NARRATE

Regenerative Resilient Smart Manufacturing Networks

D2.1 RESILIENCE STRATEGY & TOOL

2025/02/18

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D2.1 RESILIENCE STRATEGY & TOOL

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Version	1.0
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Abstract	D2.1 outlines key findings and recommendations from the "**Resilience Strategy and Tool**" task, focusing on risks and disruptions in Smart Manufacturing Networks. These Risks and Disruptions can arise from unforeseen events, such as natural disasters and geopolitical incidents, which may lead to the loss of critical assets, including inventory, resources, and information. Such losses appear as risks and disruptions across various operations, including production, transportation, and warehousing. The report categorizes these challenges into Internal and External Risks and Disruptions. D2.1 proposes resilience strategies at both System and Operational levels. It also presents key performance indicators for assessing resilience, defined based on the loss of resilience in terms of cost, quality, quantity, and time (delay). Additionally, we developed measures for analysing the maturity of companies' networks regarding resilience. These measures help organizations better recognize the gaps between their resilience goals and their current situation. Finally, a resilience framework developed by the BUL team in the NARRATE project is introduced to assist companies in enhancing resilience and effectively responding to risks and disruptions, ensuring continued operations within their Supply chain network.
Keywords	RISK & DISRUPTION; RESILIENCE KPIs; RESILIENCE FRAMEWORK; RESILIENCE STRATEGIES AT SYSTEM LEVEL; RESILIENCE STRATEGIES AT OPERATIONAL LEVEL, MATURITY OF COMPANY'S RESILIENCE

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Version	Date	Description of change	List of contributor(s)
0.1	2024/07/28	Develop resilience strategies, codifying the risks and disruptions, developed resilience KPIs, and proposed the resilience framework	BUL
0.2	2024/008/23	Review the D2.1 V0.1 and gave comments	BUD and FhG
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0.6	2025/02/14	D2.1 has been revised based on the comments	BUL
1.0	2025/02/15	Last review by the coordinator	AID

STATEMENT ON MAINSTREAMING GENDER

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

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1	INSTITUTO TECNOLOGICO METALMECANICO, MUEBLE, MADERA, EMBALAJE Y AFINES-AIDIMME	AID	ES
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4	INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE LYON	INSA	FR
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ABBREVIATIONS

DFD	Data Flow Diagram
DSS	Decision Support System
ERD	External Risks and Disruptions
HVAC	Heating, Ventilation, and Air Conditioning
IMC	Intelligent Manufacturing Custodian
IRD	Internal Risks and Disruptions
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MaaS	Manufacturing as a Service
MPS	Master Production Schedule
MHE	Material Handling Equipment
OTIF	On-Time In-Full
OEE	Overall Equipment Effectiveness
RDM	Resilience Digital Module
SCN	Supply Chain Network
SMN	Smart Manufacturing Network

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EXECUTIVE SUMMARY

Deliverable D2.1 presents key findings and recommendations from the "Resilience Strategy and Tool" task (T2.1), addressing the critical Risks and Disruptions faced by Manufacturing Networks. As manufacturing companies navigate an increasingly complex landscape, ***unforeseen events*** (including natural disasters, geopolitical events, machine breakdown, supply shortage, operational shortage, and pandemic) pose significant challenges that can result in the loss of ***Critical Assets*** (including inventory, resources, and information). This report categorizes risks and disruptions into two categories: ***Internal Risks and Disruptions*** (e.g., Production shortcomings, Raw material quality issue, Lack of operational capacity, and Facility disruptions) and ***External Risks and Disruptions*** (e.g., Cancelled or changed orders, Damaged final product during transportation, Shortage of raw material/component/Consumable resource, and Regulatory and policy changes). While Internal Risks and Disruptions include issues within lead manufacturer facilities, External Risks and Disruptions encompass the network of the company such as suppliers, sub-contractors, logistics service providers, and customers.

To combat the identified challenges, the deliverable proposes ***resilience strategies*** at both System and Operational levels. These strategies are designed to enhance the overall resilience of manufacturing company's networks, ensuring that they can effectively mitigate, respond to and recover from any risks and disruptions. Details of these strategies are presented in Chapter 2. The report defines ***Key Performance Indicators*** (KPIs) for assessing resilience, grounded in the concept of ***Loss of Resilience***. These KPIs estimate the deviation in a company's performance concerning critical metrics such as Time to Recovery and loss of Operating Level. Specifically, Loss of Resilience is conceptualized as a function of deviations in critical assets necessary for operations at the network level, encompassing ***production***, ***transportation***, and ***warehousing***. By quantifying these deviations in terms of ***cost***, ***quality***, ***quantity***, and ***time (delay)***, companies can gain insights into how risks and disruptions impact their operational efficiency and overall performance. For instance, deviations may include delays in order delivery, variances in the amount of inventory available in the warehouse, and fluctuations in the costs associated with production, transportation, or warehousing. These KPIs serve as essential tools for companies to measure their resilience capabilities. Additionally, we developed measures for analysing the ***maturity of companies' networks*** concerning resilience. This framework allows companies to better recognize gaps between their current resilience status and their strategic goals. Examples of maturity metrics include flexibility in production operations and redundancy among suppliers. Finally, a comprehensive ***resilience framework*** developed by the BUL team in the NARRATE project is introduced. This framework aims to assist companies in enhancing their resilience and effectively addressing risks and disruptions, thereby ensuring continued operations within their supply chain networks.

D2.1 has been led by the Brunel team and represents the culmination of tight collaboration with other project partners throughout various stages, including data collection, interviews, feedback, and revisions. This collaborative effort has ensured that the deliverable is comprehensive and relevant to the needs of the manufacturing networks. The findings were presented at two General Assembly meetings, where we received valuable feedback from the entire consortium, further refining our approach. Furthermore, observations from pilots have significantly informed the development of this deliverable, ensuring that it aligns closely with the requirements and expectations of manufacturing companies and their networks. This practical approach has established a strong foundation based on real-world challenges, making our findings actionable and relevant.

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CHAPTER 1. RISKS & DISRUPTIONS IN MANUFACTURING NETWORKS

SECTION 1.1 DEFINITION: RISKS AND DISRUPTIONS

The manufacturing sector encompasses a diverse range of companies that produce a wide array of goods, from consumer products to industrial machinery. Many of these manufacturing companies have adopted a model where they outsource a portion of their operations to subcontractors (suppliers). This approach allows them to focus on their core competencies, reduce overhead costs, and take advantage of the specialized expertise and capabilities of external partners.

In the outsourced manufacturing model, these companies typically maintain control over the overall production process, but they may outsource specific tasks or components to subcontractors. This could involve outsourcing the production of specific parts or assemblies, or even the entire manufacturing of certain products. As shown in *Figure 1,* the manufacturing networks enables them to leverage the strengths of multiple stakeholders, while maintaining oversight and control over the end-to-end production process [1].

The rise of Manufacturing as a Service (MaaS) has become a prominent trend in the manufacturing networks [2]. In this model, the lead manufacturing company outsources a significant portion of its production activities to subcontractors, often referred to as service providers. The relationship between the ***lead manufacturer*** and the ***subcontractor*** is critical, as it requires a high degree of trust, collaboration, and coordination. The MaaS approach can offer several benefits to the lead manufacturer, such as reduced capital expenditures, increased flexibility, and access to specialized expertise [3]. However, it also introduces additional complexities and risks. The lead manufacturer must now manage the logistics of transporting raw materials to the subcontractor and finished goods back to their own facilities or distribution centres. This can increase the overall network complexity and the risks and disruptions, delays, or quality issues. Moreover, the lead manufacturer must carefully examine and monitor the subcontractor's performance to ensure product quality, on-time delivery, and compliance with the company's standards. Striking the right balance between the benefits and risks of MaaS is a critical strategic decision for manufacturing companies in today's competitive landscape [4][5].

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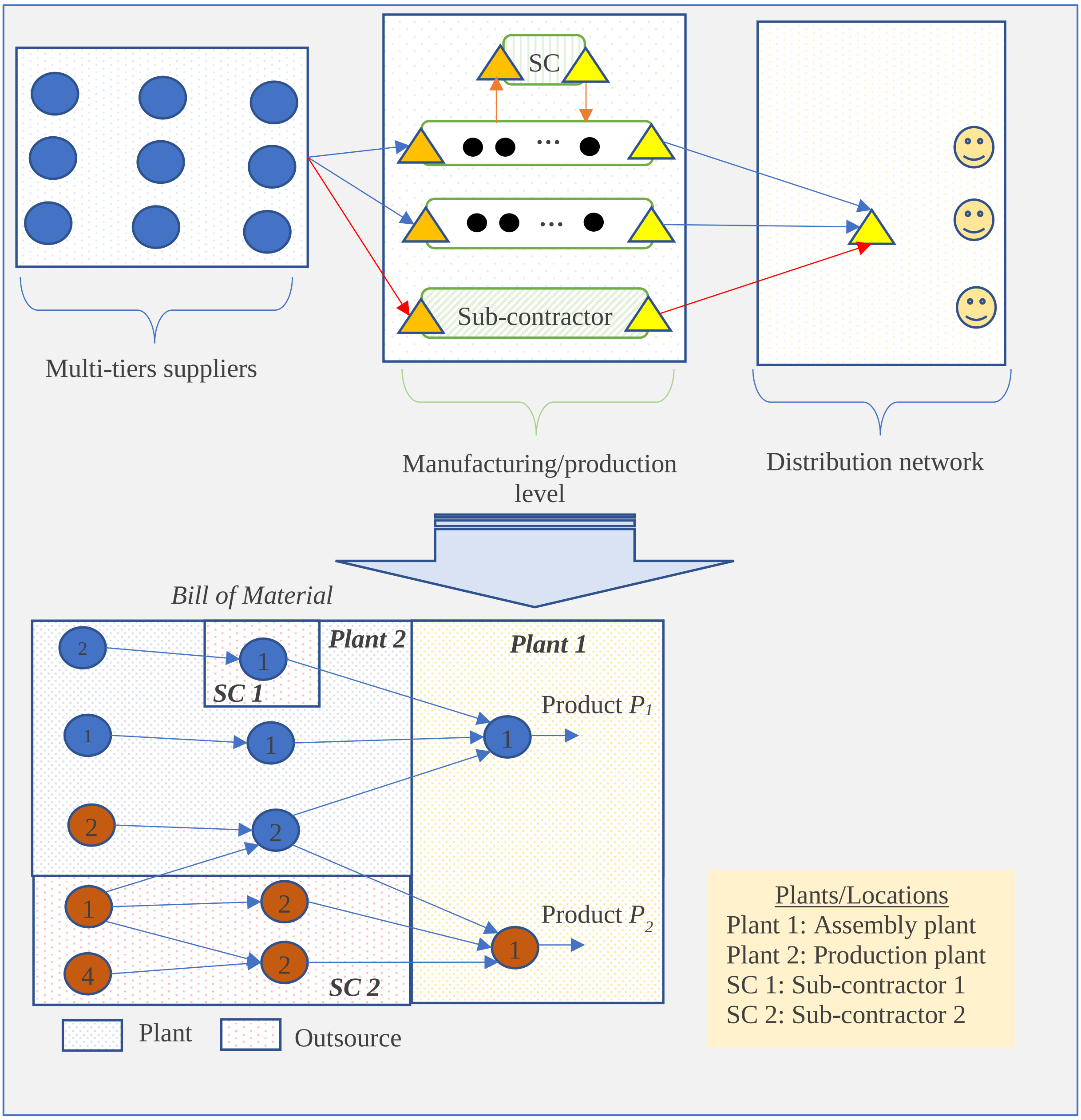

FIGURE 1.THE MANUFACTURING NETWORK OF A COMPANY

Risks and Disruptions in the manufacturing networks can be broadly defined as the potential for unforeseen events, circumstances, or conditions that can adversely impact the company's ability to achieve its objectives [6]. The International Organization for Standardization (ISO) defined risk in ISO-31000:2009 as the effect of uncertainty on an organization's objectives. They emphasized that organizations of all types and sizes face internal and external factors and influences that make it uncertain whether and when they will achieve their objectives [7]. Expanding on this definition, we can include ***unforeseen events*** as sources of deviation i.e. ***Risks and Disruptions*** within an organization's objectives. Furthermore, the risk can be positive (e.g., increasing profits beyond financial goals) or negative (e.g., selling less than the desired financial targets in a given year). For example, an unforeseen event like a pandemic can have both positive and negative impacts on two companies simultaneously. For example, the COVID-19 pandemic had a positive impact on face mask producers but a negative impact on restaurants and high-street shops [8].

Figure 2 illustrates the definition of risks and disruptions for the companies based on ISO-22301. In the context of manufacturing, this risk can appear in various forms, from unstable market conditions and unpredictable demand to supply chain disruptions and unexpected changes in the availability or pricing

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of raw materials. The inherent volatility and uncertainty in the manufacturing landscape make accurate decision-making and forecasting a significant challenge.

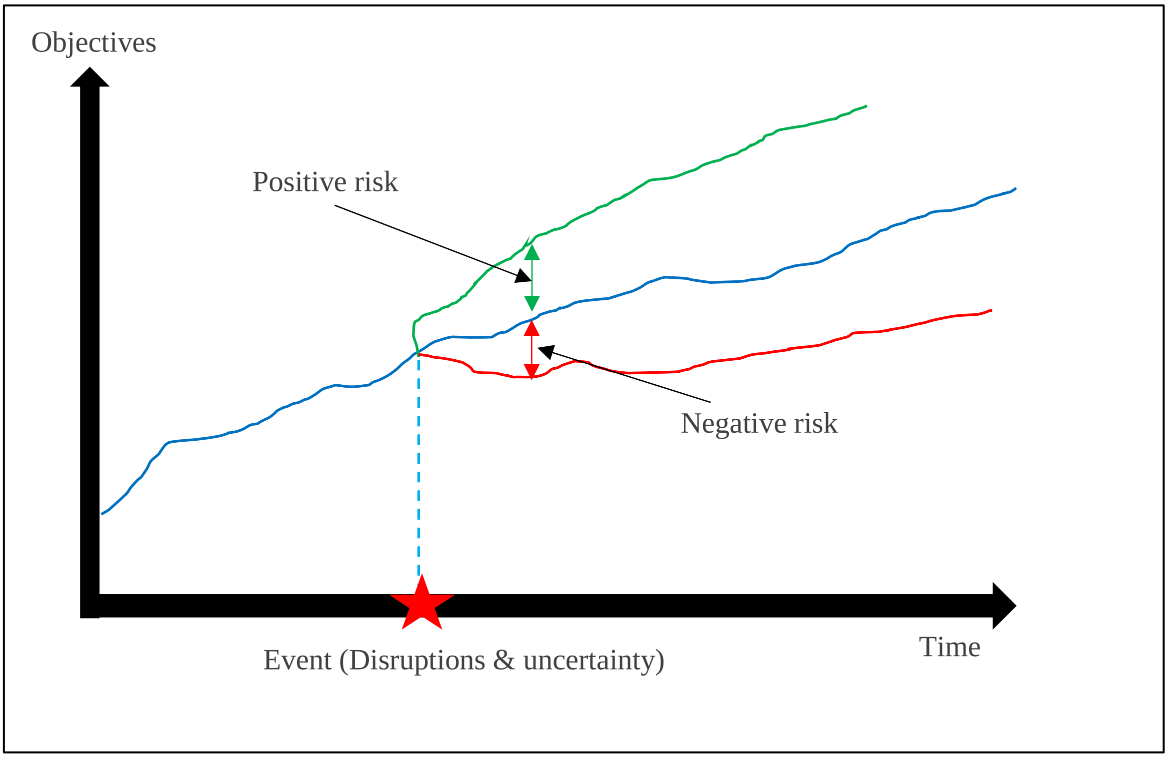

FIGURE 2. DEFINITION OF RISK & DISRUPTION

Manufacturing companies, especially those adopting the MaaS model, face significant risks due to the challenges in predicting key operational parameters. Forecasting demand and the future price and availability of raw materials is complex, influenced by numerous external factors. Additionally, reliance on subcontractors and logistics adds layers of risk, as disruptions in the supply chain can affect production and delivery timelines. The reliability of critical infrastructure, like energy supplies and transportation networks, further compounds these risks. Effectively identifying and mitigating these challenges is essential for maintaining competitiveness and ensuring long-term sustainability [9].

Manufacturing companies might lose their operating level after an unforeseen event. Once an unforeseen event happens, it might influence ***resources, inventory, and information***. Resources include all the equipment, machines, and human resources (internally and externally) that should be used to produce the products and services. The inventory includes the raw materials, components, and consumable resources that must be consumed to produce a product or service in the company. Information includes both raw data and analysed data essential for managing the business. To continue operations, companies need to first estimate the amount of loss in resources, inventory, and information. Then they can resume their critical operations partially with the available resources after an unforeseen event. In the meantime, they must have a plan to recover their operations and return to a normal situation [10].

Manufacturing companies operate with various partners, including suppliers, subcontractors, transportation companies, logistics providers, and retailers. Therefore, any unforeseen events can disrupt operations at multiple levels. By categorizing risks and disruptions as internal or external based on their impact, companies can gain a clearer understanding of the challenges they face. This understanding enables them to implement targeted mitigation strategies and build resilience within their operations. Hence, Risks and disruptions in the manufacturing networks can be categorized based on their impact as internal or external, influenced by unforeseen events (see ***¡Error! No se encuentra el origen de la referencia.***) [11]. ***Internal Risks and Disruptions (IRD)*** refer to disruptions that occur within the manufacturing facility itself, such as operational failures or inefficiencies that halt production. In

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contrast, ***External Risks and Disruptions (ERD)*** arise from disruptions occurring outside the company's facilities, including issues at supplier plants, transportation delays, or interruptions in retail operations. These disruptions, whether internal or external, can significantly impact a company's ability to meet production targets, maintain quality standards, and ensure financial stability. A comprehensive understanding and proactive management of both IRD and ERD are crucial for manufacturing companies to navigate the complex and ever-evolving industry landscape, especially in the context of the MaaS model, where the reliance on external service providers can amplify certain risk exposures [12]. By categorizing and detailing the various risk and disruption, manufacturing companies can develop a comprehensive understanding of the challenges they face, enabling them to implement targeted mitigation strategies and build resilience within their operations [13], particularly in the context of the MaaS model. In the next section, we will introduce the unforeseen events that can lead to these risks and disruptions in the scope of NARRATE project.

