.
4. **Inventory:** Holding higher levels of safety stock, which incurs carrying costs but provides a buffer against supply-side disruptions.

These examples illustrate the fundamental trade-off between cost efficiency and operational resilience that manufacturers must navigate.

The goal of Deliverable D2.4 in WP2 is to support the implementation of effective resilience strategies. Companies must develop such strategies to ensure the continuity of key operations, including procurement, production, transportation, and warehousing. For example, research indicates that redundancy (e.g., additional machines) and flexibility (e.g., reconfigurable production routes) significantly enhance a system's ability to sustain throughput and adapt to disruptions [11]. Furthermore, the network configuration is critical; systems with parallel machine arrangements are generally more resilient than single-machine configurations, and buffers can mitigate the impact of short-term interruptions [12].

However, these strategies are not without cost. A company cannot implement every possible resilience measure for each node in its network. More resilient networks typically demand greater investment in resources and inventories. Therefore, companies must estimate the amount of resilience improvement gained from a strategy and weigh it against the implementation cost. Achieving an optimal balance between robustness and resource expenditure remains the key strategic consideration in the design and management of resilient manufacturing networks [13].

To address this challenge, the Resilience and Strategies Tool (D2.4) introduces the Resilience Strategy Tool, developed by BUL. The RST is designed to empower manufacturers to move beyond reactive problem-solving, delivering actionable intelligence through a proactive framework that enhances network resilience. It operates by systematically analysing vulnerabilities across the manufacturing network, quantifying the risk exposure for each entity, and simulating the impact of various resilience strategies. Crucially, its core function is to estimate the reduction in resilience loss that

each strategy would achieve, thereby facilitating a critical trade-off analysis between cost and robustness. Thus, as a strategic decision support system, the RST provides managers with the foresight to quantify the consequences of their choices in a virtual environment. This transforms complex strategic planning into a clear, data-driven process. Ultimately, it enables companies to select and implement the most effective and cost-efficient strategies with confidence, before committing any real-world resources.

4. NETWORK MODELING IN THE RESILIENCE STRATEGY TOOL

To accurately simulate and analyse a manufacturing network, the Resilience Strategy Tool first constructs a detailed digital representation of it. The foundation of our modelling approach, developed by BUL in WP2, is built on two core components: **Resources** and **Inventories** (See Figure 3).

- **Resources** represent the operational assets required for production. These are categorized into human resource and machine & equipment.
- **Inventories** represent all forms of material within the network, including raw materials, work-in-process (WIP), and finished goods.

```

CREATE TABLE resource_static (
  resource_id SERIAL PRIMARY KEY,
  name TEXT NOT NULL,
  code TEXT NOT NULL UNIQUE,
  type TEXT NOT NULL CHECK (type IN ('human_resource', 'machine_equipment')),
  description TEXT,
  status TEXT NOT NULL CHECK (status IN ('active', 'not_active')),
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);

CREATE TABLE inventory_static (
  inventory_id SERIAL PRIMARY KEY,
  code TEXT NOT NULL,
  type TEXT NOT NULL CHECK (type IN ('WIP', 'Raw-material', 'Finished-goods')),
  name TEXT NOT NULL,
  description TEXT,
  unit_of_measure TEXT,
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);

```

Figure 3. Data Structure within RST for resources and inventories

By defining these core components, BUL establishes a structured framework that allows us to apply graph theory to model the entire manufacturing network in detail. This approach provides a powerful and flexible way to represent complex operational relationships. Using this foundation, the manufacturing network is formally modelled as a graph consisting of Nodes and Edges. This clear separation between processing/storage activities (Nodes) and transfer operations (Edges) allows for a precise and explicit analysis of network flows and vulnerabilities.

Note 1: To capture and manage foundational resilience data, BUL developed a dedicated database for the RST. This database is architecturally aligned with the NARRATE Blueprint, repository structures, and standardized libraries, ensuring semantic

consistency across the platform ecosystem. This approach serves a dual purpose: it provides the RST's algorithms with data in the precise format required for vulnerability analysis and strategy generation, while simultaneously ensuring that all data inputs and outputs remain fully compatible with other modules and tools within the broader NARRATE platform. The API-based integration between the RST and IMC ensures seamless interoperability, enabling the RST to exchange data in formats that satisfy both its internal computational requirements and the data exchange standards established across the NARRATE project. This architectural alignment guarantees that the RST operates as a fully integrated component of the platform while maintaining the flexibility to execute its specialized resilience analytics independently.

- **Nodes** represent the operational entities where materials are sourced, processed, stored, or consumed. A node is any point in the network that acts as a source or transformation point for inventories.
- **Edges** represent the transfer mechanisms that govern the movement of inventories between nodes. They do not perform any processing and only facilitate transportation.

4.1 NETWORK NODES: THE OPERATIONAL ENTITIES

Nodes are the static locations and functional units within the manufacturing network. We define four primary types of nodes: Suppliers, Customers, Workspaces, and Warehouses.

4.1.1 Suppliers

This inclusive definition is crucial, as it directly supports the NARRATE project's goal of enabling **Manufacturing as a Service (MaaS)**. Within the RST, subcontractors are modelled as available suppliers that can be activated to maintain operational continuity during a disruption. This enables the RST to quantitatively analyse the use of MaaS as a powerful strategy for increasing the resilience of the manufacturing network. The Supplier Data Structure is shown in [Figure 4](#).

```
CREATE TABLE supplier_static (
  supplier_id SERIAL PRIMARY KEY,
  supplier_code TEXT NOT NULL UNIQUE,
  registered_name TEXT NOT NULL,
  address TEXT,
  postal_code TEXT,
  locality_city TEXT,
  email TEXT,
  country TEXT,
  phone TEXT,
  status TEXT NOT NULL CHECK (status IN ('active', 'inactive')) DEFAULT 'active',
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);
```

Figure 4. Data Structure within RST for Supplier

4.1.2 Customers

Customers are the driving force of the manufacturing network. In alignment with the NARRATE project's scope, the network operates on a **Make-to-Order (MTO)** basis. This means that production is initiated and the entire material flow is driven by specific customer orders, rather than being produced for stock. Consequently, the primary

objective of the manufacturing network is to ensure that each customer order is fulfilled precisely according to its requirements: *delivered on time, in the exact quantity ordered, and at the expected level of quality*. Therefore, in our model, customers are the active demand points whose orders dictate the network's performance and whose satisfaction is the ultimate measure of its resilience. The Customer Data Structure is shown in [Figure 5](#).

```
CREATE TABLE customer_static (
  customer_id SERIAL PRIMARY KEY,
  customer_code TEXT NOT NULL UNIQUE,
  customer_name TEXT NOT NULL,
  address TEXT,
  postal_code TEXT,
  locality_city TEXT,
  email TEXT,
  country TEXT,
  phone TEXT,
  status TEXT NOT NULL CHECK (status IN ('active', 'inactive')) DEFAULT 'active',
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);
```

Figure 5. Data Structure within RST for Customer

4.1.3 Workspaces

Within the RST model, workspaces are the core value-adding nodes where transformations occur. A workspace is not merely a location but a composite entity. Its definition begins with a physical or logical area, to which specific human and machine resources are assigned via a dedicated assignment table. Furthermore, each workspace is characterized by the manufacturing operations it can execute, a capability also linked through an assignment table. This multi-layered data structure ensures that a Workspace Node is defined by its location, its allocated resources, and its operational capabilities. The RST data structures for workspaces, resource assignments, and operational assignments are illustrated in [Figure 6](#).

Note 2: In our model, small, temporary buffers located next to machines are treated as attributes of the corresponding Workspace node rather than as standalone warehouse nodes. This simplifies the network topology while preserving the essential function of buffers in absorbing variability.

```

CREATE TABLE workspace_static (
  workspace_id SERIAL PRIMARY KEY,
  workspace_code TEXT NOT NULL UNIQUE,
  workspace_name TEXT NOT NULL,
  location TEXT,
  description TEXT,
  status TEXT NOT NULL CHECK (status IN ('active', 'inactive')) DEFAULT 'active',
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);

CREATE TABLE workspace_resource_assignment (
  workspace_id INTEGER REFERENCES workspace_static(workspace_id) ON DELETE CASCADE,
  resource_id INTEGER REFERENCES resource_static(resource_id) ON DELETE CASCADE,
  notes TEXT,
  assigned_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  PRIMARY KEY (workspace_id, resource_id)
);

CREATE TABLE operations_static (
  operation_id SERIAL PRIMARY KEY,
  operation_code TEXT NOT NULL UNIQUE,
  operation_name TEXT NOT NULL,
  description TEXT,
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);

CREATE TABLE workspace_operation_assignment (
  workspace_id INTEGER REFERENCES workspace_static(workspace_id) ON DELETE CASCADE,
  operation_id INTEGER REFERENCES operations_static(operation_id) ON DELETE CASCADE,
  notes TEXT,
  assigned_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  PRIMARY KEY (workspace_id, operation_id)
);

```

Figure 6. Data Structure within RST for Workspace, resource assignment, manufacturing operations, and operations assignment to workspace

4.1.4 Warehouses

Warehouses are nodes dedicated to the storage of inventories (raw materials, WIP, or finished goods). These can be internal facilities owned by the company or external facilities managed by a third-party logistics (3PL) provider (e.g., a strategic warehouse operated by DHL).

4.2 NETWORK EDGES: THE TRANSFER MECHANISMS

Edges connect the nodes in our graph model, representing the physical movement of inventory. A defining characteristic of an edge is that it only transfers the location of an inventory; it does not alter its physical or chemical nature. We distinguish between two types of edges:

4.2.1 External Transportation

These edges model the movement of inventory between geographically distinct nodes, including suppliers, the manufacturing plant, and customers. This function is especially critical for implementing a **Manufacturing as a Service** strategy during disruptions. The RST is designed to analyse complex logistical paths, such as shipping materials to a supplier (e.g., subcontractors) for processing and return or directing shipments to the customer. By modelling these transportation times and routes, the RST can evaluate the true effectiveness of MaaS as a resilience solution, enabling informed decision-making.

4.2.2 Internal Material Handling

These edges represent the movement of inventory *within* the manufacturing plant itself. This includes transporting raw materials or WIP between different workspaces according to the product's process map.

By modelling the manufacturing network with this level of detail (grounded in a robust relational database) the RST creates a dynamic and accurate model. This model serves as the backbone for all subsequent resilience analyses, enabling precise simulations of disruptions and effective evaluation of mitigation strategies.

4.3 THE RST ENGINE: AN AGENT-BASED CONTROL TOWER

To bring the static network model to life and analyse its dynamic behaviour, the RST employs a simulation engine that operates on two distinct input categories. The static data, as previously described, provides the network's structural foundation: nodes, edges, and their potential capabilities. To initialize a simulation run, the engine also captures dynamic data, which represents a snapshot of the network's real-time operational status at the moment the analysis begins. This dynamic snapshot includes time-sensitive information such as current inventory levels at each location, active customer order portfolios, and the immediate availability status of production machines and transportation links. Together, these two data layers enable the RST to simulate realistic manufacturing network behaviour under various disruption scenarios. Once initialized with both static and dynamic data, the RST simulation engine operates on an Agent-Based Modelling principle. Each node in the network (suppliers, warehouses, production facilities, and transportation service providers) functions as an autonomous agent with specific behavioural rules and a state that evolves over time in response to events and decisions. The entire simulation is orchestrated by a central "Control Tower" agent, which serves as the coordination hub of the manufacturing operation, managing information flow and decision-making across the network. The simulation process unfolds throughout the manufacturing network in a structured, event-driven sequence, with customer demand serving as the primary driver of network activity as follows:

- **Step 1: Order Initiation and Task Decomposition**

As the network operates on a Make-to-Order basis, the simulation is triggered by a portfolio of incoming customer orders. When the IMC invokes the RST for analysis, order data is transferred from the BMS to the RST through the IMC's API interface and subsequently recorded within the RST's internal data structures for processing by the simulation engine. The customer order data schema is illustrated in Figure 7.

```
CREATE TABLE customer_order (
  order_id SERIAL PRIMARY KEY,
  customer_id INTEGER REFERENCES resource(resource_id),
  order_date TIMESTAMP NOT NULL,
  delivery_date TIMESTAMP,
  status TEXT,
  total_amount NUMERIC,
  created_by INTEGER REFERENCES user_account(user_id),
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);
```

