NARRATE

Regenerative Resilient Smart Manufacturing Networks

D4.1 RESILIENCE, SUSTAINABILITY & CIRCULARITY STRESS TESTING TOOL (A)

2025/03/26

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D4.1 RESILIENCE, SUSTAINABILITY & CIRCULARITY STRESS TESTING TOOL (A)

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Abstract	Given the critical role the SMN plays in NARRATE, regular testing is essential to ensure reliability, accuracy, and optimal performance. The testing framework is structured into test sequences, each composed of distinct use cases that simulate real-world scenarios and validate system responses. This systematic approach to testing ensures that the SMN remains robust, adaptive, and capable of addressing dynamic manufacturing challenges. By continuously refining the testing methodology and integrating emerging technologies, the system fosters resilience, minimizes downtime, and enhances overall supply chain efficiency.

Keywords	Smart Manufacturing Network (SMN), use cases, supply chain efficiency, complex event processing, predictive analytics

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STATEMENT ON MAINSTREAMING GENDER

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

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ABBREVIATIONS

CEP	Complex Event Processing
EC	European Commission
KPI	Key Performance Indicator
LCA	Life-cycle assessment
LLM	Large Language Model
MSx	Milestone x
Mx	Month x
OAS	OpenAPI Specification
RDF	Resource Description Framework
RSCST	Resilience, Sustainability & Circularity Stress Testing
SMN	Smart Manufacturing Network
SPARQL	SPARQL Protocol and RDF Query Language (a recursive acronym)
Tx.x	Task x.x
WP	Work Package

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EXECUTIVE SUMMARY

The Smart Manufacturing Network (SMN) serves as the backbone of a company's supply chain and production infrastructure, leveraging a network of Digital Twins (DTs) to enhance operational efficiency, real-time monitoring, and predictive analytics. This interconnected ecosystem ensures that every input to the network is first processed by a Complex Event Processing (CEP) system, which assesses data streams for potential hints, warnings, or alarms, enabling proactive decision-making and issue mitigation.

Given the critical role this infrastructure plays in maintaining smooth and uninterrupted operations, regular and rigorous testing is essential to ensure reliability, accuracy, and optimal performance. The testing framework is structured into test sequences, each composed of distinct use cases that simulate real-world scenarios and validate system responses.

The tests are organized as test sequences that each consist of separate use-cases. Each use-case consists of at least three steps, a CEP part (a set of CEP rules), optionally a detection of possible remedies, and optional user-actions. This systematic approach to testing ensures that the SMN remains robust, adaptive, and capable of addressing dynamic manufacturing challenges. By continuously refining the testing methodology and integrating emerging technologies, the system fosters resilience, minimizes downtime, and enhances overall supply chain efficiency.

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1. INTRODUCTION

1.1. TESTING THE SMART MANUFACTURING NETWORK (SMN)

Within the NARRATE project, a company's supply chain and production infrastructure shall be modeled as a Smart Manufacturing Network (SMN). This should contain the complete ecosystem from the confirmation of an order to delivery in a self-orchestrated way.

- Deliverable 2.1 'Resilience Strategy & Tool' describes and categorizes challenges into Internal and External Risks and Disruptions and proposes resilience strategies at both System and Operational levels. It also presents key performance indicators for assessing resilience.
- Deliverable D3.2 'Digital Twin Design & Development (A)' introduces NARRATE Blueprint Frames (types of the real-world objects represented in the SMN) and the Digital Twin Processing Language (DTPL). DTPL enables programmable Digital Twin behaviours, supporting AI-driven insights, real-time analytics, and dynamic resource orchestration.

The SMN of a company's supply chain and production infrastructure is represented by a network of Digital Twins (DTs). The DTs are highly interconnected and of different types (also known as blueprints), e.g. routes, machines, suppliers, etc. This storage medium represents the chain and production infrastructure in its current situation. In particular, it reflects all deliveries and production steps in their structure and the contents of the respective DTs. The network receives and incorporates all events that take place within the system. Before an event reaches the network and possibly causes changes therein, the event passes through a CEP.

This infrastructure forms a crucial part of the respective company and thus it needs to be ensured that it is always up and running. This is established by regular tests. Apart from ensuring system functioning at least some tests are also checking system performance and stability. A certain time frame is required for the complete test or even parts thereof and a test error is raised, if the time is exceeded. Tests will be executed on a regular basis.