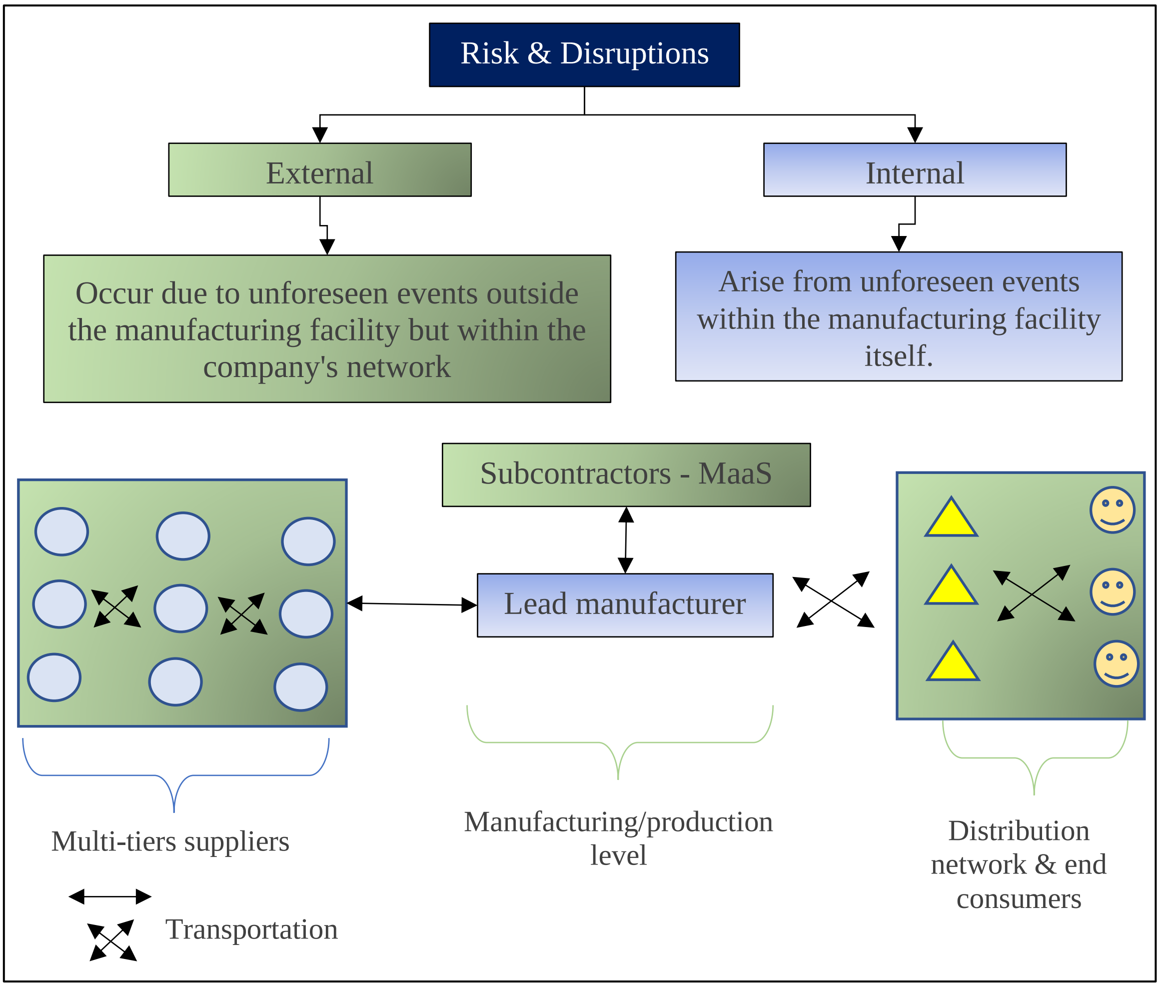

FIGURE 3. RISK AND DISRUPTION CATEGORIES

SECTION 1.2 UNFORESEEN EVENTS

Manufacturing and logistics companies frequently face unforeseen events that disrupt their supply chains, leading to production delays, reduced output, and increased costs, which ultimately hinder their ability to meet customer demand. To address these challenges, manufacturers must enhance resilience across their entire value chain [14]. In the context of SMNs and MaaS, such disruptions can significantly undermine the resilience of all entities within the supply chain, potentially causing broader failures. Both large and small companies are increasingly recognizing the need to evolve their practices to address unforeseen events effectively [15]. Therefore, it is essential to define unforeseen events, classify them, and illustrate their relevance within the scope of our project as outlined in the proposal (see *Figure 4*).

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According to the literature [16][17] and case studies [18][19], ***unforeseen events*** are defined as unexpected occurrences that are not predicted or planned for, often due to their low probability or unprecedented nature. These unforeseen events can arise from a variety of sources, including ***natural disasters*** (e.g., earthquakes, floods), ***human-made crises*** (e.g., geopolitical conflicts), or ***technological*** (e.g., cyberattacks). To fully grasp the ramifications of unforeseen events, it is crucial to investigate the case studies and recognize their profound impact on manufacturing and logistics companies. Disruptions caused by natural disasters, geopolitical events, and pandemics have created significant challenges over the past years, including suppliers struggling to meet demand, shortages of critical parts, shipping delays, rising material and transportation costs, inventory gaps, reduced orders, backlogs of work, and delays or cancellations of deliveries. These risks and disruptions not only hinder production and logistics but also ripple across the entire SMNs, amplifying their consequences. To address these challenges, companies have to prioritize the design of resilience SMNs capable of adapting to frequent value chain changes [20]. Ultimately, resilient supply chains are indispensable for ensuring economic stability and maintaining Europe's technological leadership in an increasingly dynamic global market.

The ***NARRATE project*** uses the development of an Intelligent Manufacturing Custodian (IMC), which is enhanced by the creation of a "digital twin" of a lead manufacturer's SMN and its direct suppliers. This digital twin facilitates support for human experts in decision-making by offering a comprehensive, real-time representation of the supply chain. The IMC integrates advanced AI capabilities with robust models, simulators, decision-making tools, and planning technologies. It utilizes data from diverse sources, including product and production data, supply chain information, and inputs from machines, sensors, IoT devices, and quality monitoring systems. Additionally, it incorporates external data sources such as events, news feeds, the WEF's Global Value Chain Barometer, and information on geographic concentrations of critical supply chains. By acting as a nerve centre for the SMNs, the IMC enables proactive decision-making and provides real-time monitoring and coordination of intelligent production processes and logistics. This integrated approach enhances the resilience and efficiency of supply chain operations, allowing organizations to predict and identify potential unforeseen events that could cause disruptions in production and transportation, and to respond swiftly and effectively to dynamic conditions.

The ***NARRATE*** project focuses on SMNs, comprising a lead manufacturer, first-tier suppliers, warehouses, and logistics providers. Unforeseen events in these networks can arise from various sources, including supply-side issues such as inconsistencies in supply, inferior or scarce materials, and suboptimal choices of suppliers or substitutes; demand-side challenges like sudden demand fluctuations or inaccurate forecasting; logistical problems such as delivery delays and erroneous shipments; and external factors, including natural disasters, geopolitical events, and pandemics (see *Figure 4*). As outlined in the project proposal and in the scope of ***NARRATE*** project, unforeseen events have been classified into the following categories:

- ***Natural Disasters***:

  Unforeseen events like earthquakes, floods, or hurricanes that disrupt manufacturing operations, damage infrastructure, and halt production.

- ***Geopolitical Events***:

  Political tensions, wars, or changes in trade policies that affect global supply chains, causing delays, cost increases, or market instability.

- ***Machine Breakdowns***:

  Unexpected malfunctions or failures of key production machinery, leading to production delays, downtime, and potential loss of output.

- ***Supply Shortage***:

  Disruptions in the supply of raw materials or components, caused by factors like transport issues, market fluctuations, or supplier problems, affecting production schedules.

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- ***Operational Shortage***:

  Insufficient resources, such as workforce shortages or inadequate capacity, that hinder a company's ability to maintain regular operations and meet production targets.

- ***Pandemic***:

  A global health crisis, like COVID-19, that disrupts workforce availability, supply chains, and manufacturing capacity, significantly affecting production and business continuity.

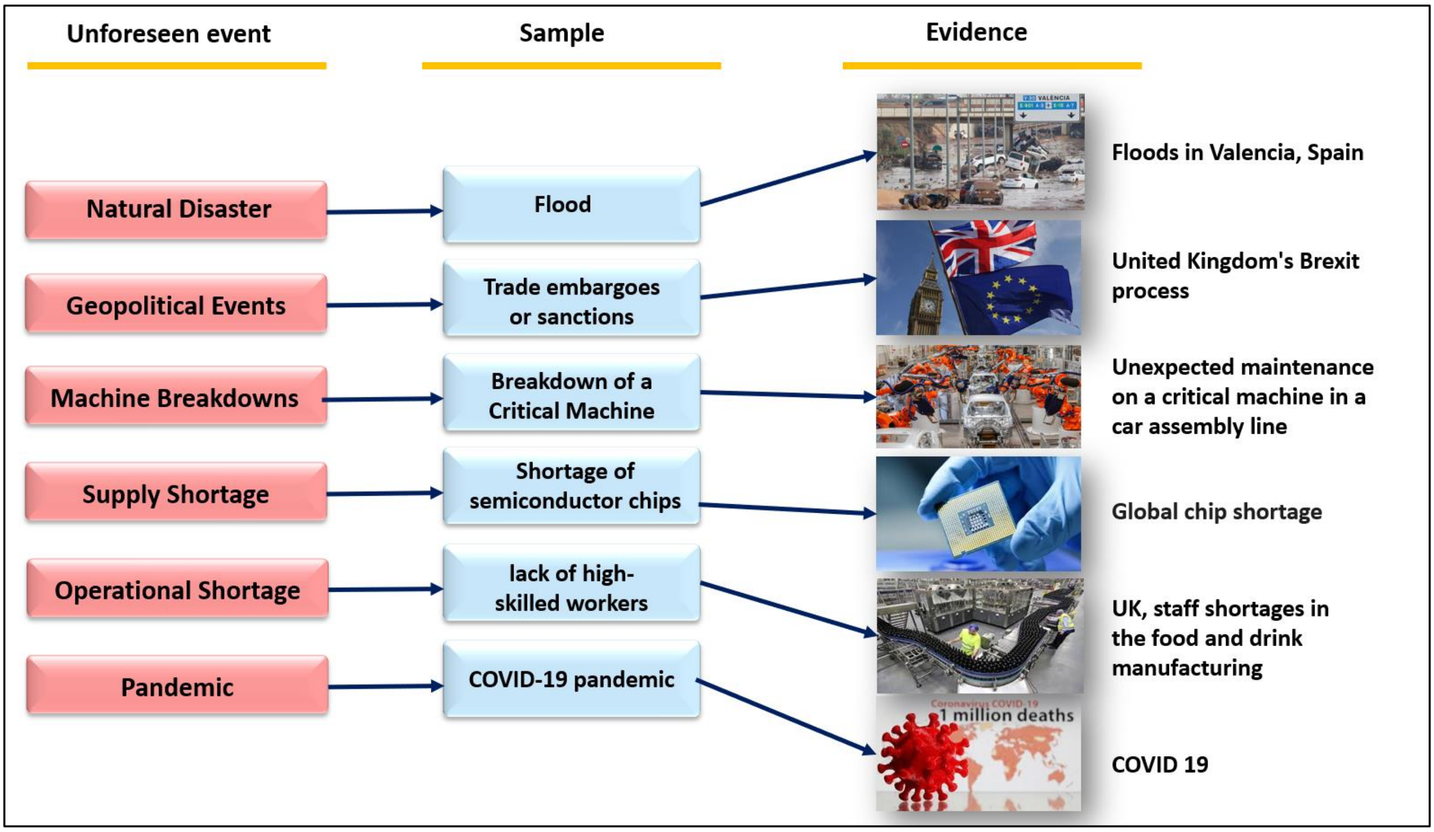

FIGURE 4. UNFORSEEN EVENTS IN SCOPE OF NARRATE PROJECT

SECTION 1.3 INTERNAL RISKS AND DISRUPTIONS

In *Section 1.1 Definition: Risks and Disruptions*, we introduced two categories of risks and disruptions including IRD and ERD. *Section 1.2 Unforeseen events*, focused on unforeseen events as the causes and sources of these risks and disruptions. In this section, we will identify each category in detail, exploring the relationship between unforeseen events and the resulting internal and external risks. Unforeseen events serve as the catalyst for disruptions, manifesting their effects within a company's SMNs as risks and disruption challenges. For example, a geopolitical conflict, such as Russia's invasion of Ukraine, represents an unforeseen event that can lead to significant consequences, such as the loss of a key supplier in Russia. This loss exemplifies how external risks arise from unforeseen events, i.e. geopolitical conflict that is beyond a company's control, ultimately impacting production capabilities and supply chain stability. By examining these relationships, we can better understand how unforeseen events translate into tangible risks and disruptions at different levels through SMNs (such as suppliers, logistics service providers, manufacturing, sub-contractors, distribution network, customers.

The University of Brunel conducted a comprehensive risk and disruption assessment for the manufacturing network in the context of SMNs through a structured multi-step process. First, they reviewed relevant academic literature, reports, and guidelines to compile an initial list of potential IRDs and ERDs. In the next step, the team engaged in multiple rounds of interviews with subject matter experts

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to refine and validate the list. The experts within NARRATE as well as expert from universities such as Newcastle Business School in the UK, Maynooth University School of Business in Ireland and Deakin University in Australia, provided valuable insights, leading to modifications and additions to the initial list. In the third round, the refined list of IRDs and ERDs was circulated among the NARRATE project partners. The partners, mainly the pilot´s partners, provided their feedback, which was incorporated to finalize the comprehensive list facing companies in the manufacturing network. *Table 1* summarizes the IRDs identified through this rigorous assessment process. This detailed understanding of the key risk factors will enable manufacturing companies to develop more effective mitigation strategies and enhance their operational resilience [21].

TABLE 1. INTERNAL RISKS & DISRUPTIONS

IRD	Code	Example of Unforeseen events	Impact	Description	References
Production shortcomings	IRD1	Machine Breakdowns, Operational Shortage	Resources	Various shortcomings or suboptimal practices within the internal operations of the production process, including machine failures that impact the entire production operation	[22][23]
Raw material quality issue	IRD2	Supply Shortage, Geopolitical Events	Inventory	In the warehouse of raw materials within the lead manufacturer	[24][25]
Work-in-process quality issue	IRD3	Machine Breakdowns, Operational Shortage	Inventory	During production in the production shops, along with the production process	[26][27]
workforces related challenges	IRD4	Pandemic, Operational Shortage	Resources	In different departments within the lead manufacturer, particularly in the production shop	[28][29]
Lack of operational capacity	IRD5	Operational Shortage, Machine Breakdowns	Resources	Loss of capacity due to lack of labour, over-estimation of capacity, inefficient scheduling, and delays in the process	[30][31]
MHE shortcomings	IRD6	Machine Breakdowns, Operational Shortage	Resources	Failure of Material Handling Equipment (MHE) such as conveyors and forklifts	[32][33]
Warehousing operations failure	IRD7	Machine Breakdowns, Operational Shortage, Natural Disasters	Resources	Disruptions or breakdowns in the execution of warehouse activities such as equipment breakdowns, inadequate storage capacity, and labour shortages	[34][35]
Information system failure	IRD8	Machine Breakdowns, Operational Shortage	Information	Breakdown of the technology, software, or DSS tools, for example ERP, software glitch, or database corruption	[36][37]

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IRD	Code	Example of Unforeseen events	Impact	Description	References
Unplanned/corrective maintenance of machines	IRD9	Machine Breakdowns, Operational Shortage	Resource	Unexpected breakdowns and immediate repair or servicing outside of the regular maintenance schedule including mechanical failures, electrical problems, or sensor malfunctions	[38][39]
Unplanned/corrective maintenance on information system	IRD10	Machine Breakdowns, Operational Shortage	Information	Unplanned Upgrades or Updates to ISs and DSSs with significant disruptions in the operations including underlying software, databases, or analytical models causing malfunctions, data integrity issues, or unexpected changes in system outputs.	[40][41]
Facility disruptions	IRD11	Natural Disasters, Operational Shortage	Resource/inventory	Facility Disruptions, such as issues with buildings, utilities (water, electricity, gas), or Heating, Ventilation, and Air Conditioning (HVAC) systems with significantly impact operations	[42][43]
Other Production Uncertainty/Micro & real-time Disruption	IRD12	Machine Breakdowns, Operational Shortage, Natural Disasters	All	Unpredictable changes in key production metrics, such as manufacturing time, capacity, machine availability, and material handling duration. These fluctuations can disrupt the intended production schedule, leading to delays, lost output, and increased costs - ultimately impacting an organization's ability to meet customer demand reliably.	[44][45]

SECTION 1.4 EXTERNAL RISKS AND DISRUPTIONS

The Brunel conducted a comprehensive risk and disruption assessment for the manufacturing network through a structured multi-step process. First, they reviewed relevant academic literature, reports, and guidelines to compile an initial list of potential external risks and disruptions. In the next step, the team engaged in multiple rounds of interviews with subject matter (experts within NARRATE as well as expert from universities such as Newcastle Business School, UK, Maynooth University School of Business,

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Ireland, Deakin University, Australia) to refine and validate the list. The experts provided valuable insights, leading to modifications and additions to the initial list. In the third round, the refined list of risks and disruptions was circulated among the NARRATE project partners. The partners provided their feedback, mainly the pilot´s partners, which was incorporated to finalize the comprehensive list of risks and disruptions facing companies in the manufacturing network. *Table 2* summarizes the ERDs identified through this rigorous assessment process. This detailed understanding of the key risk factors will enable manufacturing companies to develop more effective mitigation strategies and enhance their operational resilience.