Figure 7. Data Structure within RST for customers' order

Upon receiving these orders, the RST initiates the production planning process. The IMC retrieves the relevant BOM and process plans for the ordered products from the **Product & BoM Blueprints** module and transmits them to the RST via the API interface. The RST then utilizes this integrated data structure (see Figure 8), which combines both BOM specifications and process routing information, to decompose each customer order into a detailed sequence of executable jobs assigned to specific workspaces, along with their corresponding inventory requirements. This decomposition precisely defines which manufacturing operations must be performed, at which production facilities, the sequence of operations, and the materials consumed (inputs) and produced (outputs) at each processing step. The resulting job list serves as the operational blueprint for the simulation engine to execute the manufacturing process.

```
CREATE TABLE process_plan (
  product_inventory_id INTEGER NOT NULL, -- Final product from inventory_static
  operation_id INTEGER NOT NULL, -- From operations_static
  material_inventory_id INTEGER NOT NULL, -- Raw material/WIP from inventory_static

  PRIMARY KEY (product_inventory_id, operation_id, material_inventory_id),

  -- Foreign Key Constraints
  FOREIGN KEY (product_inventory_id) REFERENCES inventory_static(inventory_id) ON DELETE CASCADE,
  FOREIGN KEY (operation_id) REFERENCES operations_static(operation_id) ON DELETE CASCADE,
  FOREIGN KEY (material_inventory_id) REFERENCES inventory_static(inventory_id) ON DELETE CASCADE,

  operation_sequence INTEGER NOT NULL,
  io_type TEXT NOT NULL CHECK (io_type IN ('input', 'output')),
  quantity_required DECIMAL(10,3) NOT NULL,
  unit_of_measure TEXT NOT NULL,
  notes TEXT,
  created_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  updated_at TIMESTAMP DEFAULT CURRENT_TIMESTAMP
);
```

Figure 8. Data Structure within RST for process plan table and bill of material

```
class TowerControl:
    @staticmethod
    def Order_to_Jobs(order, Orders, Nodes, Products, ProcessMaps, BOMs, Parts, jobsassignment="user", user_defin):
        # check the validity of the user defined operation_workspace matrix
        if jobsassignment == "user" and user_defined_operation_workspace is not None:
            for oper, ws in user_defined_operation_workspace.items():
                if oper not in Nodes[ws].operation:
                    raise ValueError(
                        f"There is an issue with the selected node {ws}, it cannot perform the operation {oper}")

        current_order_object = Orders[order]
        current_order_product_id = current_order_object.product_id
        current_order_product_object = Products[current_order_product_id]
        current_order_bom_id = current_order_product_object.product_BOM_id
        current_order_bom_object = BOMs[current_order_bom_id]
        current_product_unit_requirement = current_order_bom_object.bom_partquantity
        current_order_size = current_order_object.order_size
        current_order_requirement = current_product_unit_requirement.copy()
        current_order_requirement["quantity"] *= current_order_size
        current_product_ProcessMap_id = current_order_product_object.product_ProcessMap_id
        current_product_ProcessMap_object = ProcessMaps[current_product_ProcessMap_id]
        current_product_machinery = current_product_ProcessMap_object.processmap_machinery

        jobtodo = []
        jobtodolist = {}

        for index, row in current_order_requirement.iterrows():
            part_id_RMorder = row['part_id']
            quantity_RMorder = row['quantity']
            unit_RMorder = row['unit']
```

Figure 9. Dynamic Job Assignment

Note 3. It is important to differentiate between the two types of data used by the RST:

- **Static Data** defines the architecture of the manufacturing network. It represents the stable, long-term structure of manufacturing network, such as the existence Nodes, the machines assigned to it, the defined External Transportation Edges, and the list of suppliers. This data changes infrequently, for example, when a new machine is purchased or a new supplier is qualified.
- **Dynamic Data** defines the state of the network at a specific point in time (T=0 for the RST). It is a real-time snapshot of operational variables that might change frequently. For example, the current quantity of a specific raw material in a Warehouse Node, and the current transit time or availability of a transportation edge. This data provides the starting data for the RST (See [Figure 10](#)).

```

CREATE TABLE resource_dynamic (
  resource_dynamic_id SERIAL PRIMARY KEY,
  resource_id INTEGER REFERENCES resource(resource_id),
  transaction_type_id INTEGER REFERENCES resource_transaction_type(transaction_type_id),
  current_cost REAL,
  current_resource_availability REAL,
  current_resource_rate REAL,
  resource_record_time TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  last_sync_time TIMESTAMP
);

CREATE TABLE inventory_dynamic (
  inventory_dynamic_id SERIAL PRIMARY KEY,
  inventory_id INTEGER REFERENCES inventory_static(inventory_id),
  transaction_type_id INTEGER REFERENCES inventory_transaction_type(transaction_type_id),
  current_cost REAL,
  current_quality REAL,
  current_resource_level REAL,
  rawmaterial_source INTEGER REFERENCES supplier_static(supplier_id),
  WIP_source INTEGER REFERENCES workspace_static(workspace_id),
  inventory_record_time TIMESTAMP DEFAULT CURRENT_TIMESTAMP,
  inventory_source_system TEXT,
  last_sync_time TIMESTAMP
);

```

Figure 10. Data Structure within RST for dynamic resources and inventories

• Step 2: Job Assignment

With the high-level order requirements established, the Control Tower begins the critical process of dynamic job assignment and scheduling. This is not a simple dispatch function; rather, it is a sophisticated orchestration mechanism that translates customer orders into an executable production plan aligned with the network's current operational state. To achieve this, the RST sends a query to the IMC requesting the production plan for the order portfolio. The IMC retrieves and transfers the relevant data from the **Production Blueprints** (developed by the Production Planning and Scheduling tools in WP4) to the RST. Using this information, the Control Tower assigns tasks to the manufacturing network and generates a "**job-to-do list**" for each node and edge in the network (See [Figure 9](#)). For example, a procurement task is assigned to a specific supplier node with defined material quantities and delivery timelines, while a sequence of manufacturing operations is assigned to the relevant production nodes in the correct processing order (according to the process routing plan). Similarly, transportation tasks are assigned to logistics edges connecting facilities. This centralized assignment mechanism ensures that all operations are perfectly synchronized with product specifications (BOM and process routing) and coordinated across the distributed manufacturing network. [Figure 11](#) illustrates the

manufacturing network. To achieve this, the RST evaluates the output of each job at each node and edge regarding four key resilience metrics: **Quality, Quantity, Profit, and Delay (Q-Q-P-D)**. For more details, see [Deliverable D2.1](#). For instance, a Workspace is assigned a job to produce **10 units** of a WIP. Due to inherent process variability or a disruption, the RST models a realistic, heterogeneous output:

- **7 units** are produced at target quality (A), with the expected cost and time.
- **2 units** are produced at a lower quality (B), requiring rework. This increases their individual production time and cost.
- **1 unit** is lost as scrap, representing a direct quantity loss.

Crucially, this detailed inventory (with its mixed quality and accumulated costs, time, quality, and quantity, see [Figure 13](#)) becomes the precise input for the subsequent node and edge in the process plan. This ensures that any loss of quality, delay, or cost increase is propagated through the network, allowing the RST to model cascading effects with high reliability.

```
#####
@staticmethod
def show_job_history(combined_jobs_sorted, combined_edge_jobs):
    """
    Display history of jobs for both nodes and edges.
    """
    # Node jobs
    records = []
    for node, jobs in combined_jobs_sorted.items():
        for job in jobs:
            records.append({
                "Node": job.node_id,
                "Order": job.order,
                "Job Code": job.job_code,
                "Workspace": job.workspace,
                "Unit": job.unit,
                "Output Part ID": job.Output_partID,
                "Release Time": job.ReleaseTime,
                "Start Time": job.StartTime,
                "Duration": job.DurationTime,
                "Completion Time": job.CompletionTime,
                "Input Qty": job.InputQuantity,
                "Output Qty": job.OutputQuantity,
                "Input Quality": job.InputQuality,
                "Output Quality": job.OutputQuality,
                "Execution Type": job.typeofExecution,
                "Operation Cost": job.OperationCost
            })
    df = pd.DataFrame(records)
    df["Waiting Time"] = df["Start Time"] - df["Release Time"]
    df["Quality Deviation"] = df["Output Quality"] - df["Input Quality"]
    #####
```

Figure 13. Performance tracking in RST simulator

• **Step 4: Aggregating Network-Wide Resilience Loss**

In RST, from the initial suppliers to the final customer delivery, the Control Tower tracks and aggregates performance deviations at every node and edge. The final output is not just a "pass/fail" on the customer order, but an aggregated quantification of the total **Loss of Resilience**, broken down by its constituent parts (See [Figure 14](#)).

- **Total Quantity Loss:** The cumulative number of units lost or scrapped.
- **Total Quality Degradation:** The final mix of product quality delivered.
- **Total Time Delay:** The deviation from the planned delivery date.
- **Total Profit Loss:** The accumulated extra costs from rework, inefficiencies, and

premium freight.

```
#####
@staticmethod
def show_job_history(combined_jobs_sorted, combined_edge_jobs):
    """
    Display history of jobs for both nodes and edges.
    """
    # Node jobs
    records = []
    for node, jobs in combined_jobs_sorted.items():
        for job in jobs:
            records.append({
                "Node": job.node_id,
                "Order": job.order,
                "Job Code": job.job_code,
                "Workspace": job.workspace,
                "Unit": job.unit,
                "Output Part ID": job.Output_partID,
                "Release Time": job.ReleaseTime,
                "Start Time": job.StartTime,
                "Duration": job.DurationTime,
                "Completion Time": job.CompletionTime,
                "Input Qty": job.InputQuantity,
                "Output Qty": job.OutputQuantity,
                "Input Quality": job.InputQuality,
                "Output Quality": job.OutputQuality,
                "Execution Type": job.typeofExecution,
                "Operation Cost": job.OperationCost
            })
    df = pd.DataFrame(records)
    df["Waiting Time"] = df["Start Time"] - df["Release Time"]
    df["Quality Deviation"] = df["Output Quality"] - df["Input Quality"]
    #####
```

Figure 14. Aggregating Network-Wide Resilience Loss

These component-level indicators are the fundamental variables that are impacted by the three causes of resilience loss introduced in next section (see Section 4). Table 1 defines the key performance indicators for each component type within the manufacturing network and describes how they are used to calculate the evolving Q-Q-P-D values for an order as it moves through the system.

Table 1. Component-Level Indicators for aggregating Network-Wide Resilience Loss

Component	Indicator	Description of Impact on Order Q-Q-P-D
Supplier (Node)	<ul style="list-style-type: none"> Inventory Cost (€/unit) Lead Time (days) Delivered Quantity (units) Material Quality (Grade) 	Initializes the order's Q-Q-P-D values. <ul style="list-style-type: none"> Profit: inventory (raw material) is the first cost added. Delay: Lead Time is the initial delay before production starts. Quantity: Delivered Quantity sets the starting material amount. Quality: Material Quality sets the baseline quality.
External Transport (Edge)	<ul style="list-style-type: none"> Transit Time (days) Transportation Cost (€/shipment) In-Transit Loss/Damage Rate (%) 	Adds transit-related losses. <ul style="list-style-type: none"> Profit: Transportation Cost is added to the cumulative cost. Delay: Transit Time is added to the cumulative delay. Quantity: In-transit loss reduces the available quantity. Quality: Damage can degrade the material

Component	Indicator	Description of Impact on Order Q-Q-P-D
		quality.
Warehouse (Node)	<ul style="list-style-type: none"> •Holding Time (days) •Holding Cost (€/unit/day) •holding Damage Rate (%) 	Adds storage-related losses. <ul style="list-style-type: none"> • Profit: Holding Cost (cost multiplied by time) is added. • Delay: Holding Time (waiting for capacity or pickup) is added to the delay. • Quantity: Holding damage can reduce the quantity of usable material. • Quality: Improper storage can degrade quality over time.
Workspace (Node)	<ul style="list-style-type: none"> •Processing Time (hours/unit) •Operational Cost (€/hour) •Yield / Scrap Rate (%) •Output Quality (Grade/Defect %) 	Performs value-added transformation. This is where the most significant changes occur. <ul style="list-style-type: none"> •Profit: Operational Cost is added. •Delay: Processing Time is added. •Quantity: Yield/Scrap Rate reduces the output quantity. •Quality: The process determines the new quality level of the output (WIP or final product).
Internal Transport (Edge)	<ul style="list-style-type: none"> •Transfer Time (hours) •Transfer Cost (€/trip) •Handling Damage Rate (%) 	Moves materials between internal stages. <ul style="list-style-type: none"> •Profit: Transfer Cost (e.g., forklift operation) is added. •Delay: Transfer Time is added. •Quantity: Handling damage can cause minor quantity loss. •Quality: Generally neutral unless a specific incident occurs.
Customer (Node)	<ul style="list-style-type: none"> •Target Production Cost (€) •Required Delivery Date •Required Quantity (units) •Required Quality Standard 	Calculation Network-Wide Resilience Loss at the last edge: <ul style="list-style-type: none"> •Profit Loss: Cumulative Actual Cost - Target Production Cost. •Delay: Final Delivery Date - Required Delivery Date •Quantity Loss: Required Quantity - Final Delivered Quantity. •Quality Loss: Required Quality Standard - actual Quality Standard (e.g., downgrade from 'A' to 'B')

By aggregating these indicators step-by-step, the RST provides a dynamic and transparent calculation of an order's performance as it traverses the network. For instance, after an operation in Workspace 1 adds 50€ in cost and takes 2 days, the order's cumulative profit metric decreases by 50€ and its cumulative delay increases by 2 days. This granular, component-based approach is essential for pinpointing exactly where and why resilience loss occurs within the manufacturing system.