1.2. THE TESTS

There are tests serving different purposes, namely:

1. Stress tests: These tests check whether the system is stable under load. With regard to tests running upon test data, it is sufficient to run some tests with three steps that involves heavy CEP checking (many rules, more than one that fires), more than one network-query that does deep querying and suggests many options plus choosing an option involving lots of changes to the data. These tests do only work on test data.
2. Performance tests: These tests check whether a certain use-case can be accomplished in time. Different from stress testing these tests do not imply heavy parallelism. Thus, it can be tested

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whether the steps the test consists of can completely be run in an expected time frame both per step as well as the complete use-case. These tests make sense upon both the test and the company-specific data.

3. Algorithm correctness tests: These are meant to check parts of the overall executive system individually. CEP tests might only consist of one step and check whether the CEP reacts as expected. Tests concerning the network querying may stop after having done so and only check these results. These tests make sense upon both the test and the company-specific data.

4. Data correctness tests: These tests are only applied to company-specific data and check whether the current network allows us to fulfil those obligations which are considered required, for example, a material that should be always available is stored or can be ordered in a way that will not arouse any leakage. A product that is currently to be delivered or ordered by customers should be the result of a production chain that currently is executed. These tests do not utilize CEP but query the network directly.

The tests ensuring SMN availability are organized as test sequences that each consist of separate use-cases. Some sequences operate on specific network data that is fixed, i.e. it is especially provided for the tests and thus not specific to the company owning the network to be tested. Other parts deal with company specific data. The company specific tests need to be broader with respect to what is expected as results

Each use-case consists of at least three steps:

1. CEP-Part: A use-case contains one or more CEP rule tests. Every event that goes into the SMN and might cause changes therein goes through a CEP beforehand. A CEP rule that fires might be content to just provide a hint/warning/alarm to a human user and the IMC. In this case the test ends with assuring that the outcoming of the expected message type and content. If the test is not an accurate one the tests here can be vague, i.e. more than one type may be acceptable, and the text needs to contain a certain text bit instead of being the same as expected. It is important to note that a use-case may (and should) contain use-cases with rules that do not fire when the respective test is undertaken (negative tests).

2. The Remedy-Creation: A use-case contains option-creations in cases where at least one rule of the CEP rule set therein fires and requires more than a mere message creation. Each option creation uses the information contained in a message from a CEP rule and, firstly, understands what the problem is. This is understood by asking queries towards the network. Secondly, a subsequent round of queries identifies potential remedies. In the normal use of the system, the options (if any) would then be presented in a user pop-up to a human being that needs to decide whether a remedy is taken and which one. While testing the set of options is checked against a fixed set of options being provided with this test-step. The test may require equality or just a certain resemblance.

3. User-Action: Since these tests may modify the network, they are only utilized in a scenario that operates on test data. If the option-creation has created options, one or more of these options might then be simulated upon the network. Obviously, this is not an option in cases where the test sequence operates upon real company specific data. Simulation involves undertaking the changes

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and checking that the changes have the expected effects. As mentioned above, a change to the network in the non-testing mode is always preceded by a CEP rule check. This would possibly cause other rules to be fired. We do not want this here, thus in test-mode this second-level rule checking should be switched off.

Use-cases are time-boxed. Each use case has a maximum duration which is established by running the use case a number of times and seeing what can be expected. It must be noted though, that causing a disruption yields a different result (and takes a different amount of time) since the data the disruption is applied upon may vary. Still, a duration can be set by looking at all cases that did yield a sensible result and take the maximum. If a use case exceeds its time, it is stopped unless the following use cases will not be tested at all.

Each run of a test sequence should produce a test output presenting the list of use-cases that have been run and providing for each use-case the steps that were tried and what the results have been. Possible results are:

- ok
- incorrect (the test ran but the result was not as expected)
- error (the test did not reach the end)
- exceeded (did not complete in time)

In addition, time-stamps need to be given to see, when exactly a case was executed and how long it took. Test outputs should be provided in a machine-readable form and stored in a database so that analysing queries can be utilized.

1.3. LIFE-CYCLE ASSESSMENT TESTS

Life-cycle assessment (LCA) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service. If environmental impacts can be detected while executing a certain step in the network, a test sequence that reflects all steps necessary to produce a certain product can be used to provide information about this product's impact.