TABLE 2. EXTERNAL RISKS & DISRUPTIONS

External Risk & Disruptions	Code	Example of Unforeseen events	Impact	Description	References
Market uncertainty (order)	ERD1	Geopolitical Events, Pandemic	Inventory	Changing in preferences/options of the customers/demand size, date, specifications	[46][47]
Cancelled or changed orders (Order rectification and re-adjustment)	ERD2	Geopolitical Events, Pandemic	Inventory	customer changed or cancelled the order on last minute or asking for extra documents or information	[48][49]
Damaged final product during transportation	ERD3	Natural Disasters, Operational Shortage	Inventory	between lead manufacturer and customers	[50][51]
Damaged raw material/component/Consumable resource during transportation	ERD4	Natural Disasters, Operational Shortage	Inventory	between suppliers/subcontractor and lead manufacturer	[52][53]
Damage of raw material/component/Consumable resource in warehouse	ERD5	Natural Disasters, Operational Shortage	Inventory	in warehouse of a logistic companies	[54][55]
Damage of final products in warehouse	ERD6	Natural Disasters, Operational Shortage	Inventory	in warehouse of a logistic companies for last mile delivery	[56][57]
Losing supplier for raw material/component/Consumable resource	ERD7	Supply Shortage, Geopolitical Events	Inventory	Losing a critical supplier with no easy replacement permanently	[58][59]
Shortage of raw material/component/Consumable resource	ERD8	Supply Shortage, Geopolitical Events	Inventory	Lack of raw material and supplies in market for a short period of time	[60][61]
Fluctuation on raw material/component/Consumable resource price	ERD9	Geopolitical Events, Pandemic	Inventory	Changing the cost of raw material seasonality or due to inflation	[62][63]
Cybersecurity threats and data breaches	ERD10	Operational Shortage	Information	Various malicious activities that aim to compromise the	[64][65]

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External Risk & Disruptions	Code	Example of Unforeseen events	Impact	Description	References
				confidentiality, integrity, and availability of digital information[1].	
Regulatory and policy changes	ERD11	Geopolitical Events, Pandemic	Inventory	Government change the trade regulation, carbon footprint certificate for government and customers	[66][67]
Transportation delay for final product	ERD12	Geopolitical Events, Natural Disasters	Inventory	Between lead manufacturer and customers/wholesalers	[68][69]
Transportation delay for raw material/component/Consumable resource	ERD13	Geopolitical Events, Natural Disasters	Inventory	Between suppliers/subcontractor and lead manufacturer	[70][71]

SECTION 1.5 RISKS AND DISRUPTIONS MATRIX

In the NARRATE project, the Brunel team developed the ***Risk and Disruption Matrix*** to systematically record the impacts of unforeseen events on lead manufacturers and their networks. This matrix serves as a crucial tool for companies to document historical data, which is essential for analysing risks and disruptions and implementing a robust resilience framework. Without a clear understanding of past unforeseen events and their impact, companies cannot effectively devise efficient and effective resilience strategies tailored to the specific needs of lead manufacturers at the network level. Importance of Risks and Disruptions matrix tool are:

- ***Enhanced Preparedness***: By understanding past disruptions, companies can better prepare for future incidents, minimizing operational downtime and financial losses.
- ***Data-Driven Decisions***: Historical data empowers organizations to make informed decisions regarding resource allocation and risk mitigation strategies.
- ***Continuous Improvement***: Analysing recorded disruptions allows companies to identify patterns and trends, fostering continuous improvement in their resilience planning.
- ***Stakeholder Confidence:*** A well-documented risk management process enhances transparency and builds trust among stakeholders, including customers, investors, and regulatory bodies.

Risk and Disruption Matrix allows companies to capture not only the occurrence of risks and disruptions but also their severity and impact on various operational facets, including production, transportation, and warehousing. A range of measures has been established to assess the effects of these risks and disruptions, recognizing that the implications can vary significantly between companies based on their unique characteristics and operational contexts. Particularly, the level of access to data and the anticipated resolution strategies must be considered when customizing the Risk and Disruption Matrix. For instance, companies may choose to record the precise quantity of lost sales due to a disruption or categorize the impact using qualitative descriptors such as low, medium, or high. This flexibility enables

[1] These threats can include hacking, malware, phishing, and unauthorized access, leading to the theft or destruction of sensitive data, financial losses, and reputational damage for individuals and organizations.

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organizations to tailor their approach to risk management according to their specific operational realities. *Table 3* summarizes the measures for assessing the impact of risks and disruptions.

Each entry in the Risk and Disruption Matrix includes vital information such as the date of the incident, the individual who recorded it, relevant risk and disruption codes (see *Table 1* and *Table 2* above), a brief description, and the duration of the unforeseen event. This comprehensive documentation not only aids in immediate response efforts but also contributes to long-term strategic planning by fostering a culture of learning and adaptation. The Risk and Disruption Matrix can be found in *Annex I - Risk and Disruptions Matrix*.

TABLE 3. MEASURES FOR RISK AND DISRUPTION MATRIX

Code	Measures	Definition
M1	**Lost-sale**	Represents the revenue that a company was unable to generate due to a disruptive event or disruption in its operations. A higher lost sales value indicates a lower level of resilience, as the company was unable to maintain its sales and revenue during the disruption. This measure shows how effectively a company is able to respond[2] and recover from a risk and disruption.
M2	**Defect Rate**	Defect Rate is a measure for quality KPI used to measure the resilience of a company. It represents the number of defects or errors found in the company's products per a defined unit of output. During a risk and disruption, a company's ability to maintain consistent quality and minimize defects is a crucial aspect of its resilience. A high defect rate can indicate that the company is struggling to uphold its quality standards and adapt its processes effectively in the face of the disruption.
M3	**Customer Satisfaction**	Customer Satisfaction is a measure for analysing quality KPI used to measure the resilience of a company's customer-facing operations and its ability to maintain strong relationships with its customers during risks and disruptions. Customer satisfaction reflects the degree to which a company's products, services, and overall customer experience meet or exceed the expectations of its customers. During a risks and disruptions, a company's ability to continue delivering a satisfactory customer experience is a critical aspect of its resilience.
M4	**Delay (deviation in time)**	Delay is a measure for responsiveness KPI used to measure the resilience of a company's operations and its ability to maintain timely delivery of products or services during risks and disruptions. Delay refers to the time difference between the expected or promised delivery time and the actual time of delivery.
M5	**Resources Cost**	Cost of resources, inventory, and information are measures for cost KPI used to measure the resilience of a company's financial during risks and disruptions. Cost refers to the expenses incurred by the company in maintaining its operations, delivering its products or services, and responding to the disruption. During a risk and disruption, a company may face increased costs due to its Response plan (e.g., reallocation and substitution).
M6	**Inventory Cost**	
M7	**Information Cost**	

[2] Response refers to the resilience strategies at the operational level, including the response plan that is implemented temporarily at an early stage once a disruption occurs.

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CHAPTER 2. RESILIENCE STRATEGIES IN MANUFACTURING INDUSTRIES

SECTION 2.1. RESILIENCE STRATEGIES AND DECISION LEVELS

Resilience strategies in manufacturing companies encompass both ***proactive*** and ***reactive*** plans designed to enhance their ability to withstand, adapt to, and recover from unexpected risks and disruptions. Unforeseen events are defined as unforeseen, high-impact occurrences that can significantly interrupt a company's normal operations, SMNs, or overall business continuity. In contrast, uncertainty challenges arise from the inability to accurately predict or anticipate decision parameters that may profoundly affect a company's operations and performance. Within the scope of the NARRATE project, *Chapter 1. Risks & Disruptions in manufacturing networks* identifies a series of unforeseen events, as well as internal and external risks and disruptions specific to manufacturing companies operating in the context of SMN. As a result of these unforeseen events—whether they manifest as disruptions or uncertainties—companies must develop robust resilience strategies to ensure they can maintain operational continuity and effectively navigate the complexities of modern manufacturing environments. *Chapter 2. Resilience strategies in manufacturing industries* develops Resilience strategies aiming to ensure the continuity of operations, minimize the impact on productivity and output, and maintain the competitiveness of the companies in the face of various ERDs and IRDs, such as SCN interruptions, equipment failures, natural disasters, or regulatory changes [72][73].

Resilience strategies in manufacturing are typically involved with the decision-making process at the strategic, tactical, and operational levels [74]. At the ***Strategic-level***, these may include diversifying the resources, building redundancy in inventory, and aligning organizational structures and processes to support resilience. ***Tactical-level*** strategies may focus on inventory management, transportation optimization, and incident response planning. ***Operational-level*** resilience strategies may involve enhancing production flexibility, implementing predictive maintenance, and fostering a culture of continuous improvement and adaptability within the manufacturing companies. By adopting a multi-level resilience strategy that encompasses the decision-making process at the strategic, tactical, and operational levels, manufacturing companies can achieve both ***system resilience*** and ***operational resilience***. This enhances their ability to anticipate, respond to, and recover from disruptions, thereby maintaining their competitive edge and ensuring long-term sustainability [75].

The Brunel team in the NARRATE project emphasizes the importance of developing resilience strategies at both the system and operational levels for manufacturing companies. These strategies must be established, tested, and refined during normal operations, prior to any unforeseen events that could lead to risks and disruptions within the manufacturing network. System-level resilience strategies focus on strategic decisions, such as securing additional resources like manufacturing equipment and forming horizontal alliances to ensure production continuity. Operational-level strategies pertain to daily decision-making processes, including production re-planning and raw material substitution in response to shortages [76], [77], [78]. Both sets of strategies are essential; companies must be trained to implement them effectively before a real unforeseen event occurs. This proactive approach not only enhances the resilience maturity of the organization but also ensures that critical operations can continue seamlessly during disruptions. While system-level strategies are permanent and foundational, operational strategies are adaptable and activated in response to specific risk and disruption, allowing companies to return to normal operations once stability is restored [79].

To better understand the fundamentals of the resilience framework being developed by the Brunel team in the NARRATE project for SMNs, *Figure 5* illustrates how resilience strategies should be developed and implemented for lead manufacturers in SMN. At the outset of implementing our framework, companies must develop, examine, and improve their operations and SMN design based on resilience strategies at both the system and operational levels. Under resilience strategies at the system level, our model may

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recommend adding an additional supplier for a critical raw material or purchasing a new machine to increase flexibility in the manufacturing shop. However, allocating orders to a new supplier might raise supply costs, as companies may need to split orders between two suppliers, resulting in a loss of bulk discounts. Similarly, purchasing and installing a new machine incurs costs for both acquisition and setup. Additionally, under resilience strategies at the operational level, our model may advise substituting a raw material with an alternative, which could also lead to increased costs or extended production times or re-planning production processes. Indeed, these recommendations, rooted in resilience strategies at both levels, drive a new design and planning approach for the company and its SMNs, which we refer to as ***Predictive Planning & Configuration***. While this predictive planning may increase costs, it simultaneously enhances the company's resilience.

We define two situations: ***Situation 1***, where no unforeseen event occurs, and ***Situation 2,*** where an unforeseen event does happen. Now, let's examine what could happen under the two situations. In Situation 1, where no unforeseen events occur, the company incurs additional costs due to the resilience design and planning. Conversely, in Situation 2, when an unforeseen event leads to risks and disruptions within the company's network, the company can continue operations with minimal losses and quickly return to normalcy, thanks to the ***predictive planning & configuration*** in place [80] [81]. It is worth noting that those companies that use robust planning based on the predictive planning & configuration can cut the negative impact of the unforeseen event rather than those companies that don't consider uncertainty in their planning and configuration during normal situations. This raises the question of how companies can trade-off these two situations, weighing resilience costs against risks. In the NARRATE project, we will develop models to help companies navigate the trade-offs between the costs and benefits of resilience, tailored to their specific risk appetite.

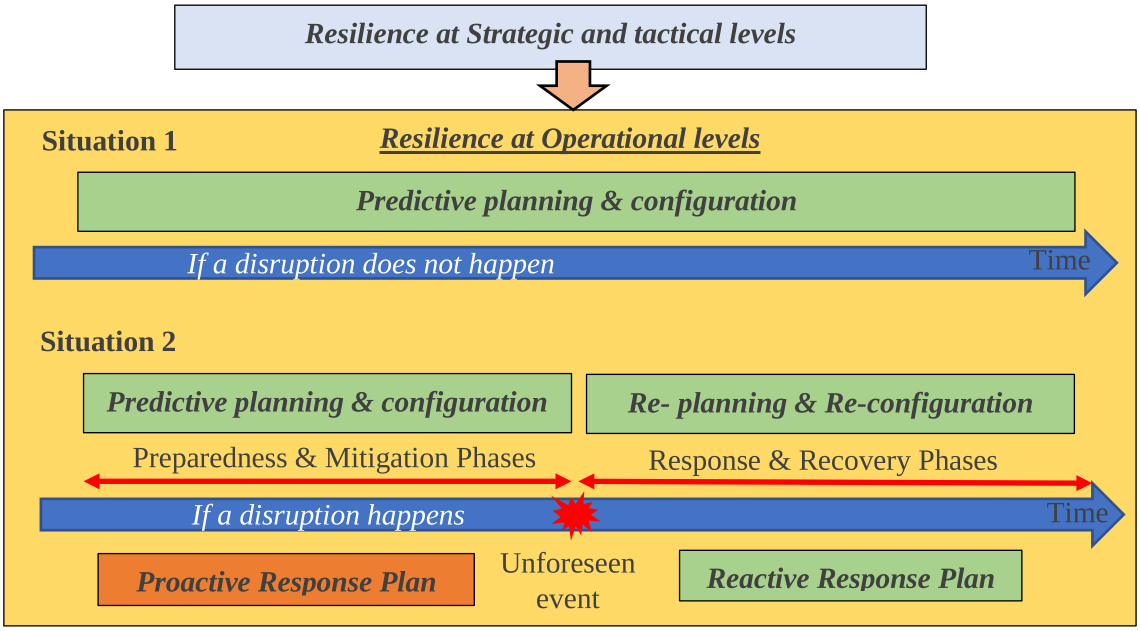

FIGURE 5. PREDICTIVE PLANNING & CONFIGURATION

SECTION 2.2. RESILIENCE STRATEGIES AT SYSTEM LEVEL

This section summarizes resilience strategies for the explored IRDs and ERDs in Task T2.1 (See *Chapter 1. Risks & Disruptions in manufacturing networks*). These strategies are intended to be general and adaptable to different companies with different products and sizes, so that companies of different sizes and specifications can apply them as needed based on their unique circumstances and requirements.

Resilience strategies can be defined and applied at the system level within manufacturing companies. Companies can utilize these strategies at both the strategic and tactical levels of decision-making.

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Generally, strategic decisions are considered long-term, often spanning 3 years or more, while tactical decisions are medium-term, typically developed for a 6-month horizon. However, the specific length of strategic and tactical decisions can vary depending on various internal factors, such as the size of the company, as well as external circumstances, like market stability. It is important to note that implementing resilience strategies for strategic and tactical planning may increase the overall cost for companies (see *Section 2.1. Resilience strategies and decision levels*). However, this investment is necessary, as without incorporating resilience strategies at the strategic and tactical decision levels, companies will be unable to effectively leverage them at the operational level. Even if resilience strategies are applied at the operational level, the cost and time required to return to normal operations in the face of disruptions will be significantly higher, leading to increased losses due to a lack of resilience [82].

A key question facing many companies is what level of resilience they should target when making strategic and tactical decisions. While there is no simple answer, companies must carefully weigh the costs and benefits of building resilience. The appropriate level of resilience can vary significantly between companies, depending on the nature of their business, risk appetite, size, product portfolio, market dynamics, supply chain situation, and financial circumstances. However, achieving full resilience in a single step is generally not a realistic or advisable approach. Building a resilient company is instead a combination of radical and continuous improvement efforts. *Table 4* presents a range of resilience strategies at system level that manufacturing companies can deploy across their strategic and tactical decision-making to enhance system-level resilience.

TABLE 4. RESILIENCE STRATEGIES AT SYSTEM LEVEL

Resilience strategy	Definition	References
Diversification	Diversification refers to the strategy of expanding the range of resources, inventory, or information sources available to a company, reducing its dependence on any single source	[83][84]
Visibility	Visibility is the ability to access and share information across the company and its value chain, enabling better sensing and anticipation of unforeseen events that could impact the company's resources, inventory, and information flows.	[85][86]
Flexibility	Flexibility is the capacity to rapidly adapt and reconfigure a company's resources, inventory, and information systems in response to changing conditions or unforeseen events.	[87][88]
Redundancy	Redundancy refers to the intentional duplication or backup of inventory, resources, and information, ensuring that the company can maintain essential functions even in the face of disruptions.	[89][90]

Here are examples of the resilience strategies at strategic and tactical decision levels:

1. ***Diversification***:
   - ***At the strategic level***, this may involve diversifying the supplier base, expanding into new markets, or developing a diverse product portfolio.
   - ***At the tactical level***, diversification could manifest as maintaining multiple transportation modes or distribution channels.
2. ***Visibility***:
   - ***At the strategic level***, this could involve collaborating with SCN partners to enhance data-sharing and joint planning.
   - ***At the tactical level***, visibility may be achieved through the implementation of tracking systems and real-time monitoring of operations.
3. ***Flexibility***:
   - ***At the strategic level***, flexibility can be demonstrated through the adoption of modular product designs or the ability to pivot to new markets. For example, develop modular product designs, establish agile sourcing and procurement processes, or explore and adopt more flexible manufacturing technologies.