5. MODELLING RESILIENCE LOSS

In an ideal manufacturing environment (where suppliers deliver on time and all production and transport processes operate with perfect predictability) the system

functions at its optimal state, and there is no loss of resilience. However, real-world operations are subject to constant deviation from this perfect plan. The gap between planned performance and actual outcomes is what we define as Loss of Resilience in terms of Quality, Quantity, Profit, and Delay (Q-Q-P-D). To quantify this loss, in task T2.1, RST categorises it into three distinct but interconnected causes. This allows for a precise analysis of how different types of causes degrade system performance. We express this relationship as:

$$\text{Loss of resilience} = f(\text{Deterministic Deviations, Stochastic Variability, Discrete Disruptions})$$

where:

- **Deterministic Deviations:** Represents the performance loss resulting from intentional, planned changes to the operational plan, such as altering the production plan, modifying transportation plans, or switching order of raw material to suppliers.
- **Stochastic Variability:** Accounts for the impact of inherent, continuous randomness in process parameters, including natural fluctuations in task durations, transportation times, and material costs.
- **Discrete Disruptions:** Captures the effects of sudden, unforeseen incidents that shock the system. These correspond to the internal and external risks and disruptions defined in [Deliverable D2.1](#), such as machine breakdowns, quality failures, or major supplier defaults.

By distinguishing between these causes, decision-makers can identify the primary sources of system vulnerability and determine where interventions will be most effective. The following subsections explore how the Resilience Digital Model is designed to simulate and analyse each of these factors.

Note 4. While D2.4 identifies three distinct causes of resilience loss (Deterministic Deviations, Stochastic Variability, and Discrete Disruptions) it is crucial to clarify the primary focus of the NARRATE project. The project's central objective, particularly for the RST developed by BUL, is to provide a data-driven strategic decision support system for enhancing resilience against Risk and Disruptions. Our analysis concentrates on quantifying the impact of the specific risk and disruption codes defined in Deliverable D2.1. The comprehensive RST algorithm is developed to model all three causes, the strategic decision-making capabilities of the RST are primarily geared towards helping managers prepare for and mitigate the effects of these unforeseen events. The other two factors are included to ensure the model's realism but are not the central subject of our strategic resilience analysis.

5.1. DETERMINISTIC DEVIATIONS: THE IMPACT OF PLANNED CHANGES

The first cause of resilience loss comes from intentional, top-down changes to the plan. While these adjustments are controlled and predictable, they force the network to operate in a suboptimal state compared to the original (given optimized) schedule.

The RST captures how these "deterministic deviations" create loss of resilience. Common scenarios that trigger such changes include:

- **Shifting Customer Priorities:** A customer may request an expedited delivery due to an urgent need, or management may decide to prioritize a new, more profitable order. This forces the Control Tower to re-order jobs, reallocate resources, and adjust schedules for other orders, creating a ripple effect of delays and re-planning across

the shop floor.

- **Changes to Internal Policies and Infrastructure:** The network must also adapt to planned internal changes. These include scheduled **machine maintenance** or replacement, which temporarily reduces capacity; shifts in **logistics providers** or transport modes, which alter lead times and costs; and modifications to **inventory strategy** (e.g., moving from just-in-time to holding safety stock), which changes material flow and buffering capacity.

Even though these changes are planned, they introduce complexity and force the manufacturing network to deviate from its most efficient plan. The cumulative effect leads to loss of time (delay), increased costs (e.g., supplying raw material from supplier with higher price), and reduced throughput. By modelling these deterministic changes, the RST quantifies the inherent "cost of flexibility" and helps managers evaluate the trade-offs between adapting to new plans and maintaining operational stability.

5.2. STOCHASTIC VARIABILITY: PARAMETERS UNCERTAINTY

The second cause of resilience loss addresses the uncertainty and inherent randomness, present in every manufacturing network. Key operational parameters are not certain values but fluctuate continuously. The RST uses **Monte Carlo simulation** to model this variability by defining probability distributions for critical parameters across the network. Key sources of stochastic uncertainty include:

- **Time Uncertainty:** Processing times vary due to tool wear, operator skill, or material differences. Transportation times are affected by traffic, weather, and carrier reliability.
- **Cost Uncertainty:** Raw material costs fluctuate with market prices, while energy and labour costs vary with demand and overtime.
- **Quality Uncertainty:** Defect rates are probabilistic, and dimensional accuracy or material properties naturally vary within statistical limits, even in a controlled process.
- **Quantity Uncertainty:** Supplier deliveries may be incomplete due to their own production issues, and manufacturing yields are never 100%, leading to scrap and quantity shortfalls.

To model this, we assign appropriate probability distributions to each variable (e.g., a log-normal distribution for processing times, a binomial distribution for defect rates). During a simulation run, the RST model generates random numbers from each distribution to create a unique and realistic scenario.

By running number of these Monte Carlo simulations, RST can analyse how independent variations propagate and compound across the network. This probabilistic approach provides critical insights that a deterministic model cannot: it reveals the full range of potential performance outcomes, quantifies the likelihood of missing deadlines or exceeding budgets, and identifies which sources of uncertainty have the greatest impact on overall system performance in terms of loss of resilience (Q-Q-P-D). This enables managers to make risk-informed decisions.

5.3. DISCRETE DISRUPTIONS: SIMULATING RISKS AND DISRUPTIONS

The third and most severe cause of resilience loss happen because of discrete, unpredictable incidents (Risk and Disruption) that shock the manufacturing network.

Although these incidents might involve changes to resource availability, like deterministic deviations, they differ fundamentally in their unpredictability. They are not planned and only become apparent upon occurrence. The NARRATE project centrally focuses on risks and disruptions as the key causes to resilience within manufacturing networks. To analyse their impact, the RST uses a scenario generation approach, where potential disruption events are defined and their consequences are simulated using Discrete-Event Simulation (DES).

Unlike the continuous uncertainty modelled with Monte Carlo simulation, these incidents are discrete occurrences that dramatically alter the system state at specific points in time. DES is uniquely capable to model how these events trigger cascading effects throughout the network, affecting downstream operations and requiring dynamic recovery actions. As detailed in [Deliverable D2.1](#), these incidents are systematically categorized as either internal or external. The simulation process integrates these defined scenarios into the manufacturing network model.

1. **Scenario Generation:** Disruptive incidents are generated, and the simulation's input data is modified to reflect risk and disruptions' consequences. For example, a scenario might specify a critical machine failure or a missed supplier delivery. Key parameters (such as the incident's likelihood and impact on specific resources and/or inventories) are systematically generated across multiple scenarios (see [Figure 15](#)).
2. **Dynamic Simulation:** The simulation runs based on generated scenarios for each core components of the manufacturing network including nodes and edges. Once we change input data under a scenario (as described in Section 3.2 Dynamic Job Assignment), the Control Tower detects these changes and updates its "job-to-do list," re-planning and reassigning jobs to workspace and calculate the loss of resilience.

```

self.Edge_1 = Edge(edge_id="edge0001",
                  edge_name="Lift_Truck01",
                  edge_type="Internal_transport",
                  output_PartID="part0001",
                  deterministic_processing_time=2,
                  deterministic_processing_cost=2,
                  input_node=self.Node_1,
                  output_node=self.Node_2,
                  pallet_size=pd.Series({"part0001": 1}),
                  conversion=pd.Series({"part0001": 1}))

self.Edge_2 = Edge(edge_id="edge0002",
                  edge_name="Lift_Truck02",
                  edge_type="Internal_transport",
                  output_PartID="part1836",
                  deterministic_processing_time=2,
                  deterministic_processing_cost=2,
                  input_node=self.Node_2,
                  output_node=self.Node_3,
                  pallet_size=pd.Series({"part1836": 1}),
                  conversion=pd.Series({"part1836": 1}))

self.Edge_3 = Edge(edge_id="edge0003",
                  edge_name="Lift_Truck03",
                  edge_type="Internal_transport",
                  output_PartID="part1972",
                  deterministic_processing_time=2,
                  deterministic_processing_cost=2,
                  input_node=self.Node_3,
                  output_node=self.Node_4,

```

Figure 15. Scenario generation in RST

6. RST FRAMEWORK FOR RESILIENCE STRATEGY TOOL

The RST framework, detailed in [Figure 16](#), provides a structured, data-driven methodology to systematically analyse, quantify, and enhance the resilience of manufacturing networks. The BUL's framework operates as an iterative, 10-step that transforms a baseline network configuration into a resilience manufacturing network interactive. The process begins by initializing a graph model of the network based on "Blueprint" in NARRATE platform and establishing its baseline performance under normal conditions (Steps 1-2). The model is then subjected to a series of analyses to understand its behaviour under various conditions: planned operational changes (Deterministic Analysis, Step 3), inherent operational variability (Stochastic Analysis, Step 4), and a comprehensive set of potential disruption scenarios affecting individual nodes and edges (Steps 5-6).

The core of the framework lies in its Vulnerability Assessment (Step 7), where the performance degradation (Δ_i) caused by each disruption is calculated. This identifies the network's most vulnerable components. A key decision point follows in the Threshold Evaluation (Step 8), where the worst-case impact ($\max_i(\Delta_i)$) is compared against a predefined risk tolerance threshold (ϵ). If the network's vulnerability exceeds this threshold, the framework enters an iterative improvement loop (Step 9), where targeted resilience strategies are applied to the most vulnerable components. The modified network is then re-analysed from the beginning. This process continues until the network meets the required resilience criteria, at which point the final, validated configuration and its performance indicators are generated (Step 10).

Note 5. It is important to emphasize the specific context of the strategies detailed in this deliverable (D2.4), which stem from the work in Task 2.1. This task focuses on proactive strategic reconfiguration during normal operational conditions. The analysis is performed from a pre-disruption standpoint, aiming to identify and mitigate inherent structural vulnerabilities within the manufacturing network. Crucially, the focus is on quantifying the impact of a potential failure (e.g., the loss of a resource or inventory) without regard to its specific cause. The question is, "What is the network resilience loss if a component fails?" rather than "What is the likelihood of a flood disabling this component?" This structural vulnerability assessment is distinct from the work in Task 2.3 (D2.3), which is dedicated to the analysis and assessment of specific risk and disruption.