Different to other tests, Life-cycle assessment tests cater for an addition type of failure, namely lca-failure which occurs when the environmental impact is more than regarded appropriate. The values which are regarded as appropriate are stored as fixed values within the test. An 'Appropriate Impact' herein means not much above the average.

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2. COMPLEX EVENT PROCESSING (CEP)

Any action that takes place in (or in certain cases also outside) the SMN is not only reflected in the DT network but also passes through a Complex Event Processing (CEP) beforehand to check whether the action is worth a hint, warning or even an alarm that should be brought to a human's attention, and, if the human decides so, might even cause changes to the system. As CEP system we will probably use Perseo that is part of the open-source FIWARE [1] software stack.

The samples provided within this deliverable have so far been run with Esper [2] which is also open-source and does not differ from Perseo and especially uses the same rule language namely the Event Processing Language (EPL). The EPL is commonly used in Complex Event Processing engines, and it enables real-time pattern detection over event streams.

Example: Anomaly Detection in Machine Temperature (CEP in EPL)

This EPL rule detects if a machine's temperature exceeds 100°C for three consecutive readings.

```
SELECT machineId, avg(temperature) as avgTemp

FROM TemperatureEvent.win:time_batch(10 sec)

HAVING avg(temperature) > 100
```

Explanation:

- TemperatureEvent.win:time_batch(10 sec): Processes temperature events in 10-second windows.
- avg(temperature) > 100: Flags an event when the average temperature is above 100°C.

The Digital Twin Programming Language in D3.2 is a relatively new paradigm designed for Digital Twins to query, simulate real-world processes, and trigger actions. While EPL and DTPL serve different primary purposes, EPL can be embedded within DTPL models to facilitate event-driven behaviour in Digital Twins, particularly for handling data that inhabits Digital Twin and real-time analytics.

The following is an example of DTPL, which detects delays in raw material delivery and reallocates stock from an alternative supplier in the Medwood Supply Chain.

```
Detecting a Delay in Raw Material Delivery
DTPL Query: Check if any supplier shipments are delayed /* Event */
SELECT shipment_id, supplier, expected_arrival, delay_time
FROM SMN(Medwood SupplyChain.LOGISTICS_SERVICES)
WHERE status = "delayed";


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

This example could be expressed in DTPL in terms of embedded EPL as follows.