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- ***At the tactical level***, flexibility may involve the use of versatile production equipment or the ability to reroute transportation in response to disruptions. For example, Implement flexible production scheduling or Foster close collaboration with backup suppliers.

4. ***Redundancy***:
   - ***At the strategic level***, this may involve maintaining multiple suppliers or production facilities. For example, identify and qualify multiple backup suppliers, maintain backup supply agreements, or build strategic inventory buffers of the critical materials/components/consumables.
   - ***At the tactical level***, redundancy could manifest as the stockpiling of safety inventory or the availability of backup power sources. For example, implement supplier monitoring and early warning systems, develop contingency production plans, or maintain the ability to quickly reallocate production capacity.

SECTION 2.2. RESILIENCE STRATEGIES AT OPERATIONAL LEVEL

While resilience strategies at the system level focus on design-related decisions—such as network configuration, facility location, and capacity planning—resilience strategies at the operational level consist of response plans that enable companies to first resume their critical operations and subsequently recover their full operational capabilities. Examples of these operational-level strategies include re-planning production schedules to accommodate disruptions, substituting raw materials when shortages occur, and reallocating resources to prioritize critical tasks. These proactive measures ensure that companies can quickly adapt to unforeseen events and maintain continuity in their operations. Once a risk and disruption occur, companies may lose a portion of their resources, inventory, and information.

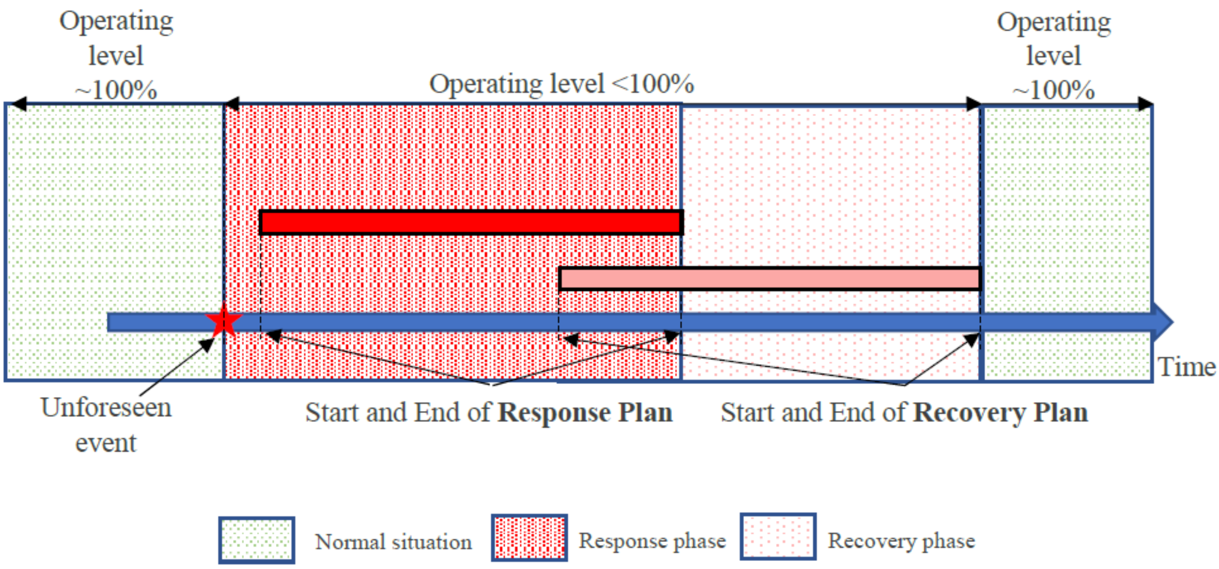

FIGURE 6. RESILIENCE PHASES

As a result, they cannot continue their operations at 100% operational capacity. They need to implement a ***Response Plan*** to resume operations. Resuming operations means continuing the business with the remaining resources, inventory, and information at a minimum acceptable level. Then, they can start the ***Recovery plan*** to return to 100% of their operating capacity. As shown in *Figure 6,* the post-disruptive phase can be divided into two phases: ***Response phase*** and ***Recovery phase***. The Brunel Team at the NARRATE project aims to develop ***Conventional Response Plans*** that help companies resume operations immediately after a risk and disruption occurs. It is worth emphasizing that the applicability and success of these operational-level resilience strategies strongly depend on the development of resilience at the system level. If a company incorporates resilience strategies at the strategic and tactical levels into their decision-making process, they can expect to implement these operational strategies successfully [91].

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Four operational resilience strategies have been defined based on the scope of the NARRATE project. We considered the nature of the manufacturing industries and the context of MaaS to develop these ***Response Plans***. Different research and studies have demonstrated the effectiveness of these strategies within the scope of the NARRATE project. However, various factors impact the usefulness of these strategies in the NARRATE pilots for example, the nature of the process and technological level of manufacturing operations. At least two dimensions must be considered to select and implement these strategies: resilience and sustainability KPIs. To this end, companies need a ***Decision Support System*** (DSS) to address the effectiveness and efficiency of these strategies once a disruption occurs (WP4). Indeed, the NARRATE's DSSs can provide a list of efficient decisions by trading off among multiple resilience and sustainability KPIs. This allows the company's decision-makers to select the most appropriate option. *Table 5* reports the list of resilience strategies at operational level [92].

TABLE 5. RESILIENCE STRATEGIES AT OPERATIONAL LEVEL

Strategies	Definition	References
Reallocation	Reallocation is an operational resilience strategy that involves the redistribution or reassignment of resources, such as personnel, equipment, or inventory, in response to a risk and disruption. The goal of reallocation is to optimize the utilization of available resources, inventory, and information to maintain critical operations and minimize the impact of the disruption.	[93][94]
Substitution	Substitution is an operational resilience strategy that involves the replacement or substitution of resources, processes, or products in response to a risk and disruption. The goal of substitution is to maintain critical operations by finding alternative solutions that can fulfil the same or similar functions as the disrupted resources or processes.	[95][96]
Procurement	Procurement is an operational resilience strategy that involves the acquisition of resources, materials, or services to maintain or restore critical operations in response to a risk and disruption. The goal of the Procurement strategy is to ensure the availability of necessary resources and supplies to sustain or resume business activities.	[97][98]
Outsource (MaaS)	Outsourcing is an operational resilience strategy that involves the delegation or transfer of specific business functions or processes to external service providers or third-party organizations in response to a risk and disruption. The goal of the Outsourcing strategy is to leverage the capabilities and resources of external partners to maintain or restore critical operations when internal resources are disrupted or insufficient.	[99][100]

Under each resilience strategy at operational level, companies need to take a series of reactions (response plans) to resume their operations. These reactions depend on the nature of the Risks and Disruptions (e.g., internal or external) as well as the circumstances of the company (e.g., size and the company's maturity regarding resilience). The Brunel team in the NARRATE project has provided examples of response plans in *Table 6* based on each operational-level resilience strategy. These response plans outline the specific actions companies can take to implement the respective strategies and maintain critical operations in the face of risks and disruptions.

TABLE 6. EXAMPLES OF RESILIENCE RESPONSE PLAN FOR RISKS AND DISRUPTIONS

Resilience strategies	Response plan	Description	R&D
Reallocation	Inventory Diversion and Reallocation	Use of redundant inventory stored in warehouses until fixing the machine	IRD1
Substitution	Changing the machine, line, process	Rapidly shift production to alternative (available) machines or manufacturing lines	IRD1
Reallocation	Temporary Production Workarounds	Manually operating equipment or using simpler production methods	IRD1
MaaS	Outsource to a subcontractor	Using MaaS to outsource component production to a subcontractor	IRD1
Reallocation	Inventory Diversion and Reallocation	Changing the affected batches or sources to alternate batch or sources	IRD2

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Resilience strategies	Response plan	Description	R&D
Substitution	Temporary Material Substitution	if feasible, using substitution of raw material/consumable resources/components temporary	IRD2
Procurement	Expedited Raw Material Procurement	If possible, procure the raw material/consumable resource/components from alternative suppliers, market, or sources	IRD2
Reallocation	Production Rework and Repair	Allocating the affected work-in-process inventory to dedicated rework stations equipped with the necessary tools and equipment	IRD3
Reallocation	Workforce Reallocation and Reassignment	temporary job rotations, overtime, or the utilization of cross-trained employees for critical production jobs	IRD4
Reallocation	Temporary Staff Outsourcing	Quickly supplement the workforce during peak demand or labour shortages	IRD4
MaaS	Outsourcing and Subcontracting	Using MaaS to supplement capacity during periods of high demand or constraints	IRD5
Reallocation	Real-time Production Rescheduling and Reassignment	Implement agile production rescheduling and job reassignment processes to mitigate the impact of capacity constraints or disruptions	IRD5
Reallocation	Replacing MHE	Can include leasing or contracting with third-party MHE providers for temporary use	IRD6
Substitution	Alternative Material Handling Methods	Use alternative MH method such as manual handling or temporary conveyor systems	IRD6
Reallocation	Inventory Redistribution	Quickly redistribute inventory from the affected warehouse to alternative storage locations, such as other warehouses, distribution centres, or temporary storage spaces	IRD7
Reallocation	Expedited Shipments from temporary warehouse or sources	Prioritize and expedite the delivery of critical raw material/component/consumable resources/final product from alternative sources or locations to mitigate the impact of the warehouse disruption	IRD7
Reallocation	Job rotation to support warehouse	Cross-train warehouse personnel to perform a variety of tasks, enabling them to support other operations in warehouse	IRD7
Reallocation	Alternate Information Access and Manual Workarounds	Use alternate information sources, backup data, and paper-based information in the event of a prolonged failure or disruption of the primary IS or DSS	IRD8/IRD10
Substitution	Switching to the alternate and backup sources	Alternative water sources or backup power generation capabilities	IRD11
Reallocation	Relocating the critical operations	Relocating their production operations to an alternative facility or their own existing manufacturing sites in different regions	IRD11
MaaS	Outsourcing and Manufacturing-as-a-Service	Outsourcing their production operations to third-party manufacturers or leveraging MaaS providers	IRD11
Reallocation	Dynamic adjustments, planning, and scheduling	Rearrange the production sequence to optimize the utilization of available resources and updating the lead time of orders	IRD12
Reallocation	Overtime production to maintain production capacity	Leverage overtime work from their existing resources to increase production capacity and make up for the lost output	IRD12

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Resilience strategies	Response plan	Description	R&D
Reallocation	Rescheduling the production and master production schedule	Assess the impact of the order change and update the Master Production Schedule, production plan and schedule	ERD1/ERD2
Procurement	Updating the procurement plan from suppliers	Re-plan the procurement based on the updated MPS, production plan and schedule	ERD1/ERD2
Reallocation	Dispatch replacement	Arrange to deliver a new product quickly from their safety stock or strategic inventory	ERD3/ERD6
Reallocation	Updating production plan for reproduction or rework	update the production plan for rework (if possible) or reproduction of the damaged products	ERD3/ERD6
Procurement	Place a new order with another supplier or subcontractor	Place a new order quickly to the next available supplier or subcontractor	ERD4/ERD5 /ERD8/ERD9
Reallocation	Use the safety stock of raw material/components/consumable resources	Request the supplier or subcontractor to resend the order; and b) utilize the company's own inventory resources.	ERD4/ERD5 ERD8/ERD9
Reallocation	Update production plan, master production schedule, and production scheduling	Must update the Master Production Schedule (MPS), production plan, and production schedule	ERD4/ERD5 ERD8/ERD9
Substitution	Replace the supplies with alternative items	Replace the damaged supplies with alternative raw materials/components/consumable resources	ERD4/ERD5/ ERD8/ERD9
Substitution	Switching to offline systems and using backup Data	Use the backup data and offline systems to continue their operations	ERD10
Reallocation	Regulatory and Policy-Driven Operational Resilience	Adapt and align the company's operations and supply chain management to comply with new regulations and policies	ERD11

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CHAPTER 3. RESILIENCE KPIs

Resilience KPIs reflect the status and capability of a manufacturing company to respond to risks and disruptions. These measures not only help us understand the impact of risks and disruptions on the operations of the network (including production, transportation, and warehousing) but also assist in developing efficient resilience response plans for the manufacturing company and its network. Rather than focusing solely on KPIs, it is essential to evaluate the company's maturity in terms of resilience. Resilience maturity refers to the extent to which a company has developed the capabilities and strategies necessary to mitigate, respond to, and recover from risks and disruptions. In the context of supply chain, a mature resilience framework enables companies to navigate future uncertainties effectively. Companies with high resilience maturity can quickly adapt to changes in demand, supply chain disruptions, and unforeseen events, thereby minimizing operational downtime and financial losses. Evaluating resilience maturity is crucial for identifying areas of improvement and ensuring that the organization is prepared well for potential risks and disruptions.

In this chapter, we will first provide definitions and terminology related to KPIs. Next, we will define the specific resilience KPIs relevant to manufacturing companies. Finally, we will present a series of measures, tools, and charts that can be used to evaluate the resilience maturity of companies and their networks.

SECTION 3.1 RESILIENCE KPIs: DEFINITION AND TERMINOLOGY

In the dynamic and competitive landscape of the manufacturing networks, companies are constantly seeking ways to measure, monitor, and improve their operational efficiency and effectiveness. This is where KPIs play a crucial role. KPIs are quantifiable metrics that help companies track their progress towards specific goals and objectives, enabling them to make data-driven decisions and drive continuous improvement. KPIs are defined as measurable values that demonstrate the effectiveness and efficiency of a company in achieving its ***key business objectives***. They provide a clear and concise way to evaluate the performance of various aspects of a manufacturing operation, from production output and quality to supply chain responsiveness and environmental impact [101]. Measuring KPIs is essential for manufacturing companies for several reasons such as:

- ***Alignment with Objectives***: KPIs help companies align their day-to-day operations with their strategic goals and objectives. By establishing clear performance targets, organizations can ensure that their resources and efforts are focused on the most critical areas [102].
- ***Performance Monitoring***: KPIs enable companies to continuously monitor their performance, identify areas for improvement, and track the impact of their initiatives. This allows them to make timely adjustments and course corrections to maintain a competitive edge [103].
- ***Decision-making***: KPIs provide manufacturing companies with data-driven insights, empowering them to make informed decisions that optimize operational efficiency, quality, and profitability [104].
- ***Accountability and Transparency***: KPIs foster accountability by clearly defining expectations and performance standards. They also enhance transparency, allowing organizations to communicate their progress and achievements to stakeholders, customers, and employees [105].

Therefore, KPIs are essential for achieving operational excellence and meeting the evolving demands of the market. By using well-defined KPIs, companies can:

- ***Improve Productivity***: KPIs help manufacturers identify and address bottlenecks, optimize critical assets including (***resource***, ***inventory***, and ***information***) utilization, and streamline production processes, leading to increased productivity and output. For example, a leading automotive manufacturer uses Overall Equipment Effectiveness (OEE) as a key productivity KPI, which measures the percentage of planned production time that is truly productive [106].
- ***Enhance Quality***: KPIs focused on quality metrics, such as defect rates and customer satisfaction, enable manufacturers to identify and address quality issues, ensuring that their products meet or

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exceed customer expectations. Major electronics company closely monitors its First Pass Yield KPI, which measures the percentage of units that pass inspection on the first attempt, to maintain its reputation for high-quality products [107].

- ***Strengthen Company Resilience***: KPIs related to companies' responsiveness, inventory management, and delivery performance help manufacturers anticipate and mitigate disruptions, ensuring the timely availability of materials and the reliable fulfilment of customer orders. For example, a global consumer goods manufacturer uses its On-Time In-Full (OTIF) delivery rate as a key supply chain KPI, tracking the percentage of orders delivered to customers on time and in the correct quantity [108].
- ***Foster Continuous Improvement***: KPIs provide a structured approach to identifying opportunities for improvement, driving innovation, and implementing lean manufacturing principles to enhance overall operational efficiency. A pharmaceutical manufacturer, for example, closely monitors its Changeover Time KPI, which measures the time it takes to transition between production runs, to optimize its flexible manufacturing capabilities [109].

However, defining appropriate KPIs is not an easy task for manufacturing industries. This is because it depends on the complexity and nature of the companies. It is worth emphasizing that the long experience of the Brunel team shows that data collection is the biggest challenge for evaluating the performance of companies. *Table 7* reports main dimensions of KPIs for manufacturing companies. Therefore, companies need to formulate their KPIs at a level where they can collect the necessary data. To be truly effective, KPIs must possess the following characteristics:

- ***Measurable***: KPIs should be quantifiable, allowing for objective measurement and comparison over time.
- ***Aligned with Objectives***: KPIs should be directly linked to the organization's strategic goals and priorities, ensuring that they drive the desired outcomes.
- ***Actionable***: KPIs should provide clear and actionable insights, enabling manufacturers to make informed decisions and take appropriate corrective actions.
- ***Balanced***: A well-rounded KPI framework should encompass various aspects of manufacturing performance, including cost, quality, responsiveness, flexibility, social impact, and environmental sustainability.

By categorizing KPIs in this manner, manufacturing companies can develop a comprehensive and balanced performance measurement system that addresses all critical aspects of their business.