<p>STEP 01 Initialize Network Configuration: The manufacturing network is configured using data retrieved from the Blueprint (<i>Network configuration: G</i>), as detailed in Section 3.1 and Section 3.2.</p> <p>STEP 02 Baseline of manufacturing network: A simulation is executed on the initial network configuration (G) to establish its baseline resilience performance. This performance is captured as the vector $QQPT_{base} = (Q_0, Q'_0, P_0, T_0)$ as detailed in Section 3.3.</p> <p>STEP 03 Deterministic Analysis (Optional): The user can introduce planned changes by updating the 'job-to-do' list for specific workspaces (see Section 4.1). The RST calculates the resilience loss resulting from these intentional deviations and outputs the deterministic performance vector $QQPT_{det}$.</p> <p>STEP 04 Stochastic Analysis (Optional): The user can assign probabilistic parameters to core components of the manufacturing network (nodes and edges) to model inherent variability (See Section 4.2). The RST is then executed to quantify the impact of this uncertainty, yielding the stochastic performance vector, $QQPT_{MC}$</p>
--

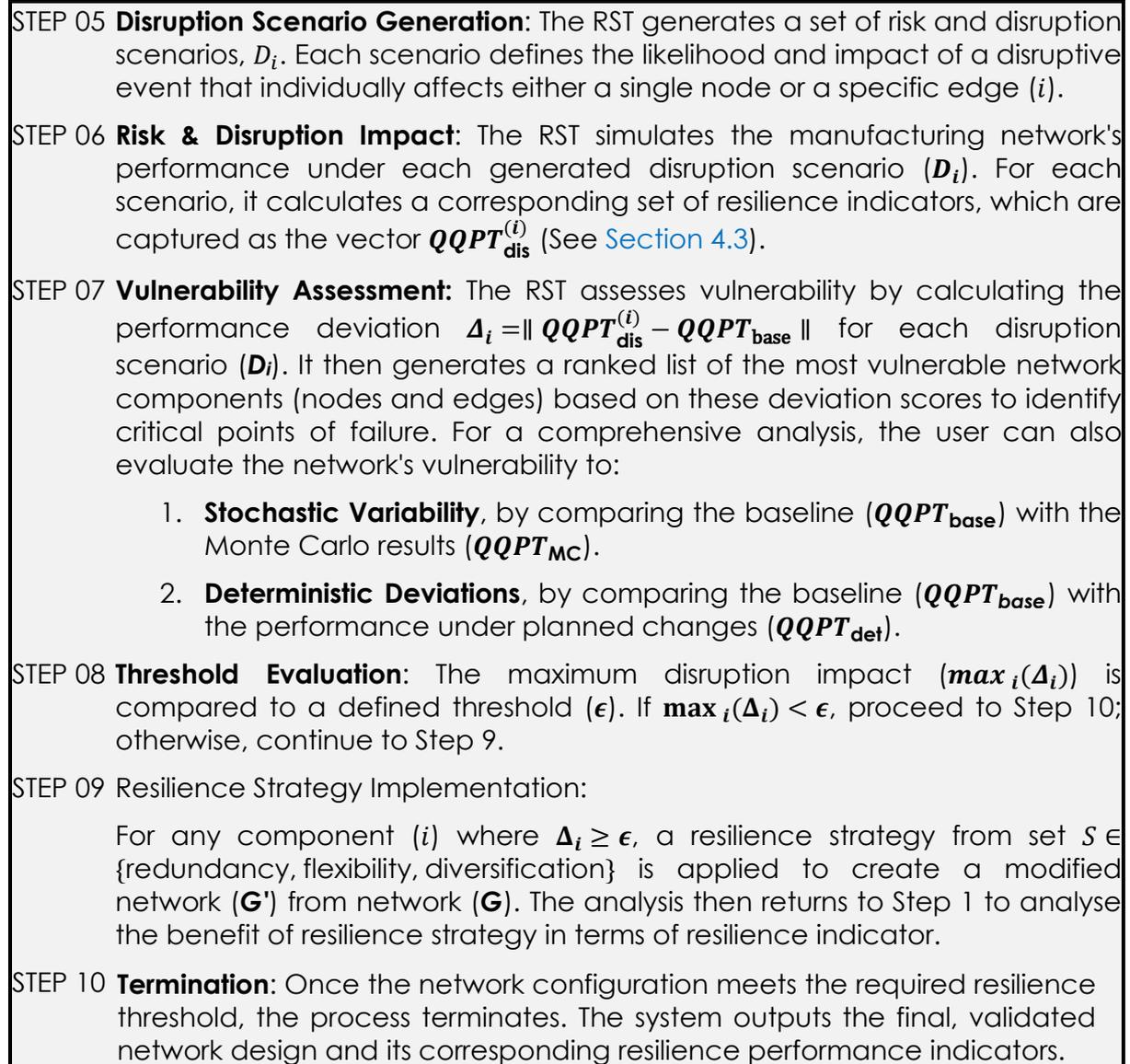


Figure 16. RST FRAMEWORK FOR RESILIENCE STRATEGY TOOL

7. RESILIENCE STRATEGY AND TOOL

The RST framework ensures that resilience investments are not made subjectively but are targeted responses to specific, quantified vulnerabilities. When a component's failure leads to an unacceptable performance deviation ($\Delta_i \geq \epsilon$), a resilience strategy must be selected from the set $S \in \{\text{redundancy, flexibility, diversification}\}$ to enhance the resilience of the manufacturing network. Building upon the resilience strategies defined at both strategic and operational levels in Deliverable D2.1, the RST tool functions as a data-driven decision support system. It empowers managers to select the most appropriate strategy by first analysing the impact of risks and disruptions on each core component to identify the most vulnerable points in the manufacturing network.

Based on this analysis, a resilience strategy is developed and applied to create a modified network configuration that is expected to be more resilient. Through an iterative process, the RST re-analyses this enhanced network, quantifying the improvement achieved in terms of the resilience indicators. This loop continues until the performance

loss falls below the predefined threshold (ϵ) for all components of the manufacturing network. Once the manager confirms that an acceptable level of resilience has been achieved, the optimal strategy and its corresponding network configuration are stored in the **NARRATE library** for future reference and implementation. Practical examples of resilience strategies are provided below.

7.1 RESILIENCE STRATEGY: REDUNDANCY

Redundancy is the practice of holding duplicate, standby assets or inventories that can directly replace a component that fails. It is a strategy of substitution, providing a "spare" to ensure continuity. [Table 2](#) summarizes four examples of the redundancy strategy.

Note 6. Strategic planning activities in [WP2](#) must be distinguished from the operational response mechanisms developed in [WP4](#). Whereas [Deliverable D2.4](#) aims to enhance the resilience capability of the manufacturing network at a strategic level before a disruption occurs, the tasks in [WP4](#) aim to provide real-time response through replanning and reconfiguration after a disruption has happened. In summary, the strategies presented here are for building a fundamentally resilience manufacturing network for the future, not for managing an incident in real-time.

Table 2. Resilience strategy: Redundancy

Vulnerability Identified By RST	Resilience strategy: Redundancy
Supplier Node (e.g., $\Delta(Supplier A) \geq \epsilon$)	Strategy 1: Increase Inventory Buffer. Maintain a higher level of safety stock for the critical materials provided by Supplier A. This creates a redundant buffer of inventory to absorb a short-term outage, ensuring production continues while the supplier recovers.
Workspace Node (e.g., $\Delta(Workspace B) \geq \epsilon$)	Strategy 2: Invest in Duplicate, Standby Capacity. Purchase and install a parallel machine (Resource) within Workspace B (or another location) that is identical or semi-identical to the primary machine. This standby asset can be activated immediately if the primary machine fails.
Warehouse Node (e.g., $\Delta(Warehouse C) \geq \epsilon$)	Strategy 3: Secure Backup Storage Space. Pre-emptively contract with a Third-Party Logistics (3PL) provider for guaranteed, on-demand overflow storage space near your facility. This provides a redundant location to hold inventory if Warehouse C becomes inaccessible or reaches capacity.
Internal Material Handling Edge (e.g., $\Delta(Edge D \rightarrow E) \geq \epsilon$)	Strategy 4: Maintain Backup Handling Equipment. Purchase and maintain a secondary piece of material handling equipment (e.g., a second forklift, pallet jack, or conveyor motor). This duplicate asset is kept on standby to ensure material flow between Workspace D and E is not interrupted.

7.2 RESILIENCE STRATEGY: DIVERSIFICATION

Diversification is the strategy of spreading risk across multiple different assets, locations, or pathways. Instead of relying on a single component, the operational load is distributed, so the failure of one component only has a partial impact. [Table 3](#) summarizes

examples of this strategy.

Table 3. Resilience strategy: Diversification

Vulnerability Identified By RST	Resilience strategy: Diversification
Supplier Node (e.g., $\Delta(\text{Supplier } A) \geq \epsilon$)	Strategy 1: Multi-Sourcing. Qualify and actively source the same inventory from a second, geographically distinct supplier ("Supplier B"). This diversifies the supply base, reducing dependency on ("Supplier A").
Workspace Node (e.g., $\Delta(\text{Workspace } B) \geq \epsilon$)	Strategy 2: Distribute Critical Capabilities. Invest in equipping a different workspace (for example, "Workspace F") with the same production capability as "Workspace B". This creates two independent nodes that can perform the same critical task, preventing a single point of failure in production.
Warehouse Node (e.g., $\Delta(\text{Warehouse } C) \geq \epsilon$)	Strategy 3: Decentralize Inventory. Split the total inventory of a critical material across two or more separate warehouse locations (e.g., 60% in Warehouse C and 40% in a secondary warehouse). This mitigates the risk of losing the entire inventory stock in a single event like a fire or flood.
External Transportation Edge $\Delta(\text{Route } X) \geq \epsilon$	Strategy 4: Utilize Multiple Transport options. Establish and use multiple transportation options. For example, ship 70% of goods via "company AB" and 30% via a secondary "company CD".

7.3 RESILIENCE STRATEGY: FLEXIBILITY

Flexibility is the ability of the system to adapt and reconfigure its resources, processes, and rules quickly in response to a disruption. It is a strategy of agility, focused on changing how things are done rather than just having backups. Table 4 summarizes examples of this strategy.

Table 4. Resilience strategy: Flexibility

Vulnerability Identified By RST	Resilience strategy: Flexibility
Workspace Node $\Delta(\text{Workspace } B) \geq \epsilon$	Strategy 1: Invest in Multi-Functional Resources. Utilize multi-purpose resources within "Workspace B" (including machines and cross-train operators). If a specialized machine in "Workspace B" fails, a flexible CNC machine in "Workspace G", operated by a cross-trained team, can be quickly re-tooled and re-programmed to take over the disrupted task.
Workspace	Strategy 2: MaaS: On-Demand Capacity via Subcontracting.

Vulnerability Identified By RST	Resilience strategy: Flexibility
Node $\Delta(\text{Workspace B}) \geq \epsilon$	Establish a master service agreement with a pre-qualified supplier (e.g., subcontractor). Instead of investing in a duplicate machine, this strategy provides the flexibility to switch production from Workspace B to an external partner on short notice when a disruption occurs.

7.4 RESILIENCE STRATEGY LIBRARY

In [Task T2.1](#), BUL aims to define the strategic, architectural changes to the manufacturing network that build inherent resilience capability. These are the proactive investments and policy decisions made in a "peacetime" environment and normal situation to prepare the manufacturing network for future, unforeseen events. Hence, deliverable D2.4 has focused on developing resilience strategy library based on the *proactive, pre-disruption actions* that fundamentally alter the manufacturing network's configuration and resilience capabilities. This library catalogues fundamental, strategic changes that can be implemented to enhance the inherent resilience of a manufacturing network. Each strategy represents a proactive investment or policy decision made *before* a disruption occurs, designed to strengthen the network's configuration and capabilities. The RST enable the NARRATE users to select and analyse these strategies and realise their impact on the network's resilience. Table 5 and [Figure 17](#) summarise the library for resilience strategies. The library of resilience strategies is structured to provide a clear and actionable **Resilience Strategy Tool** for increasing a resilience capability of manufacturing network. Each strategy is broken down into key fields to ensure clarity, context, and ease of use, including:

- Node / Edge Type:** This field categorizes each strategy by the specific component of the manufacturing network it applies to (e.g., a Supplier, workspace, or Transportation). This structure allows for targeted filtering and searching, enabling a user to find the most relevant solutions for a given area of the network.
- Strategy Code & Name:** These provide a unique identifier and a clear title for easy reference and communication within the NARRATE platform.
- Description:** This section explains *what* the resilience strategy is and details the practical actions involved in its implementation.
- Purpose:** This clarifies the strategic intent, or *why* the strategy should be implemented. It outlines the specific risks the strategy mitigates, and the resilience benefits it provides, helping to confirm its alignment with network's needs, vulnerability, and goals.
- Keywords:** This field is crucial for search, discovery, and contextual understanding. The keywords function as tags, connecting each strategy to common manufacturing network concepts, risks (e.g., 'Supplier disruption,' 'Regional risk'), and solutions (e.g., 'Multi-sourcing,' 'Backup capacity'). This enables the efficient discovery of strategies that address specific challenges and connects them to established terminology in NARRATE.