```
process ShipmentDelayDetection {
    input event ShipmentEvent(shipment_id: String, supplier: String, expected_arrival: Timestamp,
     delay_time: Integer, status: String);
    state shipment_status: String;
    when ShipmentEvent -> {
        // EPL Query for Detecting Delayed Shipments
        execute EPL {
            SELECT shipment_id, supplier, expected_arrival, delay_time
            FROM ShipmentEvent.win:time(30 min)
            WHERE status = 'delayed';
        } INTO delayedShipments;
        if exists(delayedShipments) {
            // Reallocate stock from an alternative supplier
            UPDATE SMN(MedwoodSupplyChain.LOGISTICS_SERVICES)
            SET supplier = 'Alternative_Supplier_X'
            WHERE shipment_id = delayedShipments.shipment_id;
        }
    }
}
```

For an infrastructure that runs the tests the samples provided in this deliverable will be Java JUnit tests. Herin, we are using the following tools:

- Eclipse Version: 2022-09 (4.25.0), Build id: 20220908-1902
- JavaSE-1.8
- esper-common + esper-compiler from maven in version 8.9.0.
- JUnit 5

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3. QUERYING & MODIFYING THE SMN

The network is established as an interrelated set of DTs. These DTs are represented as Resource Description Framework (RDF) documents. Querying and modifying the network is established by an AI-driven visibility model using Large Language Models (LLMs) and adhering to the OpenAPI Specification (OAS) as introduced In D4.2.

Queries towards the network can be represented as graphs.

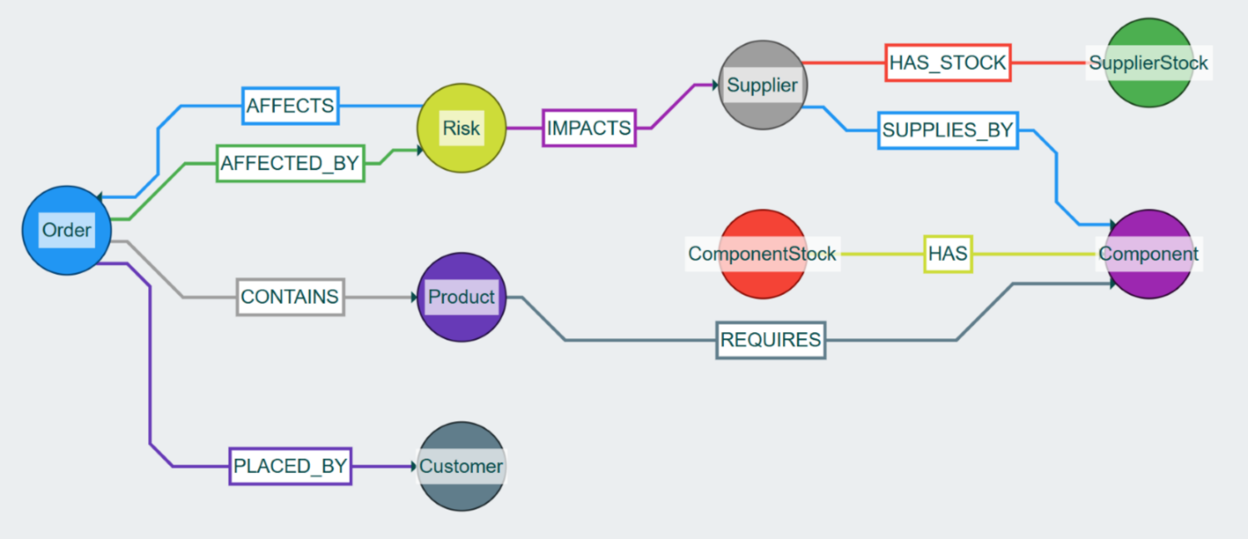

FIGURE 1: A SAMPLE NETWORK QUERY

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4. RUNNING & ANALYZING THE TESTS, MITIGATION

The tests should be run regularly, preferably at times when the system isn't too busy otherwise, i.e. at night. This however implies that both the supply chains and the production sequences do not run equally over the complete schedule.

In addition to storing query results, more alarming actions should be taken in case of tests that do not end with an 'ok' result. This could for example be sending a mail to a specified distribution list.

4.1. MITIGATION

The mitigation strategy for test failures depends on the type of test that has failed and the kind of failure. The following table provides an overview about the appropriate strategy in each case.

Test type	Failure	Mitigation
Stress test	incorrect	There should be a correction test showing the same problem in a better analysable way. If not, add that test.
Stress test	error	This is serious because it either means that there is a bug in the system and/or the tests or, that the overall system is overloaded. For the latter, first stop all testing to ensure that the available resources are spared. Then analyse which resources are not sufficient and provide more of these.
Stress test	exceeded	This is serious because it means that the overall system is overloaded. first stop all testing to ensure that the available resources are spared. Then analyse which resources are not sufficient and provide more of these.
Algorithm correctness test	incorrect	Either an algorithm works wrongly or there is incorrect data, please check
	error	Apart from an algorithm that works wrongly or incorrect data, there might also be a problem with the test itself or its running environment, please check
	exceeded	This might be an error, or the time frame is to low.
Data correctness test	any failure	Needs assistance by a business expert

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lca tests	lca-failure	Needs assistance by a business expert
	any other failure	There should be a correction test showing the same problem in a better analysable way. If not, add that test.

TABLE 1 : MITIGATION PLANS

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5. A SAMPLE CEP USE-CASE

In summary, the sample use-case functions as follows:

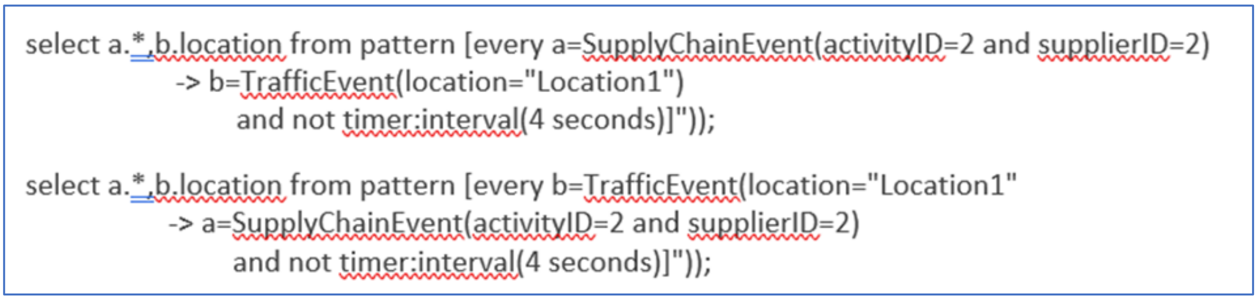
The rules belonging to this use-case should do the following: When a traffic event occurs in an area where a supplier is located from which an order is expected, a warning should be generated in cases where the time in which the traffic event occurs, and the time in which the order is sent, are close. The test triggers actions that cause one of the rules to be fired and ensures that the type and the message of the produced event are as expected.

If so, the SPARQL query belonging to the use-case asks the network for possible remedies to this and produces an explanatory text plus a set of remedies. It is checked that both the explanatory text is as expected and, also, the expected set of remedies is suggested.

The test fakes that the user selects the first remedy and executes the SPARQL query associated with this remedy upon the network. The test ensures that the actions were indeed taken.

5.1. SAMPLE CEP

For the moment we assume that the supplier in case is "Supplier1" and the location with the traffic event is "Location1". Furthermore, the activities a delivery can pass through are numbered and respective activityID "sent" is "2". Also, the suppliers are numbered, and our supplier here is also "2" The two EPL rules that reflect our use-case are the following:



```
select a.*,b.location from pattern [every a=SupplyChainEvent(activityID=2 and supplierID=2)
                    -> b=TrafficEvent(location="Location1")
                            and not timer:interval(4 seconds)]"));

select a.*,b.location from pattern [every b=TrafficEvent(location="Location1"
                   -> a=SupplyChainEvent(activityID=2 and supplierID=2)
                           and not timer:interval(4 seconds)]"));
```

FIGURE 2: TWO CEP RULES

As we see, the interval that reflects the term "close" in the plain words' version, in rule form is 4 seconds. This makes sense in a test scenario. Whether this is also reasonable in the non-test scenario is doubtful though. This was chosen to make the tests run quicker. In a non-test scenario, a value in the minute's realm would be more reasonable here. Of course, the set of rules used for test and non-test should be the same otherwise tests would be a bit useless. Still, the question arises here, whether automatic adaptions may be applied to the ruleset before a non-test set is introduces to the test infrastructure.

The following shows a JUnit test dealing with these rules:

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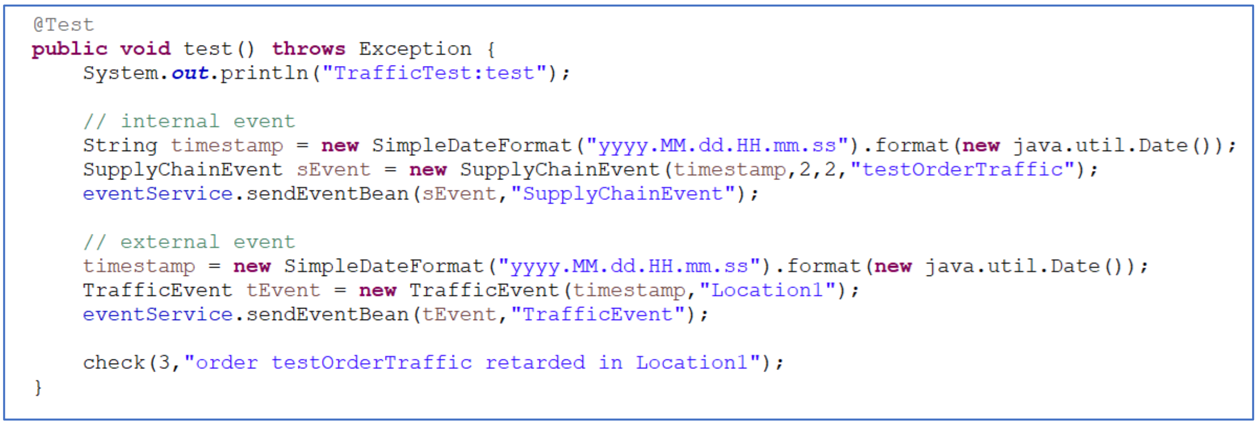