TABLE 7. DIMENSIONS OF KPIs

Dimension of KPI	Definition	Examples of measures
Cost	These KPIs focus on measuring and optimizing the financial aspects of manufacturing, such as production costs, inventory carrying costs, and energy consumption.	Cost per unit, material cost per unit, energy cost per unit
Quality	These KPIs assess the conformance of products to established standards and customer requirements, ensuring consistent quality and customer satisfaction.	Defect rate, first-pass yield, customer satisfaction score
Speed (time)	These KPIs evaluate the agility and responsiveness of the manufacturing operation, including order fulfilment, delivery performance, and supply chain time.	On-time delivery rate, lead time, inventory turnover
Quantity	These KPIs measure the ability of the manufacturing system to adapt to market demands, product mix, and production volumes.	Production changeover time, equipment utilization, production capacity utilization,
Social	These KPIs assess the impact of manufacturing operations on the well-being of employees, local communities, and society as a whole.	Employee satisfaction, safety incident rate, community engagement
Environmental	These KPIs focus on the environmental impact of manufacturing activities, including resource consumption, waste generation, and emissions.	Energy efficiency, water consumption, waste recycling rate

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SECTION 3.2 RESILIENCE KPIs

Manufacturing companies may experience a loss in their operating levels following a risk or disruption. When an unforeseen event occurs, it can significantly impact critical assets such as resources, inventory, and information. To continue operations, companies must first estimate the extent of the loss in critical assets for each operation within the SMN, which includes production, transportation, and warehousing. After assessing this loss, they can partially resume critical operations using the available assets. To achieve this, companies need an effective and efficient resilience response plan (see *Section 2.2. Resilience strategies at system level* and ***¡Error! No se encuentra el origen de la referencia.***). Additionally, a recovery plan is essential for restoring operations and returning to normalcy. *Figure 7* illustrates the impact of an unforeseen event on the operating level of manufacturing companies. The area representing the loss of resilience is determined by the loss of operating level and the duration required to resume and restore operations. In resilience literature, estimating the resilience of a company involves quantifying the "red area" in *Figure 7*. The loss of resilience is a function of the loss of operating level (L) and the duration of the disruption (T), as shown in Equation (1):

$$Loss\ of\ Resilience\ \propto\ f(L,T) \qquad (1)$$

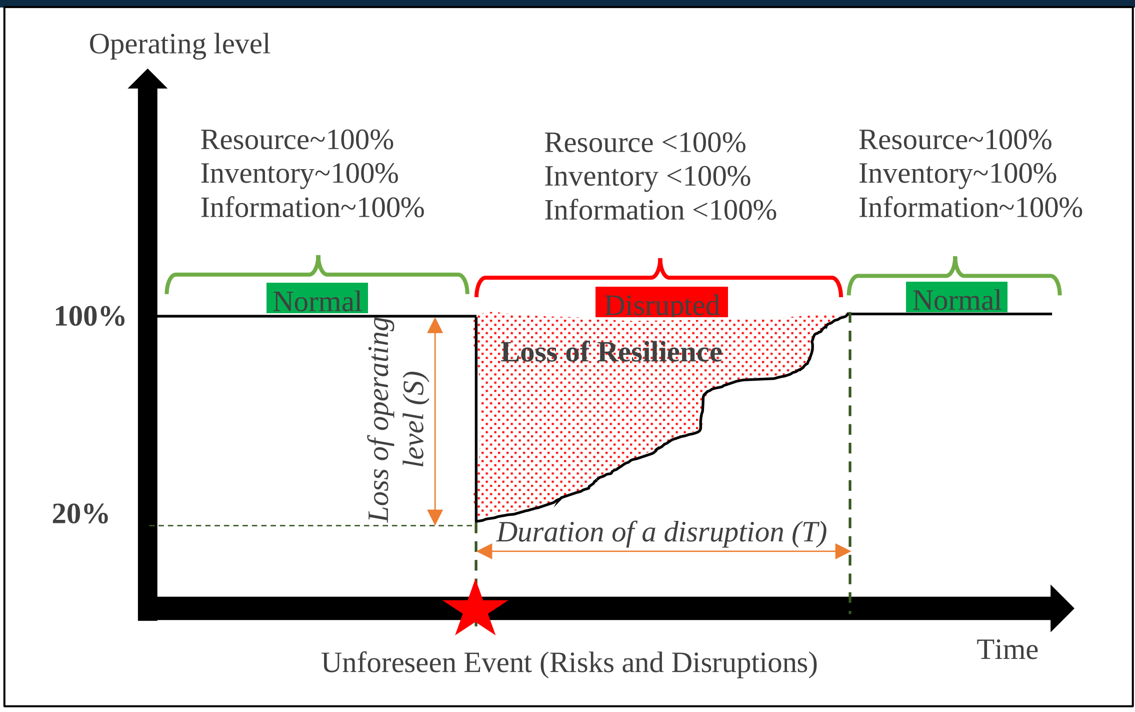

FIGURE 7. LOSS OF RESILIENCY

Assuming a risk or disruption occurs, the loss of critical assets for an operation will lead to a decreased operating level. Without sufficient resources, the company cannot maintain 100% operational capacity, and it takes time to resume normal operations. Thus, the loss of resilience is related to the loss of critical assets, as expressed in Equation (2):

$$Loss\ of\ Resilience\ \propto\ f(L,T) \propto\ f(\Delta I, \Delta R, \Delta D) \qquad (2)$$

where

- ΔI: Total amount of lost inventory
- ΔR: Total amount of lost resources
- ΔD: Total amount of lost information

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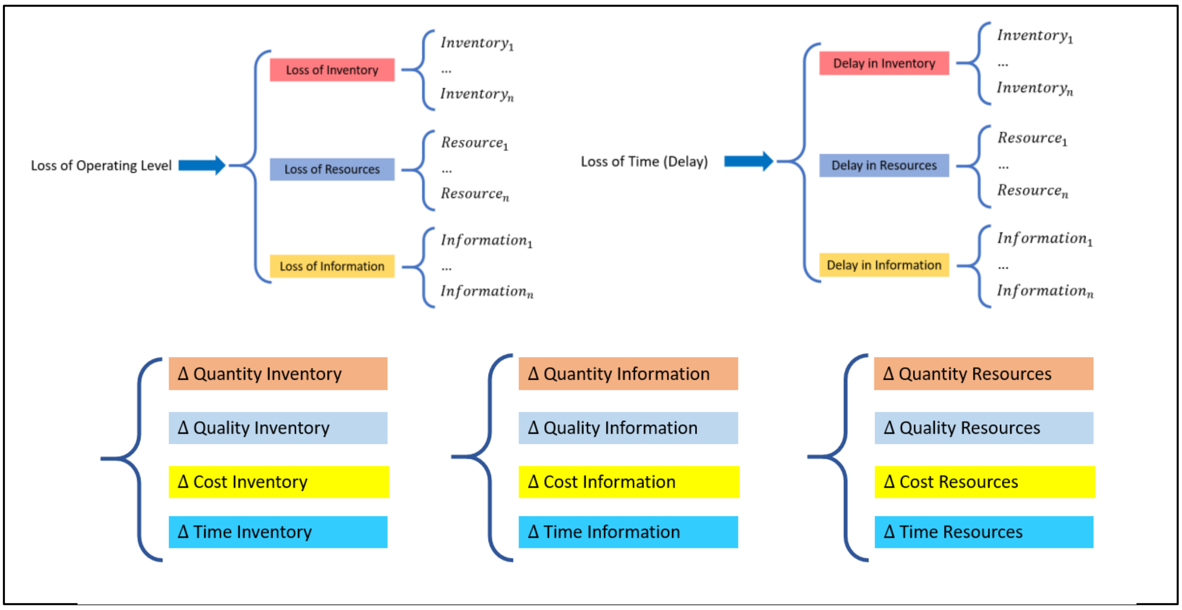

FIGURE 8. DIAGRAM OF RESILIENCE KPIs

Calculating the exact loss of operating level and the duration of a risk or disruption is challenging due to the influence of various factors. However, to maintain and ensure operational continuity, it is vital to secure the critical assets of the company, both within the manufacturing plant and across the entire supply chain network. To define the resilience KPIs, we have formulated them based on four dimensions: ***cost***, ***quantity***, ***quality***, and ***time*** (see *Figure 8*). The three critical assets for any company include:

- ***Resources***: This encompasses machines, equipment, human resources, and consumable resources like electricity and gas.
- ***Inventory***: This includes finished products, work-in-process items, and raw materials.
- ***Information***: This covers design maps, customer and supplier information, production planning, product specifications, and inventory stacks in the warehouse.

Any deviation or loss in these assets will reduce the operating level, causing the company to deviate from its operational goals. By utilizing these measures, companies can gain a clearer understanding of their losses and make informed decisions to enhance resilience. *Table 8* summarises the resilience KPIs.

TABLE 8. RESILIENCE KPIS

	Resilience KPIs			
Critical assets	Time (delay)	Cost	Quantity	Quality
Inventory	ΔI^t	ΔI^c	ΔI^q	ΔI^s
Resources	ΔR^t	ΔR^c	ΔR^q	ΔR^s
Information	ΔD^t	ΔD^c	ΔD^q	ΔD^s

The NARRATE platform utilizes the concept of "blueprints," a widely adopted approach in modular software development, to design various components and modules. This methodology ensures that different elements within NARRATE function seamlessly across its internal tools and modules. As illustrated in *Figure 9* below, the NARRATE platform incorporates seven blueprints. These blueprints play a crucial role in establishing efficient and well-structured resilience KPIs at the operational level for NARRATE users. To calculate the resilience KPIs presented in *Table 8* above, we have developed 12 proposed resilience KPIs for each operation, including production, transportation, and warehousing, which are detailed in *ANNEX II – Resilience KPIs.*

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

Supplier/Lead MfG Blueprint
- Company Background
- Products / Services
- People/skills
- Key Processes
- Capabilities & Capacity

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

Logistics Services Blueprint
- Transportation routes
- Carriers
- Modes of transportation
- Route Planning
- Tracking of shipments
- Transit Times
- Environmental Info.

Warehousing Services Blueprint
- receiving,
- storing,
- picking,
- packing,
- shipping of products

Quality Assurance Blueprint
- Inspection criteria
- Quality assurance protocols
- Production/Performance KPIs
- Rate of Production Capacity & Work in Progress

Regulatory Compliance Blueprint
- industry standards,
- safety regulations,
- environmental regulations,
- product certifications

FIGURE 9. BLUEPRINTS OF THE NARRATE PLATFORM

SECTION 3.2 RESILIENCE MATURITY AUDITING

This section defines the resilience measures at the system level, which encompass metrics reflecting the company's effectiveness in adopting resilience strategies. As discussed in0 *Section 2.2. Resilience strategies at system level*, four key resilience strategies have been identified at the system level—***diversification***, ***flexibility***, ***visibility***, and ***redundancy*** (see *Figure 10*)—to enhance resilience at both strategic and tactical levels. On the other side, as highlighted in ***¡Error! No se encuentra el origen de la referencia.***, manufacturing companies may experience a reduction in operational capacity following risks and disruptions, impacting Critical Assets (including resources, inventory, and information). To maintain operations within SMNs, all partners must have access to sufficient resources, inventory, and information. In keeping with the generality of our model, we also identify three key operations for a lead manufacturing company in the context of SMNs: production, transportation, and warehousing. Companies must ensure the continuity of these three operations to enhance the resilience of their SMNs. As illustrated in *Figure 11*, by analysing the critical assets for operations within SMNs, companies can

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evaluate their resilience maturity. Consequently, the four metrics derived from the resilience strategies at system level, combined with the Critical Assets and operations, give a total of 36 measures for analysing the maturity of a manufacturing company and its SMNs. The Brunel team has prepared a ***Maturity Analysis Questionnaire*** to assess companies' readiness in terms of resilience at the system level (see *ANNEX III – Resilience Maturity Auditing).* As shown in *Figure 12* and *Figure 13*, we recommend using radar charts to represent the maturity of a company and its SMN in terms of resilience. The radar chart not only illustrates the maturity of the company and its SMN but also highlights the gaps between the ideal (expected) level and the current positions of the companies. Companies can use radar charts to display their maturity based on critical assets, resilience measures, or even specific operations within the SMNs.

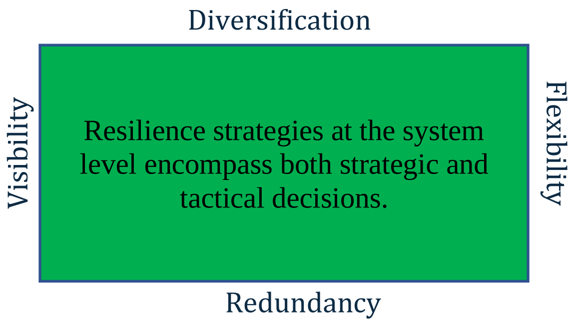

FIGURE 10. RESILIENCE STRATEGIES AT SYSTEM LEVEL

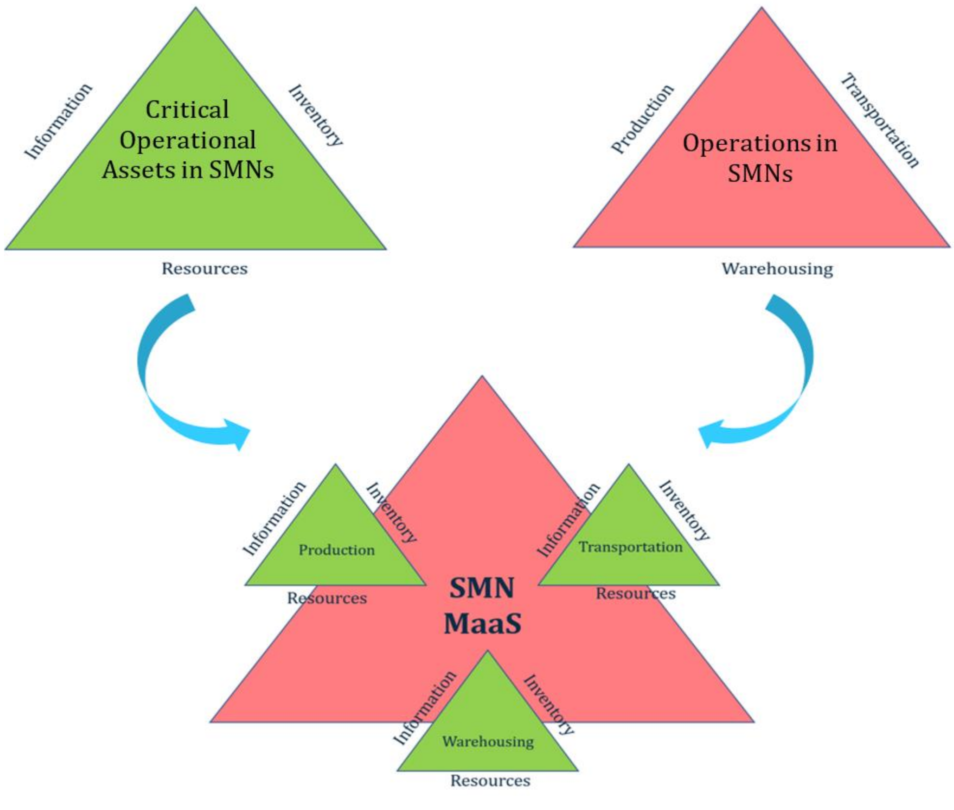

FIGURE 11.DIMENSIONS FOR MATURITY OF COMPANY RESILIENCE

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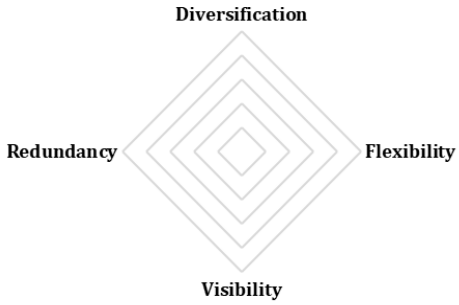

FIGURE 12. RADAR CHART - TYPE I: MATURITY OF COMPANY RESILIENCE

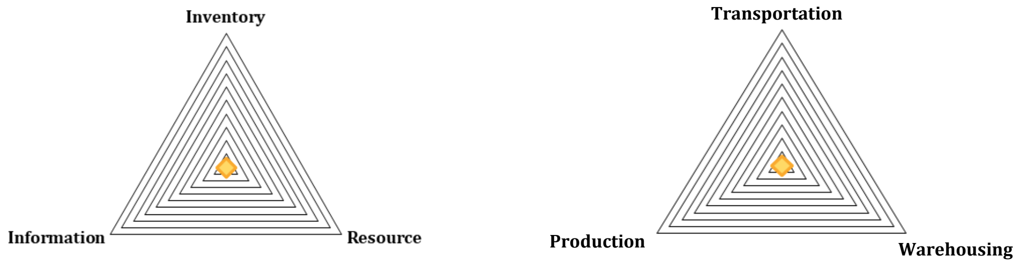

FIGURE 13.RADAR CHART - TYPE II: MATURITY OF COMPANY RESILIENCE

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CHAPTER 4. RESILIENCE FRAMEWORK FOR MANUFACTURING INDUSTRIES

SECTION 4.1 DATA FLOW DIAGRAM FOR IMPLEMENTING RESILIENCE STRATEGIES

Figure 14 shows the Data Flow Diagram (DFD) for implementing resilience strategies at the operational level. Once an unforeseen event occurs, the ***Event Recognition Process*** (see Task T2.2 Risks identification and processing in WP2 Supply chain disruption risk detection and diagnostic framework) aims to define the unforeseen event and allocate an IRDs' and ERDs' Code to the event, as well as assess the impact of the unforeseen event regarding the resilience KPIs (see *Table 8*). Then, the Stress Testing algorithm will determine whether the company needs to react or ignore the unforeseen event (see Task 2.3 Supplier and SMN risk assessment in WP2). If there is no need to take a reaction to the it, then the event can be closed, and the event record can be added to the Historical Event Sheet. Otherwise, if this is a serious unforeseen event, then the loss of resources (e.g., machine and equipment operability), inventory (e.g., raw material, consumable resources, and components), or information (order details, production schedule, delivery address of customers, and certifications) must be estimated. The Brunel Team introduces four resilience strategies at the operational level. The company must take one of the responses plans according to the presented strategies. In this way, they can continue the critical operations at a minimum acceptable level. Based on the NARRATE work plan, the response plan would be developed in WP4 based on the presented resilience strategies.