Table 5. Library for resilience strategies

Component	Value
Node / Edge Type	Supplier
Strategy Code	RED-SUP-01
Strategy Name	Strategic Inventory Buffering
Description	Increase and hold a higher-than-normal level of safety stock for critical inventory sourced from a specific supplier.
Purpose	To make a pre-planned capital investment in an inventory buffer. This buffer insulates production from the immediate impact of short-term supplier disruptions, ensuring operational continuity.
Keywords	Redundancy strategy, Supplier disruption, Safety Stock, Inventory Management, Supplier Risk Mitigation, Short-term shortage
Node / Edge Type	Supplier
Component	Value
Node / Edge Type	Supplier
Strategy Code	DIV-SUP-01
Strategy Name	Establish Dual/Multi-Sourcing
Description	Qualify, onboard, and establish a contractual agreement with one or more alternative suppliers for a critical component or material.
Purpose	To create supply chain flexibility and mitigate the risk of over-reliance on a single source. Having a pre-qualified alternative enables the network to rapidly switch or supplement its primary supply in response to a disruption, ensuring a continuous inflow of critical materials.
Keywords	Diversification strategy, Supplier disruption, Multi-sourcing, Alternative supplier, Single-source risk mitigation
Component	Value
Node / Edge Type	Supplier
Strategy Code	DIV-SUP-02
Strategy Name	Geographic Supplier Diversification
Description	When selecting and qualifying alternative suppliers, prioritize those located in different and distinct geographic regions from the primary supplier.

Purpose	To mitigate risks from large-scale, region-specific disruptions such as natural disasters, geopolitical instability, or regional infrastructure failures. This ensures that a single regional event cannot disable the entire supply base for a critical material.
Keywords	Diversification strategy, Geographic diversification, Regional risk, Supplier selection, Multi-sourcing, Geopolitical risk
Component	Value
Node / Edge Type	Supplier
Strategy Code	FLX-SUP-01
Strategy Name	Strategic Inventory Standardization
Description	Intentionally design products to use common, standardized inventories across multiple product lines, minimizing the use of unique or custom-designed parts.
Purpose	To build systemic flexibility that reduces dependency on specific suppliers. Standardization allows for inventory substitution between different products and dramatically expands the potential supply base, as standard components are more widely available and easier to source from the market during a supplier disruption.
Keywords	Flexibility strategy, Inventory Standardization, Part Commonality, Sourcing Flexibility, Supplier Risk Mitigation
Component	Value
Node / Edge Type	Workspace / Plant
Strategy Code	RED-WKS-01
Strategy Name	Redundant Production Capacity
Description	Install a parallel, standby resources (Machine/Human resource). This resource is maintained in a state of readiness, providing built-in redundant capacity that can be used if the primary resource fails.
Purpose	To ensure production continuity and mitigate revenue loss from downtime caused by the failure of a critical, single-point-of-failure resources (human resource absent). This internal buffer capacity allows for immediate recovery from resource breakdowns.
Keywords	Redundancy strategy, Redundant capacity, Backup resources, Downtime mitigation, Machine maintenance, Human resource absence
Component	Value
Node / Edge Type	Workspace / Plant

Strategy Code	DIV-WKS-01
Strategy Name	Distribute Core Capabilities
Description	Strategically invest in duplicating a critical manufacturing operation or technology across two or more different physical plants or workspaces within the network. This decentralizes a single point of failure by ensuring the same function can be performed in multiple locations.
Purpose	To build geographic resilience against site-specific disruptions (e.g., natural disasters, regional power outages, local labour strikes). By ensuring a critical capability is not concentrated in one location, the overall production network can continue to function even if one plant/workspace is compromised.
Keywords	Diversification strategy, Geographic diversification, Distributed manufacturing, Network resilience, Site redundancy
Component	Value
Node / Edge Type	Workspace / Plant
Strategy Code	FLX-WKS-01
Strategy Name	Resource Flexibility (Multi-functional Machine/Equipment)
Description	Focused on acquiring flexible, multi-purpose machinery (e.g., CNC centres, reconfigurable robotics) instead of specialized, single-task machine/equipment. This builds a plant with the inherent capability to reroute production flow internally after occurrence of incident.
Purpose	To create operational resilience against internal disruptions, such as the failure of a machine/equipment, unplanned maintenance, or a sudden production bottleneck. This allows production managers to dynamically reroute work to other capable machines/equipment, minimizing downtime and maintaining output without requiring fully redundant capacity.
Keywords	Flexibility strategy, Machine/Equipment Flexibility, Multi-functional Machine/Equipment, Resource flexibility, Operational Agility, Internal Rerouting
Component	Value
Strategy Code	FLX-WKS-02
Strategy Name	Develop a Flexible Workforce
Description	Implement a long-term, strategic cross-training program to create a multi-skilled workforce. This builds human capital flexibility, ensuring operators are pre-qualified to be reassigned across different machines, lines, or workspaces as needed.

Purpose	To insulate production from disruptions caused by skill-specific labour shortages or absenteeism. A multi-skilled workforce allows managers to dynamically reallocate personnel to overcome bottlenecks, cover for absent colleagues, and adapt to changing production priorities, thereby maintaining operational continuity.
Keywords	Flexibility strategy, Flexible Workforce, Cross-training, Multi-skilling, Human resource, labour Agility, Human Capital
Component	Value
Node / Edge Type	Workspace / Plant
Strategy Code	FLX-WKS-03
Strategy Name	Establish Manufacturing-as-a-Service (MaaS) Partnership
Description	Qualify and establish an agreement with a third-party MaaS provider or supplier (e.g., subcontractor). This strategic relationship provides contractual access to external, on-demand manufacturing capacity, creating an agile extension of the internal network capacity.
Purpose	To create a flexible, on-demand capacity buffer without significant capital expenditure. This allows the organization to rapidly scale production to meet unexpected demand surges or to outsource production during an internal disruption (e.g., plant shutdown, equipment failure), effectively converting a fixed cost (for increasing internal capacity) into a variable cost.
Keywords	Manufacturing-as-a-Service (MaaS), Contract Manufacturing, On-demand Capacity, Outsourcing, Third-party manufacturing
Component	Value
Node / Edge Type	Warehouse / Inventory
Strategy Code	RED-WHS-01
Strategy Name	Secure Backup Warehouse Contracts
Description	Establish a contractual relationship with a 3rd Party Logistics (3PL) provider for guaranteed, on-demand access to overflow or emergency warehouse space. This is a strategic provision for physical storage redundancy.
Purpose	To provide immediate, pre-arranged overflow capacity to mitigate risks of storage constraints. This ensures the ability to receive inbound materials or store finished goods during unexpected inventory surges (e.g., bullwhip effect) or when the primary warehouse is inaccessible due to a site-specific disruption.
Keywords	Redundancy strategy, Backup Warehouse, Third-party logistics, Overflow storage, Emergency storage, Storage capacity

Component	Value
Node / Edge Type	Warehouse / Inventory
Strategy Code	DIV-WHS-01
Strategy Name	Design a Decentralized Warehousing Network
Description	Adopt a network design strategy that splits inventory of critical inventories (including raw material or final products) across multiple, smaller, geographically dispersed warehouses instead of a single central depot. This structural change reduces the impact of a single-facility disruption.
Purpose	To build geographic resilience against a catastrophic, single-site inventory loss. By distributing stock across the network, the failure of one warehouse does not halt the entire network, and it can position inventory closer to points of consumption, potentially reducing lead times.
Keywords	Diversification strategy, Decentralized warehousing, Distributed inventory, Network design, Geographic resilience, Inventory risk
Component	Value
Strategy Code	FLX-WHS-01
Strategy Name	Implement Postponement Strategy
Description	Increase the inventory level of WIP (specifically semi-finished products). Final customization is delayed until receive the order of customer, creating a flexible inventory pool that can serve a wide range of final product demands.
Purpose	To increase inventory flexibility and mitigate the risks of both stockouts and obsolescence driven by forecast inaccuracy. By aggregating demand at a component or semi-finished level, this strategy allows a single pool of generic inventory to satisfy a wide variety of end-product configurations, enabling a more agile response to volatile customer demand.
Keywords	Flexibility strategy, Postponement, Delayed Differentiation, Inventory Flexibility, Demand Volatility, Risk Pooling, Semi-finished product
Component	Value
Node / Edge Type	Internal Transportation
Strategy Code	RED-ITR-01
Strategy Name	Invest in Backup Material Handling Equipment

Description	Purchase and maintain spare key internal material handling equipment (e.g., backup forklifts, conveyors, autonomous mobile robots) on-site. This ensures redundancy for the physical flow of materials within a facility (between workspaces as well as internal warehouses).
Purpose	To mitigate the risk of internal production or handling bottlenecks caused by the failure of critical material handling equipment. By having pre-positioned spares, the facility can perform a rapid swap-out, minimizing downtime and maintaining the flow of materials between workspaces, storage areas, and shipping/receiving docks.
Keywords	Redundancy strategy, Backup Material Handling Equipment (MHE), Resource Redundancy, Internal handling, Internal Downtime Mitigation
Component	Value
Node / Edge Type	Internal Transportation
Strategy Code	DIV-ITR-01
Strategy Name	Design Resilient Internal Pathways
Description	Develop and maintain a robust material handling system for internal material flow by designing multiple, redundant physical pathways and access points. This includes adhering to strict standards for clear, marked corridors (HSE compliance), providing adequate space for in-process buffers, and ensuring multiple entry/exit points for critical areas like warehouses. This creates an internal material handling system that is structurally resilient and operationally flexible.
Purpose	To create structural resilience within the facility, ensuring that a single physical obstruction (e.g., a blocked aisle, equipment failure, inaccessible doorway) does not halt the entire internal material flow. This strategy guarantees operational continuity, enhances workplace safety, and provides the flexibility to adapt material handling in response to dynamic production requirements or minor disruptions.
Keywords	Diversification strategy, Flexibility strategy, Material Handling, Facility Layout, Redundant Pathways, Material Flow, Access Point Redundancy, HSE Compliance, Bottleneck Prevention
Component	Value
Node / Edge Type	External Transportation
Strategy Code	DIV-ETR-01
Strategy Name	Diversify Logistics Service Providers
Description	Contract with multiple, independent logistics service providers (LSPs), such as 3PLs or freight forwarders, for all key transportation lanes (inbound from suppliers, outbound to customers, and between manufacturers and supplier (e.g., subcontractors)). This avoids reliance

	on a single transportation partner.
Purpose	To mitigate the risk of transportation disruption caused by the failure of a single logistics provider (e.g., due to bankruptcy, labour strikes, or service quality issues). It ensures operational continuity by allowing the company to quickly shift volume to a contracted alternative provider.
Keywords	Diversification strategy, Logistics Service Provider (LSP), 3PL, Freight Forwarder, Carrier Redundancy, Transportation Network, Partner Diversification
Component	Value
Node / Edge Type	External Transportation
Strategy Code	FLX-ETR-01
Strategy Name	Establish Pre-negotiated Expedited Freight Options
Description	Set up service level agreements and pre-negotiated rate cards with carriers that offer express or expedited freight services (e.g., air freight, dedicated truckload). This provides a contractual capacity to accelerate shipments on demand across all transportation lanes (inbound from suppliers, outbound to customers, and between manufacturers and supplier (as a subcontractor)).
Purpose	To create response flexibility, allowing the company to shorten transportation lead-times to recover from upstream delays or meet urgent customer demands. This avoids the need to negotiate premium rates under crisis conditions and provides a tool to "buy back" time lost in the supply chain.
Keywords	Flexibility strategy, Expedited Freight, Express Delivery, Air Freight, Service Level Agreement, Transit Time, Lead Time Reduction, Urgent Shipment

resil...	node_edge_type	resilien...	resilience_strategy_name	resilience_strategy_description	resilience_strateg...	resilience_strategy_keywords
1	Supplier	RED-SUP-01	Strategic Inventory Buffering	Increase and hold a higher-than-normal level	To make a pre-planned capit	Redundancy strategy, Supplier disruption, Safety
2	Supplier	DIV-SUP-01	Establish Dual/Multi-Sourcing	Qualify, onboard, and establish a contractual	To create supply chain flexib	Diversification strategy, Supplier disruption, Mult
3	Supplier	DIV-SUP-02	Geographic Supplier Diversification	When selecting and qualifying alternative sup	To mitigate risks from large-t	Diversification strategy, Geographic diversificati
4	Supplier	FLX-SUP-01	Strategic Inventory Standardization	Intentionally design products to use common	To build systemic flexibility t	Flexibility strategy, Inventory Standardization, Pa
5	Workspace / Plant	RED-WKS-01	Redundant Production Capacity	Install a parallel, standby resource (Machine/	To ensure production contin	Redundancy strategy, Redundant capacity, Backu
6	Workspace / Plant	DIV-WKS-01	Distribute Core Capabilities	Strategically invest in duplicating a critical m	To build geographic resilien	Diversification strategy, Geographic diversificati
7	Workspace / Plant	FLX-WKS-01	Resource Flexibility (Multi-functional Mac	Focused on acquiring flexible, multi-purpose	To create operational resilier	Flexibility strategy, Machine/Equipment Flexibilit
8	Workspace / Plant	FLX-WKS-02	Develop a Flexible Workforce	Implement a long-term, strategic cross-traini	To insulate production from	Flexibility strategy, Flexible Workforce, Cross-tra
9	Workspace / Plant	FLX-WKS-03	Establish Manufacturing-as-a-Service (Ma	Qualify and establish an agreement with a thi	To create a flexible, on-deme	Manufacturing-as-a-Service (MaS), Contract Ma
10	Warehouse / Inventory	RED-WHS-01	Secure Backup Warehouse Contracts	Establish a contractual relationship with a 3rc	To provide immediate, pre-ar	Redundancy strategy, Backup Warehouse, Third-
11	Warehouse / Inventory	DIV-WHS-01	Design a Decentralized Warehousing Net	Adopt a network design strategy that splits ir	To build geographic resilien	Diversification strategy, Decentralized warehousi
12	Warehouse / Inventory	FLX-WHS-01	Implement Postponement Strategy	Increase the inventory level of WIP (specific	To increase inventory flexib	Flexibility strategy, Postponement, Delayed Diffe
13	Internal Transportation	RED-ITR-01	Invest in Backup Material Handling Equip	Purchase and maintain spare key internal mat	To mitigate the risk of intern	Redundancy strategy, Backup Material Handling
14	Internal Transportation	DIV-ITR-01	Design Resilient Internal Pathways	Develop and maintain a robust material handl	To create structural resilien	Diversification strategy, Flexibility strategy, Mate
15	External Transportation	DIV-ETR-01	Diversify Logistics Service Providers	Contract with multiple, independent logistics	To mitigate the risk of transp	Diversification strategy, Logistics Service Provide
16	External Transportation	FLX-ETR-01	Establish Pre-negotiated Expedited Freight	Set up service level agreements and pre-negi	To create response flexibility	Flexibility strategy, Expedited Freight, Express De