```
@Test
public void test() throws Exception {
    System.out.println("TrafficTest:test");

    // internal event
    String timestamp = new SimpleDateFormat("yyyy.MM.dd.HH.mm.ss").format(new java.util.Date());
    SupplyChainEvent sEvent = new SupplyChainEvent(timestamp,2,2,"testOrderTraffic");
    eventService.sendEventBean(sEvent,"SupplyChainEvent");

    // external event
    timestamp = new SimpleDateFormat("yyyy.MM.dd.HH.mm.ss").format(new java.util.Date());
    TrafficEvent tEvent = new TrafficEvent(timestamp,"Location1");
    eventService.sendEventBean(tEvent,"TrafficEvent");

    check(3,"order testOrderTraffic retarded in Location1");
}
```

FIGURE 3: A JUNIT TEST

Also, it needs to be said that our sample rule is a bit non-generic. Surely such a rule will exist for any supplier that isn't in-house and for any location that may cause a traffic-induced hassle to this supplier. The latter is an information that needs to available in the network. So, our CEP rules providing facility needs to cater for this kind of rule generation. This is a topic dealt with in the second Work Package (WP) however.

5.2. SAMPLE SMN QUERY

If one of these rules is triggered, in a non-test scenario, a pop-up should occur telling the user that there might be a problem and, eventually, the system suggests remedies. In the test scenario there is no pop-up, but the message explaining the problem and the list of suggestions likewise. So, in both scenarios, a SPARQL query associated with the ruleset is run upon the network.

Since there is no exact understanding of the network by now, the query can here be suggested only in plain words and might look as such:

Find all soon processes which require the materials that are part of the order that possibly gets delayed. For each of these processes, find out how things can be amended. Possible amendments are, firstly, getting the materials from elsewhere, getting the parts that are built using this material from elsewhere as a whole, or producing without this material. The latter can be done by using stored material, ordering from a different supplier, or using a congenial material that is available.

And the result for the non-test case might look as follows:

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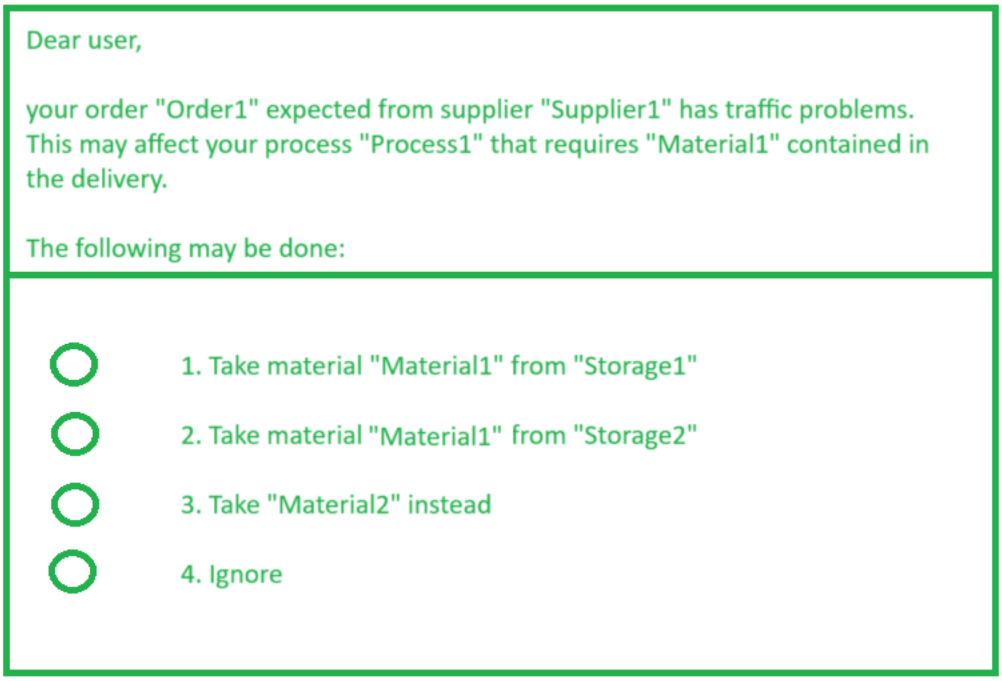

Dear user,

your order "Order1" expected from supplier "Supplier1" has traffic problems. This may affect your process "Process1" that requires "Material1" contained in the delivery.

The following may be done:

○ 1. Take material "Material1" from "Storage1"

○ 2. Take material "Material1" from "Storage2"

○ 3. Take "Material2" instead

○ 4. Ignore

FIGURE 4: A SAMPLE POP-UP

It seems that the algorithm here is still a bit rough. In addition to what we see here, it might be advisable to do prioritisation or otherwise provide more help to the user, how helpful the different remedies might be. In our case that would mean a hint, how much time will probably be lost in each case especially compared to the "ignore" case. Furthermore, there might be new risks associated to the remedies that might be interesting. Also, a tree structure would look better here than a simple listing. For the test sample we ignore that for now.

5.3. SAMPLE USER-ACTION

The test now fakes that the user chooses the first remedy, this is, taking the material from "Storage1". Executing this means that the network representing the storage is modified. The test checks that the item is in a situation expected pre-test, executes the SPARQL query that does the modification, and compares the item's post-test situation with the one the test expects.