SECTION 4.2 RESILIENCE FRAMEWORK FOR MANUFACTURING NETWORKS

In today's dynamic and complex business environment, organizations are facing an increasing number of risks and disruptions that can have significant impacts on their supply chain operations. These risks and disruptions can arise from various unforeseen events, including natural disasters, political instability, cybersecurity breaches, and supplier failures. [112]. To address these challenges, the Brunel team has developed a comprehensive resilience framework [17] to help companies enhance their resilience at network level. This framework consists of five key steps that guide companies through the process of identifying, assessing, and responding to risk and Disruption.

Step 1: Identification of the company's Supply Chain Network

The first step in the resilience framework is to identify the company's supply chain network, including the first and second tiers of suppliers, as well as the downstream side of the supply chain network, such as distributors and wholesalers. This step also requires the company to determine the number of facilities and operations within each facility, as well as the warehouse operations.

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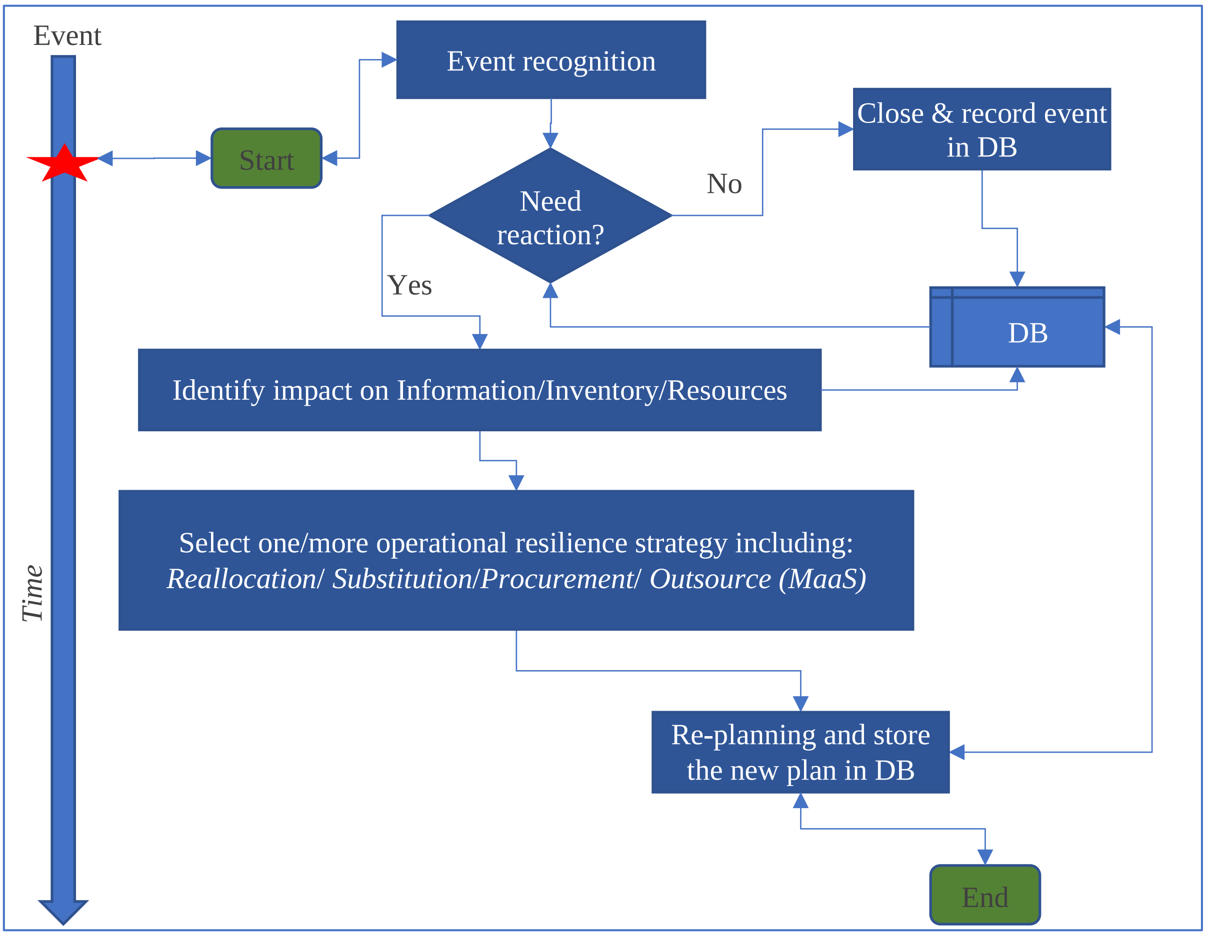

FIGURE 14. DATA FLOW DIAGRAM FOR RESILIENCE FRAMEWORK IN NARRATE

By mapping out the SCN, the company can gain a comprehensive understanding of the various components and interdependencies within the manufacturing network. This information is crucial for identifying potential points of vulnerability and assessing the potential impact of disruptions on the SMN's performance. For example, a company may discover that it relies heavily on a single supplier for a critical component, making it vulnerable to disruptions at that supplier's facility. ***¡Error! La autoreferencia al marcador no es válida.*** summarises information that must be collected to identify SCN of the company.

TABLE 9. SAMPLE CHECKLIST FOR COMPANY'S SUPPLY CHAIN IDENTIFICATION

SC Network	Facility (manufacturing shops and warehouses) locations, capacity, suppliers, customers, transportation companies, warehousing service providers
Inventory	Position and level of inventory within SC
Transportation	Service providers, mode, fleet, capacity
Information flow	Information systems
SC interrelationship	Process mapping
SC strategy	Agile, lean, or Leagile

Step 2: Supply Chain Performance Assessment and Resilience Goal Setting

The next step in the proposed resilience framework is to define the company's goals in terms of resilience and identify the current values of the relevant resilience KPIs. This step involves a thorough assessment of the company's performance in terms of resilience, considering resilience KPIs (see *Table 8*) and the level of maturity (see *Section 3.2 Resilience maturity auditing* and *ANNEX III – Resilience Maturity Auditing*). By establishing clear resilience goals and benchmarking the current performance, the company can identify areas for improvement and develop targeted strategies to enhance its resilience. This step also provides a baseline for measuring the effectiveness of the resilience strategies implemented in the later stages of the framework. For instance, a company may set a goal of reducing the delivery delay by

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10% within the next year and then use the resilience KPIs to track its progress towards this objective.

Step 3: Risk & Disruptions Identification and Assessment

In the third step, the company must collect historical data on the various risks and disruptions that have affected its operations. In *Chapter 1. Risks & Disruptions in manufacturing networks, Table 1* and *Table 2* report a list of internal and external Risks and Disruptions. This includes identifying the duration, impact, and probability of each risk and disruption. As shown in *Figure 15*, the Brunel team will develop an algorithm to analyse and classify the risks and disruptions into three groups: red, yellow, and green. This algorithm uses the historical data of the risk and disruption (see *Section 1.5 Risks and Disruptions Matrix and Annex I - Risk and Disruptions Matrix*).

The red risks and disruptions are considered severe and require immediate action from the company. These may include risks and disruptions as results of unforeseen events such as a major supplier going out of business or a natural disaster that destroys a key production facility. The yellow risks and disruptions are moderate and may require some level of response, such as a temporary shortage of a critical component. The green risks and disruptions are considered low-impact and may not require a direct response, such as minor fluctuations in demand or short-time machine failures. By categorizing the risks and disruptions in this manner, the company can prioritize its efforts and allocate resources more effectively to address the most critical threats to its supply chain resilience. This step also helps the company to develop a better understanding of the frequency and severity of the disruptions it faces, which can inform the development of more targeted resilience strategies.

Step 4: Resilience Stress testing

In this step, the company must identify the impact of losing critical resources, inventories, or information regarding the resilience KPIs. This involves determining the effect of losing a unit of a resource, inventory, or information on the production, transportation, and warehousing operations. For example, the company may find that the loss of a single production machine would result in a 20% reduction in inventory quantity of final product (increase lost-sale and delay), or that the loss of a critical raw material would lead to a 15% increase in inventory costs for the raw material.

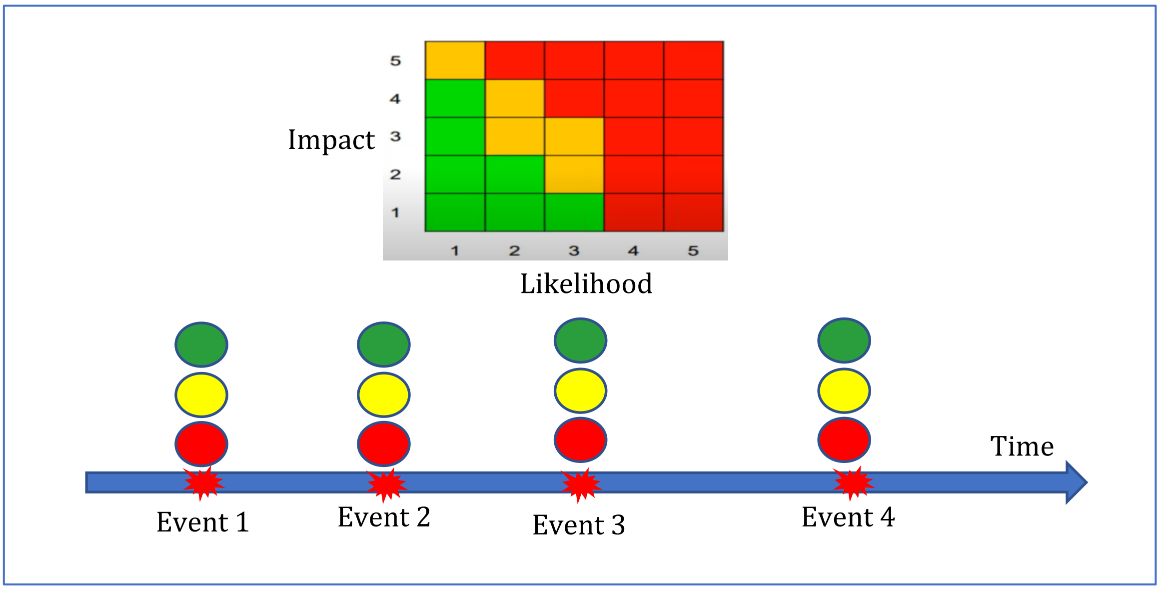

FIGURE 15. RISK AND DISRUPTION ASSESSMENT

Stress testing means understanding these vulnerabilities and potential impacts that allows the company to develop more targeted and effective resilience response plan to mitigate the risks and disruptions. This step also provides insights into the interdependencies within the manufacturing network. E.g., the company may discover that the loss of a particular supplier would have a cascading effect on inventory quantity and quality in production operations, highlighting the need for a more diversified supplier base.

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Conducting the stress testing for a manufacturing company and its SCN is a complex task, as the network may be large, and it is difficult to assess all upstream and downstream partners. Additionally, manufacturing processes are often multi-staged and rely on specialized machines and skilled workers. Further, the visibility into the supply chain network beyond the direct suppliers is limited. To address these challenges, the Brunel team will:

- Model the manufacturing process as a "black box" to improve the generality of the solution.
- Generate random scenarios to estimate the resilience KPIs for the company and its supply chain network.
- Model the SCN at three levels: supplier (two tiers), manufacturing (lead manufacturer and subcontractors), and customer (see *Figure 16*).
- Generate and analyse scenarios, such as the impact of losing inventories and resources.

The Brunel team's Stress testing algorithm will analyse the impact of losing resources, inventories, and information through the companies' supply chain network, using the developed resilience scenarios as a form of stress testing. For example, *Figure 16* illustrates five potential scenarios within the NARRATE project. Scenarios 1 and 4 focus on the supplier level, aiming to estimate the impact of losing inventory at a supplier node in either the first or second tier of the network. While it can be challenging to quantify the impact of upper-tier suppliers, understanding these vulnerabilities is crucial for improving supply chain resilience. Scenarios 2 and 5 enable an assessment of the impact if resources at a subcontractor or a specific manufacturing facility (in this case, Shop 4) were to be disrupted at the manufacturing level. Finally, scenario 3 highlights the vulnerability of the company's supply chain if one of their customers were to be lost. By analysing these diverse scenarios, the Digital Resilience Module can provide valuable insights into the potential risks and cascading effects throughout the supply chain. This understanding can help the company develop more robust contingency plans and strengthen its overall supply chain resilience.

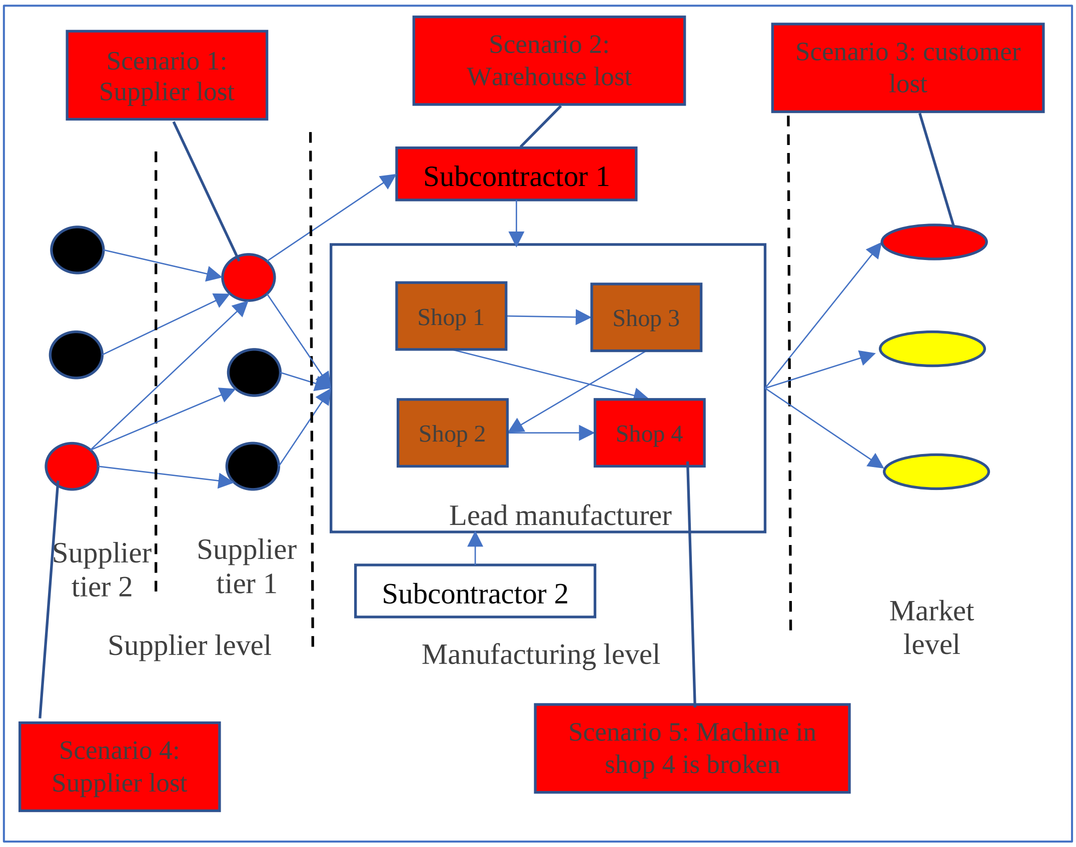

FIGURE 16. SAMPLE SCENARIOS FOR STRESS TESTING

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Step 5: Resilience Response plan

The final step in our resilience framework is to assess the risks and disruptions and determine whether the company needs to act or not. The Brunel team's algorithm developed in the previous step can assist the company in this decision-making process. The algorithm analyses the stress of identified risks and disruptions, considering their severity, probability, and potential impact on the SMN. Based on this analysis, the algorithm suggests the most appropriate resilience response plan according to the defined resilience strategies at the operational level, as presented in *Section 2.2. Resilience strategies at operational level.* For example, the algorithm may recommend that the company implement a substitution strategy to responding the risk of a critical supplier failure. Alternatively, the algorithm may suggest a reallocation strategy to enhance the company's ability to respond to fluctuations in demand or supply. By using RDM tool, companies can make decisions about which risks and disruptions require a quick response, and which resilience strategy at operational level is most suitable for mitigating the identified risk and disruption. This step ensures that the company's resilience efforts are targeted and effective, helping to minimize the impact of disruptions on its supply chain operations.

To achieve this, the Brunel team is feeding the outcomes of Step 3: Risks and Disruptions Identification & Assessment and Step 4: Stress Testing into RDM's decision-making algorithm. This algorithm maps the outcomes of the previous steps and provides a response plan for an unforeseen event. These response plans will be in line with the resilience target defined in Step 2: Supply Chain Performance Assessment and Resilience Goal Setting. *Figure 17* represents the relationship between different steps of the resilience framework. The Brunel team's resilience framework provides a comprehensive and structured approach to enhancing companies' resilience at the operational level. By following the five steps outlined in this report, companies can systematically identify, assess, and respond to the various risks and disruptions that threaten their supply chain operations.