Figure 17. Library for Resilience Strategies in RST data base

8. EXPERIMENTAL VALIDATION

To demonstrate the practical application of the proposed Resilience Digital Model framework and validate its algorithmic approach (shown in Figure 16), this section presents an experimental example. The experiment is conducted on a synthetic manufacturing network, which serves as a controlled and transparent testbed for evaluating resilience. Using a synthetic manufacturing network allows for a systematic and reproducible analysis of how **Resilience Strategy Tool** perform under various conditions, ensuring the generalizability of the results without relying on an industrial case. The entire experiment is designed to systematically simulate and quantify the impact of the three primary causes of resilience loss previously defined in Section 4: *Deterministic Deviations*, *Stochastic Variability*, and *Discrete Disruptions*. This structure enables a precise diagnosis of system vulnerabilities and showcases the RST's ability to measure the effectiveness of targeted resilience interventions.

The synthetic network represents a realistic production environment, comprising multiple suppliers, series and parallel workspaces, and internal/external transportation links serving various customer demand points. The analysis unfolds in stages, each corresponding to a cause of resilience loss. First, a baseline is established under ideal, deterministic conditions, representing the normal state against which all losses are measured. Next, the model introduces Stochastic Variability, using the Monte Carlo framework to simulate inherent operational uncertainty in parameters like processing times, costs, and quality. Finally, the scenarios incorporate Discrete Disruptions, simulating Risk & disruption scenarios. Throughout each stage, the RST assesses the network-wide impact across the four critical dimensions of Quality, Quantity, Profit, and Delays (Q-Q-P-D), providing an evaluation of how resilience is compromised and how it can be restored.

8.1 SYNTHETIC MANUFACTURING NETWORK

This section uses an illustrative example of a synthetic manufacturing network operating under a Make-to-Order model. The entire process is driven by customer demand and is visualized in the network diagram. The process begins with a customer, C1 (Node ID: 0005), who places three distinct orders for the final products including Part1860, Part1861, and Part1862 (see Figure 18)

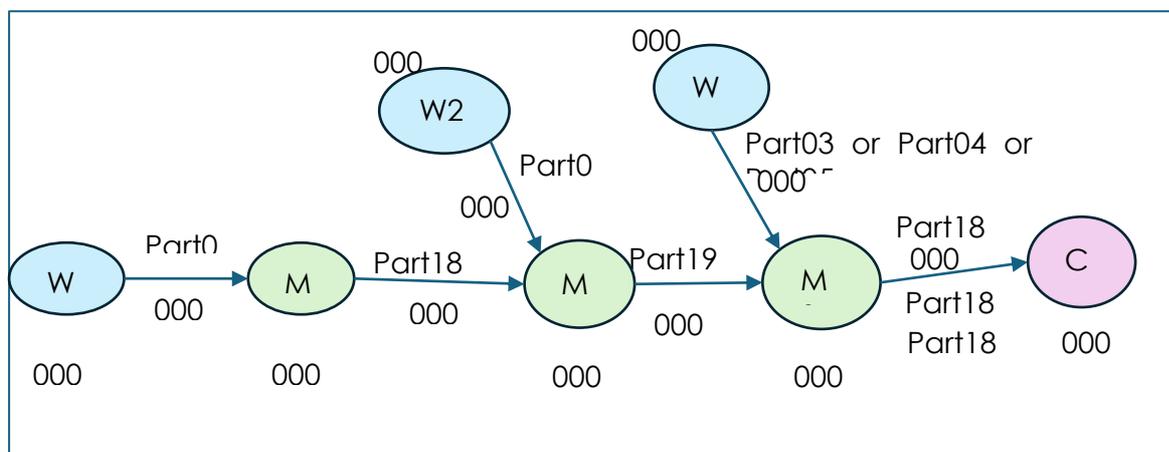


Figure 18. Synthetic manufacturing network

The production path follows a multi-level process. First, workspace M1 transforms raw

material Part01 into the WIP, Part1836. Next, M2 combines this component with Part02 from warehouse W2 to produce the WIP, Part1972. Finally, M3 performs the final assembly by combining Part1972 with an WIP from W3 to create the final products:

- Part1972 + Part03 → Part1860
- Part1972 + Part04 → Part1861
- Part1972 + Part05 → Part1862

Appendix A shows how the node and edge classes are coded in the RST. As reported in Table 6, each order is defined by its own set of performance targets which serve as the benchmark for calculating resilience loss: Target Production Cost (€), Required Delivery Date, Required Quantity (units), and Required Quality Standard. The manufacturing network consists of three sequential workspaces and three corresponding warehouses that supply them.

- Workspaces (Production Nodes):
 - **M1 (Node ID: 0002):** A machine dedicated to initial processing.
 - **M2 (Node ID: 0003):** A machine for intermediate assembly.
 - **M3 (Node ID: 0004):** A machine for final assembly.
- Warehouses (Supply Nodes):
 - W1 (Node ID: 0001): Stores Part01.
 - W2 (Node ID: 0006): Stores Part02.
 - **W3 (Node ID: 0007):** Stores Part03, Part04, and Part05.

The production path follows a multi-level process. First, workspace M1 transforms raw material Part01 into the WIP, Part1836. Next, M2 combines this component with Part02 from warehouse W2 to produce the WIP, Part1972. Finally, M3 performs the final assembly by combining Part1972 with an WIP from W3 to create the final products:

- Part1972 + Part03 → **Part1860**
- Part1972 + Part04 → **Part1861**
- Part1972 + Part05 → **Part1862**

Table 6. Order of customer001

Order ID	Order Name	Product ID	Order Size	Unit	Duration (days)	Unit Price (\$)	Total Price (\$)	Date
Order 001	white chairs	product001	250	number	22	12.5	4125	45748.38542
Order 002	Black chairs	product002	200	number	19	10.5	3300	45752.38542
Order 003	Yellow chairs	product003	190	number	15	11.5	3135	45757.38542

The nodes are connected by edges that represent inventory transportation and handling, including both internal and external movements:

- **Edge 0001:** Transports Part01 from Warehouse W1 to Workspace M1.
- **Edge 0005:** Transports Part02 from Warehouse W2 to Workspace M2.

- **Edge 0006:** Transports Part03/Part04/Part05 from Warehouse W3 to Workspace M3.
- **Edge 0002:** Transfers intermediate WIP (Part1836) from Workspace M1 to M2.
- **Edge 0003:** Transfers sub-assembly WIP (Part1972) from Workspace M2 to M3.
- **Edge 0004:** Delivers the final products (Part1860, etc.) from Workspace M3 to the Customer C1.

To establish a performance benchmark, the initial simulation is run as a deterministic scenario. This scenario assumes ideal, "perfect world" conditions to calculate the baseline performance, against which all future disruptions and variability will be measured. The key assumptions are that all process times, transit times, and costs are fixed, certain values with no random delays. Furthermore, all production and handling processes are assumed to be defect-free, with no scrap, rework, or quality degradation at any stage. The yield at every step is 100%, with no material lost or damaged. Under these ideal conditions, the RST calculates the optimal outcome for each order, which serves as the zero-loss baseline. The output of the RST for these three orders are shown in [Figure 19](#). According to the results, there is no deviation in quantity, quality, profit, or delay. This outcome is expected under deterministic conditions. Moreover, the delivery times of products are pre-agreed between the manufacturing company and the customer. Therefore, under these ideal deterministic circumstances, no deviations occur. In the following subsection, we will relax this assumption to evaluate the performance of the manufacturing network under stochastic variables and disruption events.

While a deterministic model provides a useful baseline, it operates on the assumption that all parameters are certain and perfectly predictable. Manufacturing networks are subject to inherent uncertainty, making it impossible to assign a single, certain value to each indicator easily. For example, a workspace's Processing Time is not constant; it fluctuates with machine degradation, operator skill level, and minor stoppages. The Transportation Cost for an external shipment can vary with unstable fuel prices or the need for last-minute expedited freight. Likewise, a supplier's Lead Time can be disrupted by unforeseen customs delays, weather events, or port congestion, and the Material Quality they deliver may exhibit slight variations from one batch to the next. Because these and other factors are influenced by complex, random factors, a stochastic approach is important. To address this, RST models uncertain parameters by generating random values from carefully selected probability distributions. This allows users to capture the nature of different uncertainties. For instance, Gaussian distribution is used for symmetric variations (e.g., minor fluctuations in processing time), Weibull distributions for resource availability (e.g., production rate), and Lognormal distributions for positively skewed economic metrics (e.g., costs, which cannot be negative but can have large, unexpected spikes). This probabilistic approach allows for a realistic assessment of manufacturing network performance in terms of loss of resilience under uncertain conditions. The results are shown in [Figure 19](#).

To assess the network's resilience to a high-impact event, we introduce a disruption scenario #1 that simulates a critical supplier failure. In this scenario, the primary supplier for Part01 (the foundational raw material for the entire production line) fails to make a scheduled delivery. This results in Warehouse W1 (Node ID: 0001) being completely starved of Part01 for a period of two full days. Because the manufacturing process is strictly sequential, this disruption creates an immediate and critical bottleneck. Workspace M1 is rendered idle, halting the production of the intermediate component Part1836. This initial stoppage triggers a cascading failure that propagates downstream, starving Workspace M2 and subsequently M3. The entire production chain is effectively paralyzed until the supply of Part01 is restored.

The results (see [Figure 19](#)) reveal a distinguish between the system's performance under normal uncertainty and its collapse during the disruption scenario, exposing a critical vulnerability in its manufacturing network. The baseline deterministic model, as expected, shows zero deviation, representing an ideal situation. Under normal (with no risk and disruption) and stochastic conditions, the network demonstrates minor resilience loss: orders are delayed by 2-3 days, costs increase by approximately €150-€220, and a few units (1-2 per order) experience a quality downgrade. However, the supplier failure scenario drastically amplifies these negative impacts. The delivery delay for all orders explodes to 6-7 days, more than double the delay from normal operational variability. This reflects not only the initial 2-day material shortage but also the subsequent bullwhip effect and time needed to clear the production backlog. The financial consequences are even more severe: the cost deviation for Order002, for instance, increases from €160.7 to €1065.6, a near seven times increase driven by replacing a new supplier with higher cost and lead time. While the final quantity delivered satisfies customer's demand, the degradation in timeliness and the increase in cost demonstrate that the network is critically vulnerable. This non-resilience is tied directly to its dependency on Part01 and, more importantly, on its single supplier.

The next disruption scenario is Scenario #2, Workspace Quality Degradation. This scenario investigates a quality failure at Workspace M2 (Node ID: 0003). For instance, a sudden machine failure risk and disruption cause the Scrap Rate for the inventory Part1972 to increase by 15%. This disruption creates a material deficit for the final assembly stage (M3). To fulfil the customer's required quantities, the preceding stages (M1 and M2) must overproduce to compensate for the loss, consuming more Part01 and Part02 than planned. This directly increases material and operational costs. Furthermore, the time required to produce the extra units introduces a significant delay that propagates through the rest of the manufacturing network, impacting the final delivery dates for all three orders. The network is moderately vulnerable to this internal quality failure. While the system can eventually produce the required quantity, it does so at the expense of both time and cost. The linear, no-buffer design means that a quality issue in a mid-stream process cannot be absorbed without causing a ripple effect that delays all subsequent operations and inflates costs. The vulnerability is specifically to the *internal process stability* of its workspaces, as a single machine's poor performance degrades the efficiency of the entire network.

Scenario #3: Final Delivery Cost increase. This scenario models a purely financial disruption by considering a doubling of the Transportation Cost on Edge 0004, which handles the final delivery from Workspace M3 to the customer C1. This event could be triggered by external factors such as a regional fuel crisis, a sudden change in carrier pricing, or the need to use a premium logistics service. Because this disruption is purely economic, it has no impact on the physical flow of goods; the transit time, product quality, and delivered quantity remain unchanged. The entire impact is absorbed as a direct financial loss, causing the Cost deviation for all three customer orders to increase sharply and significantly reducing the overall profitability of the fulfilment process. As result, the network is financially vulnerable but operationally resilient to this disruption. The system successfully fulfils customer demand (delivering the correct products on time with expected quality). However, its profitability is highly exposed to volatility in the external transportation cost. This reveals a vulnerability not in its physical production capability, but in its financial vulnerability. The network's resilience depends on its ability to absorb unexpected cost shocks; if profit margins are already thin, such an event could make the orders unprofitable.

52	order_id	: Order001	16	order_id	: Order001	32	order_id	: Order001
53	Order_quality	: 4: 250.0	17	Order_quality	: 4: 250.0	33	Order_quality	: 4: 250.0
54	customer_rec_quality	: 4: 250.0	18	customer_rec_quality	: 4: 248.0 3: 2.0	34	customer_rec_quality	: 4: 249.0 3: 1.0
55	Order_quality_deviation	: 4: 0.0	19	Order_quality_deviation	: 3: 2.0 4: -2.0	35	Order_quality_deviation	: 3: 1.0 4: -1.0
56	Order_quantity	: 250	20	Order_quantity	: 250	36	Order_quantity	: 250
57	customer_rec_quantity	: 250.0	21	customer_rec_quantity	: 250.0	37	customer_rec_quantity	: 250.0
58	Quantity_deviation	: 0.0	22	Quantity_deviation	: 0.0	38	Quantity_deviation	: 0.0
59	order_delivery_agreed_time	: 2025-04-23 09:15:00	23	order_delivery_agreed_time	: 2025-04-23 09:15:00	39	order_delivery_agreed_time	: 2025-04-23 09:15:00
60	customer_rec_time	: 2025-04-23 08:59:00	24	customer_rec_time	: 2025-04-27 02:41:00	30	customer_rec_time	: 2025-04-29 16:54:19.977589
61	Time_deviation (days)	: 0	25	Time_deviation (days)	: 3	31	Time_deviation (days)	: 6
62	Order_cost	: 4125	26	Order_cost	: 4125	32	Order_cost	: 4125
63	customer_rec_cost	: 4125.0	27	customer_rec_cost	: 4345.0	33	customer_rec_cost	: 4969.1
64	Cost_deviation	: 0.0	28	Cost_deviation	: 220.0	34	Cost_deviation	: 844.1
65			29			35		
66	order_id	: Order002	30	order_id	: Order002	36	order_id	: Order002
67	Order_quality	: 4: 200.0	31	Order_quality	: 4: 200.0	37	Order_quality	: 4: 200.0
68	customer_rec_quality	: 4: 200.0	32	customer_rec_quality	: 4: 198.0 3: 2.0	38	customer_rec_quality	: 4: 199.0 3: 1.0
69	Order_quality_deviation	: 4: 0.0	33	Order_quality_deviation	: 3: 2.0 4: -2.0	39	Order_quality_deviation	: 3: 1.0 4: -1.0
70	Order_quantity	: 200	34	Order_quantity	: 200	40	Order_quantity	: 200
71	customer_rec_quantity	: 200.0	35	customer_rec_quantity	: 200.0	41	customer_rec_quantity	: 200.0
72	Quantity_deviation	: 0.0	36	Quantity_deviation	: 0.0	42	Quantity_deviation	: 0.0
73	order_delivery_agreed_time	: 2025-04-24 09:15:00	37	order_delivery_agreed_time	: 2025-04-24 09:15:00	43	order_delivery_agreed_time	: 2025-04-24 09:15:00
74	customer_rec_time	: 2025-04-23 21:39:00	38	customer_rec_time	: 2025-04-27 09:21:00	14	customer_rec_time	: 2025-05-01 05:47:58.243391
75	Time_deviation (days)	: 0	39	Time_deviation (days)	: 3	15	Time_deviation (days)	: 6
76	Order_cost	: 3300	40	Order_cost	: 3300	16	Order_cost	: 3300
77	customer_rec_cost	: 3300.0	41	customer_rec_cost	: 3460.7	17	customer_rec_cost	: 4365.6
78	Cost_deviation	: 0.0	42	Cost_deviation	: 160.7	18	Cost_deviation	: 1065.6
79			43			19		
80	order_id	: Order003	44	order_id	: Order003	20	order_id	: Order003
81	Order_quality	: 4: 190.0	45	Order_quality	: 4: 190.0	21	Order_quality	: 4: 200.0
82	customer_rec_quality	: 4: 190.0	46	customer_rec_quality	: 4: 189.0 3: 1.0	22	customer_rec_quality	: 4: 189.0 3: 1.0
83	Order_quality_deviation	: 4: 0.0	47	Order_quality_deviation	: 3: 1.0 4: -1.0	23	Order_quality_deviation	: 3: 1.0 4: -1.0
84	Order_quantity	: 190	48	Order_quantity	: 190	24	Order_quantity	: 190
85	customer_rec_quantity	: 190.0	49	customer_rec_quantity	: 190.0	25	customer_rec_quantity	: 190.0
86	Quantity_deviation	: 0.0	50	Quantity_deviation	: 0.0	26	Quantity_deviation	: 0.0
87	order_delivery_agreed_time	: 2025-04-25 09:15:00	51	order_delivery_agreed_time	: 2025-04-25 09:15:00	27	order_delivery_agreed_time	: 2025-04-25 09:15:00
88	customer_rec_time	: 2025-04-24 03:59:00	52	customer_rec_time	: 2025-04-27 15:41:00	28	customer_rec_time	: 2025-05-02 21:32:24.696945
89	Time_deviation (days)	: 0	53	Time_deviation (days)	: 2	29	Time_deviation (days)	: 7
90	Order_cost	: 3135	54	Order_cost	: 3135	30	Order_cost	: 3135
91	customer_rec_cost	: 3135.0	55	customer_rec_cost	: 3288.0	31	customer_rec_cost	: 3515.9
92	Cost_deviation	: 0.0	56	Cost deviation	: 153.0	32	Cost_deviation	: 380.9

Deterministic
Deviations

Stochastic
Variability

Discrete
Disruptions

Figure 19. OUTPUTS FOR ORDER OF CUSTOMER01

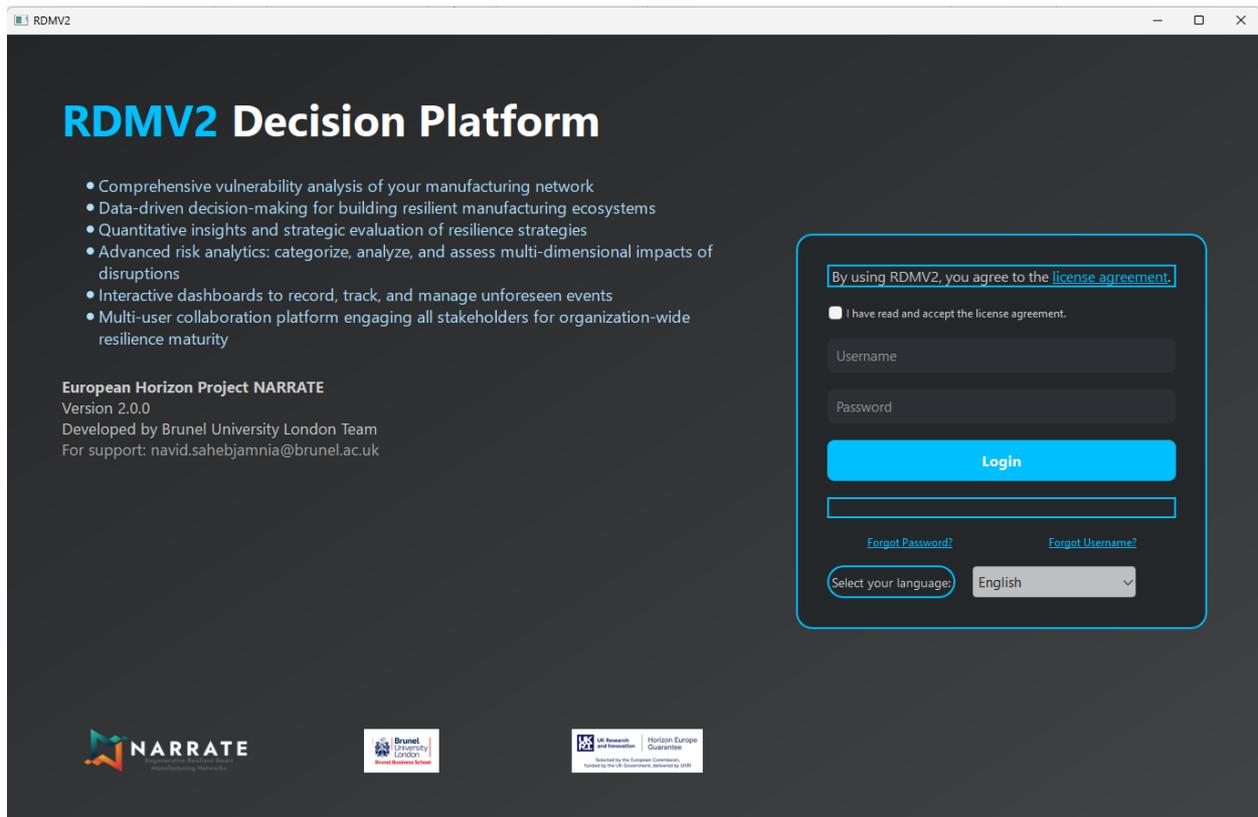
Scenario #4: Targeted Inventory Damage. This scenario introduces a targeted inventory loss within Warehouse W3 (Node ID: 0007). For instance, an incident, such as a forklift accident or water damage, results in a 20% increase in the Holding Damage Rate, specifically affecting the stock of Part03. This disruption selectively targets Order001 ("white chairs"), as Part03 is the unique component required for its final assembly. The production of Order002 and Order003 proceeds without issue. For Order001, however, production at M3 breaks due to the Part03 shortage. This triggers a significant delay for that specific order while a new batch of Part03 is procured from the supplier. The cost for Order001 also increases, reflecting the value of the written-off inventory and potential expediting fees for the replacement parts. As result, this scenario reveals a vulnerability within the network. The system as a whole is resilient to the event, as two-thirds of its orders are unaffected. However, for the specific product line (Part1860 / "white chairs"), the network is vulnerable. The vulnerability lies in the *lack of redundant inventory or a secondary supplier for specialized, product-specific components*.

Scenario #5: Final Assembly Bottleneck. This scenario examines the impact of a late-stage bottleneck by increasing the Processing Time at Workspace M3 (Node ID: 0004) by 50%. For instance, this could be caused by a machine fault that forces the production to run at a slower speed or the assignment of a less-experienced human resource to the workspace (final assembly node). Since M3 is the final workspace before delivery edge, any delay here directly translates to a delivery delay for the customer, with no opportunity for outsourcing. As a result, all three orders (Order001, Order002, Order003) will experience a significant Time deviation. Furthermore, the Operational Cost will rise as the machine runs for longer to complete the same amount of work, impacting the cost-effectiveness of all three orders. As result, the network is highly vulnerable to inefficiencies in its final production stage. The sequential flow means that the manufacturing network's

overall throughput is dictated by its slowest process. A bottleneck at the very end of the line is particularly damaging because there is no slack in the schedule left to absorb it. This highlights a critical vulnerability to the *processing capacity and reliability of its final assembly stage*. Any degradation in performance at M3 has an immediate and unavoidable negative impact on customer-facing metrics, particularly delivery time.