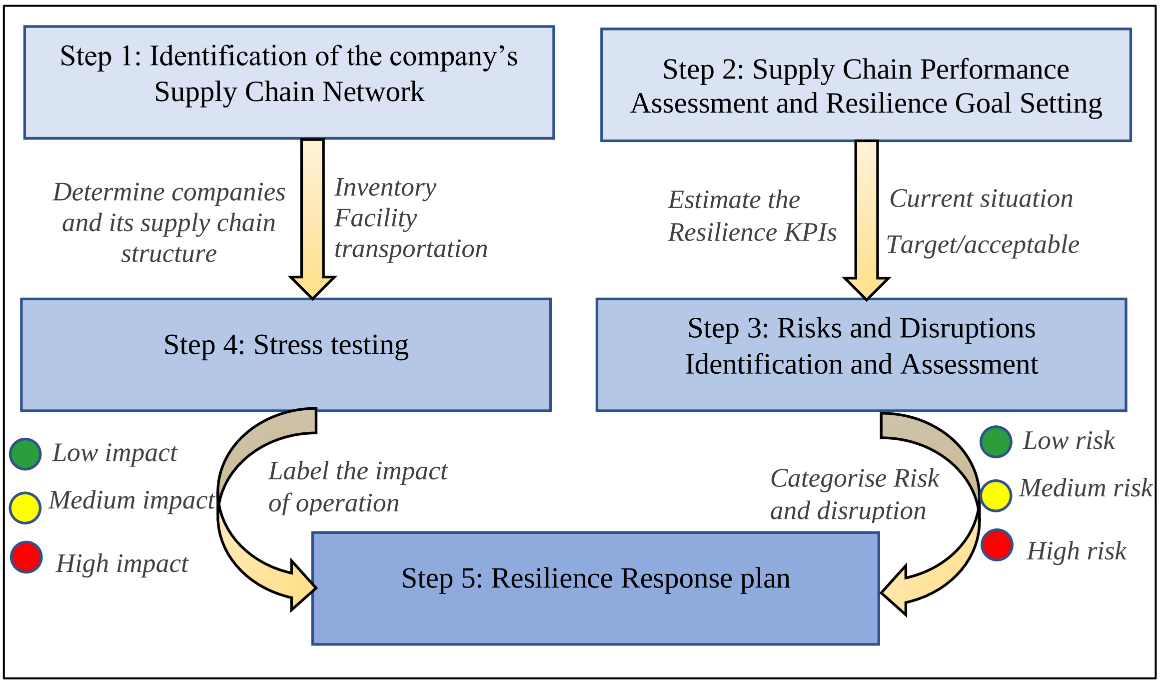

FIGURE 17. BUL'S RESILIENCE FRAMEWORK

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CONCLUSIONS

This deliverable 2.1 has provided a comprehensive examination of the Risks and Disruptions facing manufacturing networks, as well as the strategies and tools necessary to build resilience and ensure business continuity. The document has highlighted the critical importance of addressing both internal and external sources of risks and disruption, from equipment failures and workforce issues to supply chain disruptions and market changes. By understanding the potential impacts of these risks and disruptions on a company's resources, inventory, and information, manufacturers can better prepare for and respond to unforeseen events.

The resilience strategies outlined in this deliverable offer a two-pronged approach, addressing resilience at both the ***system and operational levels***. At the system level, companies can incorporate resilience into their strategic and tactical decision-making, such as implementing flexible manufacturing capabilities and cross-training workers. At the operational level, the focus is on developing robust response and recovery plans to quickly resume and fully restore operations in the event of a risk and disruption. The resilience KPIs presented in the deliverable provide a valuable framework for measuring a company's resilience capabilities, allowing them to identify strengths, weaknesses, and areas for improvement. By regularly monitoring these KPIs, manufacturers can ensure that their resilience strategies are effective and continuously adapt to changing conditions. Also, companies can deploy the resilience maturity tool for analysing their capability in terms of resilience.

The holistic framework developed by the Brunel team in the NARRATE project offers a comprehensive approach to building resilience, guiding companies through the process of identifying risks, implementing resilience strategies, and measuring performance. This framework can serve as a valuable tool for manufacturing companies looking to enhance their ability to withstand and recover from risks and disruptions. In the next step, the Brunel team will focus on developing the ***Resilience Digital Module (RDM)*** tool, which will support companies in collecting data, analysing risks and disruptions, as well as assessing their vulnerabilities and the impact of risks and disruptions on their operations. This module will further enhance the capabilities of manufacturers to build and maintain resilience in the face of an ever-changing business landscape. By implementing the strategies and tools outlined in D2.1, and leveraging the upcoming Resilience Digital Module, manufacturing companies can position themselves to better navigate the challenges of the modern business environment, ensuring their long-term success and the ability to meet the needs of their customers, even in the face of unexpected disruptions.

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ANNEX I - RISK AND DISRUPTIONS MATRIX

EXTERNAL RISKS AND DISRUPTIONS

Code	Category	External Risk & Disruptions	Impact	
ERD1	Downstream SC	Market uncertainty (order)	Inventory	Changing in preferences/options of the customers/demand size, date, specifications
ERD2	Downstream SC	Cancelled or changed orders (Order rectification and re-adjustment)	Inventory	customer changed or cancelled the order on last minute or asking for extra documents or information
ERD3	Downstream SC	Damaged final product during transportation	Inventory	between lead manufacturer and customers
ERD4	Upstream SC	Damaged raw material/component/Consumable resource during transportation	Inventory	between suppliers/subcontractor and lead manufacturer
ERD5	Upstream SC	Damage of raw material/component/Consumable resource in warehouse	Inventory	in warehouse of a logistic companies
ERD6	Downstream SC	Damage of final products in warehouse	Inventory	in warehouse of a logistic companies for last mile delivery
ERD7	Upstream SC	Losing supplier for raw material/component/Consumable resource	Inventory	Losing a critical supplier with no easy replacement permanently
ERD8	Upstream SC	Shortage of raw material/component/Consumable resource	Inventory	Lack of raw material and supplies in market for a short period of time
ERD9	Upstream SC	Fluctuation on raw material/component/Consumable resource price	Inventory	Changing the cost of raw material seasonality or due to inflation
ERD10	Up/down stream SC	Cybersecurity threats and data breaches	Information	Various malicious activities that aim to compromise the confidentiality, integrity, and availability of digital information. These threats can include hacking, malware, phishing, and unauthorized access, leading to the theft or destruction of sensitive data, financial losses, and reputational damage for individuals and organizations.
ERD11	Up/down stream SC	Regulatory and policy changes	Inventory	Government change the trade regulation, carbon footprint certificate for government and customers
ERD12	Downstream SC	Transportation delay for final product	Inventory	between lead manufacturer and customers/wholesalers
ERD13	Upstream SC	Transportation delay for raw material/component/Consumable resource	Inventory	between suppliers/subcontractor and lead manufacturer

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INTERNAL RISKS AND DISRUPTIONS

Code	Flow category	Internal Risk & Disruptions	Description
IRD1	Physical flow	Production/manufacturing/process	Various shortcomings or suboptimal practices within the internal operations of the production process, including machine failures that impact the entire production operation
IRD2	Physical flow	Raw material quality issue	In the warehouse of raw materials within the lead manufacturer
IRD3	Physical flow	Work-in-process quality issue	During production in the production shops, along with the production process
IRD4	Physical flow	Labour and workforces related challenges	In different departments within the lead manufacturer, particularly in the production shop
IRD5	Physical/information flow	Lack of operational level capacity	Loss of capacity due to lack of labour, over-estimation of capacity, inefficient scheduling, and delays in the process
IRD6	Physical flow	Material handling equipment failure	Failure of material handling equipment such as conveyors and forklifts
IRD7	Physical flow	Warehousing operations failure	Disruptions or breakdowns in the execution of warehouse activities such as equipment breakdowns, inadequate storage capacity, and labour shortages
IRD8	Information flow	Information system/DSS failure	Breakdown of the technology, software, or DSS tools, for example ERP, software glitch, or database corruption
IRD9	Physical flow	Unplanned/corrective maintenance of machines	Unexpected breakdowns and immediate repair or servicing outside of the regular maintenance schedule including mechanical failures, electrical problems, or sensor malfunctions
IRD10	Information flow	Unplanned/corrective maintenance on IS/DSS	Unplanned Upgrades or Updates to ISs and DSSs with significant disruptions in the operations including underlying software, databases, or analytical models causing malfunctions, data integrity issues, or unexpected changes in system outputs.
IRD11	Service & Support	Facility disruptions	Facility Disruptions, such as issues with buildings, utilities (water, electricity, gas), or Heating, Ventilation, and Air Conditioning (HVAC) systems with significantly impact operations
IRD12	Physical/information flow	Other Production Uncertainty/Micro & real-time Disruption	Unpredictable changes in key production metrics, such as manufacturing time, capacity, machine availability, and material handling duration. These fluctuations can disrupt the intended production schedule, leading to delays, lost output, and increased costs - ultimately impacting an organization's ability to meet customer demand reliably.

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GUIDELINES

Guideline for Filling Out the Disruption Impact Table

This table is designed to record data related to disruptions in your company's operations. The information will help assess the impact of these disruptions on various performance indicators such as lost sales, defect rates, and customer satisfaction. Below is a step-by-step guide to filling out each section of the table:

1. Event ID

A unique identifier for each disruption event (e.g., 001, 002). This helps to track and differentiate between multiple disruption events.

2. Company ID

A unique ID for your company. This is useful if multiple companies are being assessed or if the data will be shared across different departments or partners.

3. User ID

The ID of the person filling in the form. It identifies the user responsible for recording the data.

4. R&D Code

Any Resiliency and Disruption (R&D) code related to the disruption event, if applicable.

5. Disruption

A brief description of the disruption (e.g., "Raw material shortage," "Machine failure").

6. Event Date

The date the disruption occurred (format: DD/MM/YYYY).

7. Description

A brief explanation of the disruption.

Duration

8. Days

The number of days the disruption lasted.

9. Hours

The number of hours the disruption lasted (if less than one day or as a supplement to the days).

Impact Categories

You will need to assess the impact of the disruption on various aspects of the company's operations. For each category, please choose from High Impact, Medium Impact, or Low Impact (as per your company's internal evaluation).

10. Lost Sales

Evaluate how much potential sales revenue was lost due to the disruption.

11. Defect Rate

Assess if the disruption led to an increase in product defects.

12. Customer Satisfaction

Estimate how much the disruption affected customer satisfaction.

13. Delay (Deviation in Time)

Evaluate any delays in product/service delivery to customers due to the disruption.

14. Social Impact

Note if the disruption had a social impact (e.g., workforce morale, community impact).

15. Environmental Impact

Assess whether the disruption caused any environmental impact (e.g., waste, pollution).

General Notes:

Ensure that the information is as accurate as possible to reflect the true nature of the disruption. If some fields are not relevant to your disruption, you may leave them blank or write "N/A". Based on your company's nature and access to historical data, please select several metrics to report on the history of risks and disruptions. If you are unable to report on any of them, please leave those fields blank. You can find the internal and external risk and disruption codes in the first two sheets.

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HISTORIAL DISRUPTIONS

Event	Company	User	R&D Code	Disruption	Event Date	Description	Duration		Impact						
							Days	Hours	Lost-sale	Defect Rate	Customer Satisfaction	Delay (deviation in time)	Social	Cost	Environmental
1			ERD6		10-5-24		1	2	High Impact	Medium Impact	Low impact	High Impact	High Impact	Low impact	Medium Impact
2			IRD2		20-12-24		2	0	High Impact	Low impact	Medium Impact	Low impact	Low impact	High Impact	Low impact
3															
4															
5															
6															
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ANNEX II – RESILIENCE KPIS

FORMULATION OF RESILIENCE KPIS

Calculating the exact loss of operating level and the duration of a risk or disruption is challenging due to the influence of various factors. However, to maintain and ensure operational continuity, it is vital to secure the critical assets of the company, both within the manufacturing plant and across the entire supply chain network. To define the resilience KPIs, we have formulated them based on four dimensions: cost, quantity, quality, and time. The three critical assets for any company include:

- ***Resources***: This encompasses machines, equipment, human resources, and consumable resources like electricity and gas.
- ***Inventory***: This includes finished products, work-in-process items, and raw materials.
- ***Information***: This covers design maps, customer and supplier information, production planning, product specifications, and inventory stacks in the warehouse.

Any deviation or loss in these assets will reduce the operating level, causing the company to deviate from its operational goals. By utilizing these measures, companies can gain a clearer understanding of their losses and make informed decisions to enhance resilience. Table 10 summarises the resilience KPIs.

TABLE 10. RESILIENCE KPIS

	Resilience KPIs			
Critical assets	Time (delay)	Cost	Quantity	Quality
Inventory	ΔI^t	ΔI^c	ΔI^q	ΔI^s
Resources	ΔR^t	ΔR^c	ΔR^q	ΔR^s
Information	ΔD^t	ΔD^c	ΔD^q	ΔD^s

The NARRATE platform utilizes the concept of "blueprints," a widely adopted approach in modular software development, to design various components and modules. This methodology ensures that different elements within NARRATE function seamlessly across its internal tools and modules. As illustrated in Figure 9, the NARRATE platform incorporates seven blueprints. These blueprints play a crucial role in establishing efficient and well-structured resilience KPIs at the operational level for NARRATE users. To calculate the resilience KPIs presented in above, we have developed 12 proposed resilience KPIs for each operation, including production, transportation, and warehousing, which are detailed separately in ***ANNEX II – Resilience KPIs.***

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

Supplier/Lead MfG Blueprint
- Company Background
- Products / Services
- People/skills
- Key Processes
- Capabilities & Capacity

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

Logistics Services Blueprint
- Transportation routes
- Carriers
- Modes of transportation
- Route Planning
- Tracking of shipments
- Transit Times
- Environmental Info.

Warehousing Services Blueprint
- receiving,
- storing,
- picking,
- packing,
- shipping of products

Quality Assurance Blueprint
- Inspection criteria
- Quality assurance protocols
- Production/Performance KPIs
- Rate of Production Capacity & Work in Progress

Regulatory Compliance Blueprint
- industry standards,
- safety regulations,
- environmental regulations,
- product certifications

FIGURE 18. BLUEPRINTS OF THE NARRATE PLATFORM

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TABLE 11. INVENTORY RESILIENCE KPIS ACROSS PRODUCTION, TRANSPORTATION, AND WAREHOUSING

No	Measure Name	Mathematical Formula	Required data in the associated Blueprint
1	Deviation in Quantity of inventory in transportation	$\sum_{tr=1}^{TR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{Q_{tr,CI}^{t_e+1} - Q_{tr,CI}^{t_e-1}\} * \omega_{CI}$ • tr: Index for each transportation method. • CI: Index for critical inventories. • e: Index for disruptive events. • $Q_{tr,CI}^{t}$: The quantity of critical inventory CI at time t transported using transportation method tr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Product Blueprint, Warehousing Services Blueprint, Logistics Services Blueprint
2	Deviation in Quality of inventory in transportation	$\sum_{tr=1}^{TR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\frac{1}{\{DR_{tr,CI}^{t_e+1} - DR_{tr,CI}^{t_e-1}\} * \omega_{CI}}$ • tr: Index for each transportation method. • CI: Index for critical inventories. • e: Index for disruptive events. • $DR_{tr,CI}^{t}$: The defect rate of critical inventory CI at time t transported using transportation method tr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Logistics Services Blueprint, Quality Assurance Blueprint
3	Deviation in cost of inventory in transportation	$\sum_{tr=1}^{TR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{Co_{tr,CI}^{t_e+1} - Co_{tr,CI}^{t_e-1}\} * \omega_{CI}$ • tr: Index for each transportation method. • CI: Index for critical inventories. • e: Index for disruptive events. • $Co_{tr,CI}^{t}$: The cost per unit of critical inventory CI at time t transported using transportation method tr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Logistics Services Blueprint, Product Blueprint
4	Deviation in time of inventory in transportation	$\sum_{tr=1}^{TR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{Du_{tr,CI}^{t_e+1} - Du_{tr,CI}^{t_e-1}\} * \omega_{CI}$ • tr: Index for each transportation method. • CI: Index for critical inventories. • e: Index for disruptive events. • $Du_{tr,CI}^{t}$: The duration of transporting critical inventory CI at time t using transportation method tr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Logistics Services Blueprint
5	Deviation in Quantity of inventory in production	$\sum_{pr=1}^{PR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{PQ_{pr,CI}^{t_e+1} - PQ_{pr,CI}^{t_e-1}\} * \omega_{CI}$ • pr: Index for each production line. • CI: Index for critical inventories. • e: Index for disruptive events. • $PQ_{pr,CI}^{t}$: The quantity of critical inventory CI at time t used for manufacturing in shop pr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Product Blueprint, Production-Plan Blueprint
6	Deviation in Quality of inventory in production	$\sum_{pr=1}^{PR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\frac{1}{\{PDR_{pr,CI}^{t_e+1} - PDR_{pr,CI}^{t_e-1}\} * \omega_{CI}}$ • pr: Index for each production line. • CI: Index for critical inventories. • e: Index for disruptive events. • $PDR_{pr,CI}^{t}$: The defect rate of critical inventory CI at time t used for manufacturing in shop pr. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Quality Assurance Blueprint, Production-Plan Blueprint