9. RESILIENCE STRATEGY TOOL DEMONSTRATOR VIEW

RST is a tool within the NARRATE platform that operates under the overall integrity of the NARRATE platform. Initially called upon by the IMC to address end-user questions, RST contacts other tools in NARRATE, such as LLM and Blueprint, to gather the necessary data. The RST engine then runs calculations to determine quantitative values for loss of resilience, including loss of quantity, loss of quality, loss of profit, and loss of time (delay). These quantitative data on the loss of resilience for resources and inventories are sent to the IMC to provide valuable insights for users. Additionally, if users wish to interactively work with RST, the IMC can guide them to the RST dashboard. This allows users to transition from the main NARRATE platform to the RST platform. The RST dashboard enables users to interactively engage with the tool and assess the vulnerability of the manufacturing network, as illustrated in the figures below.



RDMP2
Welcome navid4
Profile
Logout
English

INCIDENT

Add Incidents

View

INCIDENT ANALYSIS

Descriptive

Diagnostic

Predictive

RESILIENCE STRATEGY TOOL

Customer Order

Network Realtime Status

Network Mapping

RST Simulator

Scenario Generator

Risk Exposure Report

PROFILE

Resource

Inventory

Supplier

Customer

Workspace

Operation

Process Plan

Logistics Provider

Warehouse

Material Handling

TASK MANAGEMENT

Customer Order

Customer Order Management

Manage customer orders

[Add Customer Order](#)
[Edit Customer Order](#)
[Delete Customer Order](#)
[View Details](#)
Refresh

Search

Filter by Status: All Status Reset

Add New Order

Final Product: *

Required Quantity: *

Required Quality Standard:

Required Delivery Date: *

Target Production Cost (€):

Save Cancel

ID	Order Code	Customer	Product	Required Qty	Delivery Date	Status	Created At
1	7	ORD006	European Manufacturing SA	Classic Adult Queen Bed	120.0	2026-02-20 16:00	Pending
2	6	ORD005	TechCorp Industries	Dining Table Set Adult	75.0	2026-02-05 08:00	Pending
3	5	ORD004	Scandinavian Solutions AB	Kids Race Car Bed	200.0	2026-01-25 12:00	Pending
4	4	ORD003	Global Automotive Ltd	Dining Table Set Adult	30.0	2026-01-10 09:00	Pending
5	3	ORD002	European Manufacturing SA	Kids Race Car Bed	100.0	2025-12-20 14:00	Pending
6	2	ORD001	TechCorp Industries	Classic Adult Queen Bed	50.0	2025-12-15 10:00	Pending

Loaded 6 orders

RDMP2
Welcome navid4
Profile
Logout
English

INCIDENT

Add Incidents

View

INCIDENT ANALYSIS

Descriptive

Diagnostic

Predictive

RESILIENCE STRATEGY TOOL

Customer Order

Network Realtime Status

Network Mapping

RST Simulator

Scenario Generator

Risk Exposure Report

PROFILE

Resource

Inventory

Supplier

Customer

Workspace

Operation

Process Plan

Logistics Provider

Warehouse

Material Handling

TASK MANAGEMENT

Network Real-time Status

Network Real-time Status

Monitor and manage real-time performance of supply chain network nodes and edges

[Supplier Performance](#)
[Warehouse Status](#)
[Workspace Operations](#)
[Transport Performance](#)
Show Historical Refresh

Supplier Performance Management

Monitor and manage real-time supplier performance and material availability

[Add Record](#)
[Edit Record](#)
[Delete Record](#)

Search

Filter: Supplier Reset

ID	Supplier	Inventory	Quantity	Unit Cost	Lead Time	Quality	Recorded At	Valid From	Valid To	
1	SUP001	Global Manufacturing Ltd	RM002	raw_material	3.0000	€0.00	0.00	A	2025-11-20T15:55:18.6...	Current
2	SUP001	Global Manufacturing Ltd	RM002	raw_material	3.0000	€0.00	0.00	D	2025-11-20T15:55:08.4...	Historical
3	SUP001	Global Manufacturing Ltd	RM002	raw_material	2.0000	€2.00	2.00	A	2025-11-20T15:54:48.1...	Current
4	SUP001	Global Manufacturing Ltd	RM002	raw_material	0.0000	€0.00	0.00	D	2025-11-20T15:54:32.6...	Historical
5	SUP001	Global Manufacturing Ltd	RM002	raw_material	2.0000	€2.00	1.00	A	2025-11-20T15:54:24.6...	Historical
6	SUP001	Global Manufacturing Ltd	RM002	raw_material	1.0000	€1.00	1.00	A	2025-11-20T15:54:15.7...	Historical

Loaded 6 records

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ID	Warehouse Code	Warehouse Name	Inventory Type	Warehouse Type	Location	Capacity (m ²)	Status	Created At	
1	2	WH-3PL-001	DHL Supply Chain - Central Hub	General	3PL	Frankfurt, Germany	15000.00	Active	2025-11-19T12:48:31.3...
2	3	WH-3PL-002	Kuehne+Nagel Logistics Center	Finished Goods	3PL	Rotterdam, Netherlands	12500.00	Active	2025-11-19T12:48:31.3...
3	4	WH-3PL-003	DB Schenker Distribution Hub	Raw Material	3PL	Hamburg, Germany	10000.00	Active	2025-11-19T12:48:31.3...
4	5	WH-3PL-004	CEVA Logistics Warehouse	WIP	3PL	Paris, France	8500.00	Active	2025-11-19T12:48:31.3...
5	6	WH-3PL-005	XPO Logistics Center	Finished Goods	3PL	Lyon, France	11000.00	Active	2025-11-19T12:48:31.3...
6	7	WH-3PL-006	Geodis European Hub	General	3PL	Brussels, Belgium	9500.00	Active	2025-11-19T12:48:31.3...
7	8	WH-3PL-007	Panalpina Logistics Park	Raw Material	3PL	Antwerp, Belgium	7500.00	Inactive	2025-11-19T12:48:31.3...
8	9	WH-INT-RM-001	Raw Material Storage Facility	Raw Material	Internal	Manchester, UK - Building A	5000.00	Active	2025-11-19T12:48:31.3...
9	10	WH-INT-FG-001	Finished Goods Distribution Center	Finished Goods	Internal	Birmingham, UK - Building B	6500.00	Active	2025-11-19T12:48:31.3...
10	11	WH-INT-GEN-001	General Purpose Warehouse	General	Internal	London, UK - Building C	4500.00	Active	2025-11-19T12:48:31.3...

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11. APPENDIX A: NODES AND EDGES FOR A MANUFACTURING NETWORK

```
self.Edge_1 = Edge(edge_id="edge0001",
    edge_name="Lift_Truck01",
    edge_type="Internal_transport",
    output_PartID="part0001",
    deterministic_processing_time=2,
    deterministic_processing_cost=2,
    input_node=self.Node_1,
    output_node=self.Node_2,
    pallet_size=pd.Series({"part0001": 1}),
    conversion=pd.Series({"part0001": 1}))
```

```
self.Edge_2 = Edge(edge_id="edge0002",
    edge_name="Lift_Truck02",
    edge_type="Internal_transport",
    output_PartID="part1836",
    deterministic_processing_time=2,
    deterministic_processing_cost=2,
    input_node=self.Node_2,
    output_node=self.Node_3,
    pallet_size=pd.Series({"part1836": 1}),
    conversion=pd.Series({"part1836": 1}))
```

```
self.Edge_3 = Edge(edge_id="edge0003",
    edge_name="Lift_Truck03",
    edge_type="Internal_transport",
    output_PartID="part1972",
    deterministic_processing_time=2,
    deterministic_processing_cost=2,
    input_node=self.Node_3,
    output_node=self.Node_4,
    pallet_size=pd.Series({"part1972": 1}),
    conversion=pd.Series({"part1972": 1}))
```

```
self.Edge_4 = Edge(edge_id="edge0004",
    edge_name="Lift_Truck4",
    edge_type="Internal_transport",
```

```

output_PartID=["part1860", "part1861", "part1862"],
deterministic_processing_time=2,
deterministic_processing_cost=2,
input_node=self.Node_4,
output_node=self.Node_5,
pallet_size=pd.Series({"part1860": 1, "part1861": 1, "part1862": 1}),
conversion=pd.Series({"part1860": 1, "part1861": 1, "part1862": 1})

self.Edge_5 = Edge(edge_id="edge0005",
edge_name="Lift_Truck05",
edge_type="Internal_transport",
output_PartID="part0002",
deterministic_processing_time=2,
deterministic_processing_cost=2,
input_node=self.Node_6,
output_node=self.Node_3,
pallet_size=pd.Series({"part0002": 1}),
conversion=pd.Series({"part0002": 1}))

self.Edge_6 = Edge(edge_id="edge0006",
edge_name="Lift_Truck6",
edge_type="Internal_transport",
output_PartID=["part0003", "part0004", "part0005"],
deterministic_processing_time=2,
deterministic_processing_cost=2,
input_node=self.Node_7,
output_node=self.Node_4,
pallet_size=pd.Series({"part0003": 1, "part0004": 1, "part0005": 1}),
conversion=pd.Series({"part0003": 1, "part0004": 1, "part0005": 1}))

# Initialize Nodes (after Edges exist)
self.Node_1 = Node(node_id="node0001",
node_name="start_node",
node_type="warehouse",
output_PartID="part0001",
deterministic_processing_time=0.2,
deterministic_processing_cost=0.2,
output_edges=self.Edge_1,
Minimum_toStart=pd.Series({"part0001": 1}),
Buffer=pd.Series({"part0001": 10000}),
conversion=pd.Series({"part0001": 1}))

self.Node_2 = Node(node_id="node0002",
node_name="workspace01",
node_type="machine",
operation="operation1",
output_PartID="part1836",
deterministic_processing_time=0.2,
deterministic_processing_cost=0.2,
Buffer=pd.Series({"part0001": 10000}),
full_buffer_capacity=100000,
buffer_minpercent_tostart=0.00001,

```

```

input_edges=self.Edge_1,
output_edges=self.Edge_2,
conversion=pd.Series({"part0001": 1}))

self.Node_3 = Node(node_id="node0003",
node_name="workspace02",
node_type="machine",
operation="operation2",
output_PartID="part1972",
deterministic_processing_time=0.2,
deterministic_processing_cost=0.2,
Buffer=pd.Series({"part1836": 10000, "part0002": 10000}),
full_buffer_capacity=100000,
buffer_minpercent_tostart=0.00001,
input_edges=[self.Edge_2, self.Edge_5],
output_edges=self.Edge_3,
conversion=pd.Series({"part1836": 1, "part0002": 1}))

self.Node_4 = Node(node_id="node0004",
node_name="workspace3",
node_type="machine",
operation=["operation3", "operation4", "operation5"],
output_PartID=["part1860", "part1861", "part1862"],
deterministic_processing_time=0.025,
deterministic_processing_cost=3.5,
Buffer=pd.Series({"part1972": 10000, "part0003": 10000, "part0004": 10000,
"part0005": 10000}),
full_buffer_capacity=100000,
buffer_minpercent_tostart=0.00001,
input_edges=[self.Edge_3, self.Edge_6],
output_edges=self.Edge_4,
conversion=pd.Series({"part1972": 1, "part0003": 1, "part0004": 1, "part0005": 1}))

self.Node_5 = Node(node_id="node0005",
node_name="customerAli",
node_type="customer",
input_edges=self.Edge_4,
conversion=pd.Series({"part1860": 1, "part1861": 1, "part1862": 1}))

self.Node_6 = Node(node_id="node0006",
node_name="start_node",
node_type="warehouse",
output_PartID="part0002",
deterministic_processing_time=0.2,
deterministic_processing_cost=0.2,
output_edges=self.Edge_5,
Minimum_toStart=pd.Series({"part0002": 1}),
Buffer=pd.Series({"part0002": 10000}),
conversion=pd.Series({"part0002": 1}))

self.Node_7 = Node(node_id="node0007",
node_name="warehouse7",

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node_type="warehouse",
output_PartID=["part0003", "part0004", "part0005"],
deterministic_processing_time=0.2,
deterministic_processing_cost=0.2,
output_edges=self.Edge_6,
Minimum_toStart=pd.Series({"part0003": 1, "part0004": 1, "part0005": 1}),
Buffer=pd.Series({"part0003": 100000, "part0004": 100000, "part0005": 100000}),
conversion=pd.Series({"part0003": 1, "part0004": 1, "part0005": 1})
    
```