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7	Deviation in cost of inventory in production	$$\sum_{pr=1}^{PR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{PCo_{pr,CI}^{t_e+1} - PCo_{pr,CI}^{t_e-1}\} * \omega_{CI}$$ • pr: Index for each production line. • CI: Index for critical inventories. • e: Index for disruptive events. • $PCo_{pr,CI}^{t}$: The production cost of critical inventory CI at time t $used\ for\ manufacturing\ in\ shop\ pr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Product Blueprint, Production-Plan Blueprint
8	Deviation in time of inventory in production	$$\sum_{pr=1}^{PR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{PT_{pr,CI}^{t_e+1} - PT_{pr,CI}^{t_e-1}\} * \omega_{CI}$$ • pr: Index for each production line. • CI: Index for critical inventories. • e: Index for disruptive events. • $PT_{pr,CI}^{t}$: The production processing time of critical inventory CI at time t $used\ for\ manufacturing\ in\ shop\ pr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Production-Plan Blueprint
9	Deviation in Quantity of inventory in warehouse	$$\sum_{wr=1}^{WR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{WQ_{wr,CI}^{t_e+1} - WQ_{wr,CI}^{t_e-1}\} * \omega_{CI}$$ • wr: Index for each warehouse. • CI: Index for critical inventories. • e: Index for disruptive events. • $WQ_{wr,CI}^{t}$: The quantity of critical inventory CI at time $t\ in\ warehouse\ wr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Product Blueprint
10	Deviation in Quality of inventory in warehouse	$$\sum_{wr=1}^{WR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\frac{1}{\{WDR_{wr,CI}^{t_e+1} - WDR_{wr,CI}^{t_e-1}\} * \omega_{CI}}$$ • wr: Index for each warehouse. • CI: Index for critical inventories. • e: Index for disruptive events. • $WDR_{wr,CI}^{t}$: The defect rate of critical inventory CI at time $t\ in\ warehouse\ wr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Quality Assurance Blueprint
11	Deviation in cost of inventory in warehouse	$$\sum_{wr=1}^{WR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{WCo_{wr,CI}^{t_e+1} - WCo_{wr,CI}^{t_e-1}\} * \omega_{CI}$$ • wr: Index for each warehouse. • CI: Index for critical inventories. • e: Index for disruptive events. • $WCo_{pr,CI}^{t}$: The warehousing cost of critical inventory CI at time $t\ in\ warehouse\ wr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Product Blueprint
12	Deviation in time of inventory in warehouse	$$\sum_{wr=1}^{WR}\sum_{CI=1}^{I}\sum_{e=1}^{E}\{WT_{wr,CI}^{t_e+1} - WT_{wr,CI}^{t_e-1}\} * \omega_{CI}$$ • wr: Index for each production line. • CI: Index for critical inventories. • e: Index for disruptive events. • $WT_{pr,CI}^{t}$: The warehousing time of critical inventory CI at time $t\ in\ warehouse\ wr$. • ω_{CI}: Weight for critical inventory CI to standardize the units.	Warehousing Services Blueprint, Product Blueprint

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TABLE 12. RESOURCE RESILIENCE KPIS ACROSS PRODUCTION, TRANSPORTATION, AND WAREHOUSING

No	Measure Name	Mathematical Formula	Required data in the associated Blueprint
1	Deviation in Quantity of resources in transportation	$$\sum_{tr=1}^{TR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{Q_{tr,rs}^{t_e+1} - Q_{tr,rs}^{t_e-1}\} * \omega_{rs}$$ • tr: Index for each transportation method. • rs: Index for critical resources. • e: Index for disruptive events. • $Q_{tr,rs}^{t}$: The quantity of critical resources rs at time $t\ used\ in$ transportation method tr. • ω_{rs}: Weight for critical resource rs to standardize the units.	Logistics Services Blueprint, Production-Plan Blueprint
2	Deviation in Quality of resources in transportation	$$\sum_{tr=1}^{TR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\frac{1}{\{RDR_{tr,rs}^{t_e+1} - RDR_{tr,rs}^{t_e-1}\} * \omega_{rs}}$$ • tr: Index for each transportation method. • rs: Index for critical resources. • e: Index for disruptive events. • $RDR_{tr,rs}^{t}$: The defect rate of critical resources rs at time t used in transportation method tr. • ω_{rs}: Weight for critical resource rs to standardize the units.	Logistics Services Blueprint, Quality Assurance Blueprint
3	Deviation in cost of resources in transportation	$$\sum_{tr=1}^{TR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RCo_{tr,rs}^{t_e+1} - RCo_{tr,rs}^{t_e-1}\} * \omega_{rs}$$ • tr: Index for each transportation method. • rs: Index for critical resources. • e: Index for disruptive events. • $RCo_{tr,rs}^{t}$: The cost per unit of critical resources rs at time $t\ used\ in$ transportation method tr. • ω_{rs}: Weight for critical resource rs to standardize the units.	Logistics Services Blueprint, Product Blueprint, Production-Plan Blueprint
4	Deviation in time of resources in transportation	$$\sum_{tr=1}^{TR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RDu_{\text{tr,rs}}^{t_e+1} - RDu_{\text{tr,rs}}^{t_e-1}\} * \omega_{rs}$$ • tr: Index for each transportation method. • rs: Index for critical resources. • e: Index for disruptive events. • $RDu_{tr,rs}^{t}$: The duration of transporting critical resources rs at time t used in transportation method tr. • ω_{rs}: Weight for critical resource rs to standardize the units.	Logistics Services Blueprint, Product Blueprint, Production-Plan Blueprint
5	Deviation in Quantity of resources in production	$$\sum_{pr=1}^{PR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RPQ_{pr,rs}^{t_e+1} - RPQ_{pr,rs}^{t_e-1}\} * \omega_{rs}$$ • pr: Index for each production line. • rs: Index for critical resources. • e: Index for disruptive events. • $RPQ_{pr,rs}^{t}$: The quantity of critical resources rs at time $t\ used\ for\ manufacturing\ in\ shop\ pr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Product Blueprint, Production-Plan Blueprint
6	Deviation in Quality of resources in production	$$\sum_{pr=1}^{PR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\frac{1}{\{RPDR_{pr,rs}^{t_e+1} - RPDR_{pr,rs}^{t_e-1}\} * \omega_{rs}}$$ • pr: Index for each production line. • rs: Index for critical resources. • e: Index for disruptive events. • $RPDR_{pr,rs}^{t}$: The defect rate of critical resources rs at time $t\ used\ for\ manufacturing\ in\ shop\ pr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Quality Assurance Blueprint, Production-Plan Blueprint

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7	Deviation in cost of resources in production	$$\sum_{pr=1}^{PR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RPCo_{pr,rs}^{t_e+1} - RPCo_{pr,rs}^{t_e-1}\} * \omega_{rs}$$ • pr: Index for each production line. • rs: Index for critical resources. • e: Index for disruptive events. • $RPCo_{pr,rs}^{t}$: The production cost of critical resources rs at time $t\ used\ for\ manufacturing\ in\ shop\ pr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Product Blueprint, Production-Plan Blueprint
8	Deviation in time of resources in production	$$\sum_{pr=1}^{PR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RPT_{pr,rs}^{t_e+1} - RPT_{pr,rs}^{t_e-1}\} * \omega_{rs}$$ • pr: Index for each production line. • rs: Index for critical resources. • e: Index for disruptive events. • $RPT_{pr,rs}^{t}$: The production processing time of critical resources rs at time $t\ used\ for\ manufacturing\ in\ shop\ pr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Product Blueprint, Production-Plan Blueprint
9	Deviation in Quantity of resources in warehouse	$$\sum_{wr=1}^{WR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RWQ_{wr,rs}^{t_e+1} - RWQ_{wr,rs}^{t_e-1}\} * \omega_{rs}$$ • wr: Index for each warehouse. • rs: Index for critical resources. • e: Index for disruptive events. • $RWQ_{wr,rs}^{t}$: The quantity of critical resources rs at time $t\ in\ warehouse\ wr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Warehousing Services Blueprint, Product Blueprint, Production-Plan Blueprint
10	Deviation in Quality of resources in warehouse	$$\sum_{wr=1}^{WR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\frac{1}{\{RWDR_{wr,rs}^{t_e+1} - RWDR_{wr,rs}^{t_e-1}\} * \omega_{rs}}$$ • wr: Index for each warehouse. • rs: Index for critical resources. • e: Index for disruptive events. • $RWDR_{wr,rs}^{t}$: The defect rate of critical resources rs at time $t\ in\ warehouse\ wr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Warehousing Services Blueprint, Quality Assurance Blueprint
11	Deviation in cost of resources in warehouse	$$\sum_{wr=1}^{WR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RWCo_{wr,rs}^{t_e+1} - RWCo_{wr,rs}^{t_e-1}\} * \omega_{rs}$$ • wr: Index for each warehouse. • rs: Index for critical resources. • e: Index for disruptive events. • $RWCo_{pr,rs}^{t}$: The warehousing cost of critical resources rs at time $t\ in\ warehouse\ wr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Warehousing Services Blueprint, Product Blueprint, Production-Plan Blueprint
12	Deviation in time of resources in warehouse	$$\sum_{wr=1}^{WR}\sum_{rs=1}^{RS}\sum_{e=1}^{E}\{RWT_{wr,rs}^{t_e+1} - RWT_{wr,rs}^{t_e-1}\} * \omega_{rs}$$ • wr: Index for each production line. • rs: Index for critical resources. • e: Index for disruptive events. • $RWT_{pr,rs}^{t}$: The warehousing time of critical resources rs at time $t\ in\ warehouse\ wr$. • ω_{rs}: Weight for critical resource rs to standardize the units.	Warehousing Services Blueprint, Product Blueprint, Production-Plan Blueprint

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TABLE 13. INFORMATION RESILIENCE KPIS ACROSS PRODUCTION, TRANSPORTATION, AND WAREHOUSING

No	Measure Name	Mathematical Formula	Required data in the associated Blueprint
1	Deviation in Quantity of information in transportation	$\sum_{tr=1}^{TR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\{Q_{tr,in}^{t_e+1} - Q_{tr,in}^{t_e-1}\} * \omega_{in}$ • tr: Index for each transportation method. • in: Index for critical information. • e: Index for disruptive events. • $Q_{tr,in}^{t}$: The quantity of critical information in at time t $used$ in transportation method tr. • ω_{in}: Weight for critical information in to standardize the units.	Logistics Services Blueprint
2	Deviation in Quality of information in transportation	$\sum_{tr=1}^{TR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\frac{1}{\{IER_{tr,in}^{t_e+1} - IER_{tr,in}^{t_e-1}\} * \omega_{in}}$ • tr: Index for each transportation method. • in: Index for critical information. • e: Index for disruptive events. • $IER_{tr,in}^{t}$: The error rate of critical information in at time t used in transportation method tr. • ω_{in}: Weight for critical information in to standardize the units.	Logistics Services Blueprint, Quality Assurance Blueprint
3	Deviation in cost of information in transportation	$\sum_{tr=1}^{TR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\{ICo_{tr,in}^{t_e+1} - ICo_{tr,in}^{t_e-1}\} * \omega_{in}$ • tr: Index for each transportation method. • in: Index for critical information. • e: Index for disruptive events. • $ICo_{tr,in}^{t}$: The cost per unit of critical information in at time t $used$ in transportation method tr. • ω_{in}: Weight for critical information in to standardize the units.	Logistics Services Blueprint
4	Deviation in time of information in transportation	$\sum_{tr=1}^{TR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\{IDu_{\mathrm{tr},in}^{t_e+1} - IDu_{\mathrm{tr},in}^{t_e-1}\} * \omega_{in}$ • tr: Index for each transportation method. • in: Index for critical information. • e: Index for disruptive events. • $IDu_{tr,in}^{t}$: The duration of transfering critical information in at time t used in transportation method tr. • ω_{in}: Weight for critical information in to standardize the units.	Logistics Services Blueprint
5	Deviation in Quantity of information in production	$\sum_{pr=1}^{PR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\{IPQ_{pr,in}^{t_e+1} - IPQ_{pr,in}^{t_e-1}\} * \omega_{in}$ • pr: Index for each production line. • in: Index for critical information. • e: Index for disruptive events. • $IPQ_{pr,in}^{t}$: The quantity of critical information in at time t $used$ for $manufacturing$ in $shop$ pr. • ω_{in}: Weight for critical information in to standardize the units.	Production-Plan Blueprint
6	Deviation in Quality of information in production	$\sum_{pr=1}^{PR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\frac{1}{\{IPER_{pr,in}^{t_e+1} - IPER_{pr,in}^{t_e-1}\} * \omega_{in}}$ • pr: Index for each production line. • in: Index for critical information. • e: Index for disruptive events. • $IPER_{pr,in}^{t}$: The error rate of critical information in at time t $used$ for $manufacturing$ in $shop$ pr. • ω_{in}: Weight for critical information in to standardize the units	Quality Assurance Blueprint, Production-Plan Blueprint

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7	Deviation in cost of information in production	$\sum_{pr=1}^{PR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\left\{IPCo_{pr,in}^{t_e+1} - IPCo_{pr,in}^{t_e-1}\right\} * \omega_{in}$ • pr: Index for each production line. • in: Index for critical information. • e: Index for disruptive events. • $IPCo_{pr,in}^{t}$: The collection cost of critical information in at time t $used\ for\ manufacturing\ in\ shop\ pr$. • ω_{in}: Weight for critical information in to standardize the units.	Production-Plan Blueprint
8	Deviation in time of information in production	$\sum_{pr=1}^{PR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\left\{IPT_{pr,in}^{t_e+1} - IPT_{pr,in}^{t_e-1}\right\} * \omega_{in}$ • pr: Index for each production line. • in: Index for critical information. • e: Index for disruptive events. • $IPT_{pr,in}^{t}$: The processing time of critical information in at time t $used\ for\ manufacturing\ in\ shop\ pr$. • ω_{in}: Weight for critical information in to standardize the units.	Production-Plan Blueprint
9	Deviation in Quantity of information in warehouse	$\sum_{wr=1}^{WR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\left\{IWQ_{wr,in}^{t_e+1} - IWQ_{wr,in}^{t_e-1}\right\} * \omega_{in}$ • wr: Index for each warehouse. • in: Index for critical information. • e: Index for disruptive events. • $IWQ_{wr,in}^{t}$: The quantity of critical information in at time t $in\ warehouse\ wr$. • ω_{in}: Weight for critical information in to standardize the units.	Warehousing Services Blueprint
10	Deviation in Quality of information in warehouse	$\sum_{wr=1}^{WR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\frac{1}{\left\{IWER_{wr,in}^{t_e+1} - IWER_{wr,in}^{t_e-1}\right\} * \omega_{in}}$ • wr: Index for each warehouse. • in: Index for critical information. • e: Index for disruptive events. • $IWER_{wr,in}^{t}$: The error rate of critical information in at time t $in\ warehouse\ wr$. • ω_{in}: Weight for critical information in to standardize the units.	Warehousing Services Blueprint, Quality Assurance Blueprint
11	Deviation in cost of information in warehouse	$\sum_{wr=1}^{WR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\left\{IWCo_{wr,in}^{t_e+1} - IWCo_{wr,in}^{t_e-1}\right\} * \omega_{in}$ • wr: Index for each warehouse. • in: Index for critical information. • e: Index for disruptive events. • $IWCo_{pr,in}^{t}$: The cost of critical information in at time t $in\ warehouse\ wr$. • ω_{in}: Weight for critical information in to standardize the units.	Warehousing Services Blueprint
12	Deviation in time of information in warehouse	$\sum_{wr=1}^{WR}\sum_{in=1}^{RS}\sum_{e=1}^{E}\left\{IWT_{wr,in}^{t_e+1} - IWT_{wr,in}^{t_e-1}\right\} * \omega_{in}$ • wr: Index for each warehouse. • in: Index for critical information. • e: Index for disruptive events. • $IWT_{pr,in}^{t}$: The time of receiving critical information in at time t $in\ warehouse\ wr$. • ω_{in}: Weight for critical information in to standardize the units.	Warehousing Services Blueprint

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ANNEX III – RESILIENCE MATURITY AUDITING

QUESTIONNAIRE: RESILIENCE KPIS AT SYSTEM LEVELS

Introduction:

This questionnaire aims to assess the resilience maturity of your company within the context of smart manufacturing networks. It focuses on four key measures: diversification, flexibility, visibility, and redundancy, across three critical operations: production, transportation, and warehousing. Additionally, it evaluates three essential assets: inventory, information, and resources. Each question is designed to gauge your companies's current status in these areas. Please respond to each question by selecting one of the following options: "Not Sufficient," "Sufficient," "Very Sufficient," or "I Don't Know." The term "Sufficient" is defined objectively based on the expectations of the company, and we understand that perceptions may vary among different staff members. Your responses will help identify strengths and areas for improvement in your resilience strategies.

KPI 1. Diversification

- ***Production***

Do you have diversification in production regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in production regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in production regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

- ***Transportation***

Do you have diversification in transportation regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in transportation regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in transportation regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

- ***Warehousing***

Do you have diversification in warehousing regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in warehousing regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have diversification in warehousing regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

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KPI 2. Flexibility

○ *Production*

Do you have flexibility in production regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in production regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in production regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

○ *Transportation*

Do you have flexibility in transportation regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in transportation regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in transportation regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

○ *Warehousing*

Do you have flexibility in warehousing regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in warehousing regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have flexibility in warehousing regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

KPI 3. Visibility

○ *Production*

Do you have visibility in production regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have visibility in production regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have visibility in production regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

○ *Transportation*

Do you have visibility in transportation regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

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Do you have visibility in transportation regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have visibility in transportation regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

- ***Warehousing***

Do you have visibility in warehousing regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have visibility in warehousing regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have visibility in warehousing regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

KPI 4. Redundancy

- ***Production***

Do you have redundancy in production regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in production regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in production regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

- ***Transportation***

Do you have redundancy in transportation regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in transportation regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in transportation regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

- ***Warehousing***

Do you have redundancy in warehousing regarding resources?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in warehousing regarding inventory?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

Do you have redundancy in warehousing regarding information systems?

☐ Not Sufficient ☐ Sufficient ☐ Very Sufficient ☐ I Don't Know

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