5.4. SAMPLE TEST OUTPUT

SID	UID	Use case	CEP-Step	Remedy-Step	User-Action Step
12	17	Delivery-Alarm	Ok Start 2025.02.20.15.17.45 End 2025.02.20.15.18.46	Ok Start 2025.02.20.15.18.47 End 2025.02.20.15.19.05	Ok Start 2025.02.20.15.19.45 End 2025.02.20.15.21.07

TABLE 2 : OUTPUT OF THE SAMPLE TEST RUN

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6. RESILIENCE, SUSTAINABILITY & CIRCULARITY STRESS TESTING TOOL

Deliverable D4.1 aims to design a Resilience, Sustainability & Circularity Stress Testing (RSCST) Tool. This tool identifies vulnerabilities and strengthens SMN resilience by minimizing the impact of disruptions and ensuring rapid recovery. The tool will use dynamic simulation within the Intelligent Manufacturing Custodian and integrate Digital Twin, AI-driven predictive analytics, IoT sensing and complex event processing to stress-test the SMN ecosystem. The RSCST Tool will leverage the CEP functionality and Event Processing Language detailed in Section 2.

The RSCST Tool herein is currently in an early design phase, serving as a foundational framework that will be continuously refined and expanded throughout the project. It will undergo iterative improvements to ensure its capabilities align with real-world manufacturing challenges and emerging technological advancements. Regular evaluations, conducted in close collaboration with pilot stakeholders and technical teams, will drive enhancements in resilience, sustainability, and circularity testing. This iterative approach will ensure that the tool remains adaptive, precise, and effectively integrated within the broader IMC and SMN context.

The RSCST Tool will consist of the key components described below.

6.1. DYNAMIC SIMULATION FOR STRESS TESTING THE SMN

To assess resilience, realistic stress-testing scenarios will be developed using the SMN digital twin, a virtual representation of suppliers, logistics, production lines, warehouses, and transportation within an SMN. The stress tests will model interactions, dependencies, and disruptions caused by unexpected events, including those detected via IoT signals.

Disruptions Modelled in Stress Testing:

In the following we consider several of the disruptions investigated and reported in D2.1. These include:

1. **Supplier Delays:**
   - Late deliveries due to supplier-side issues (raw material shortages, **labour** strikes, geopolitical factors, financial instability).
   - IoT Data Source: RFID tracking, GPS-based shipment monitoring, and real-time stock level updates from supplier ERP systems.
   - Resilience Strategy: Dynamic supplier diversification, real-time sourcing, and automated procurement adjustments.
2. **Machine Malfunctions & Factory Downtime:**
   - Breakdown of critical manufacturing equipment causing production halts.

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- IoT Data Source: Sensor-driven predictive maintenance (vibration, temperature, pressure readings) to predict machine failures.
- Resilience Strategy: AI-based predictive maintenance, redundant machinery allocation, rapid reconfiguration of production processes.

3. **Transportation Delays & Logistics Disruptions:**

- Traffic congestion, weather-related delays, fuel shortages, or route blockages.
- IoT Data Source: GPS fleet tracking, weather forecasting, and AI-driven route optimization.
- Resilience Strategy: AI-powered rerouting, dynamic warehousing solutions, and multimodal transportation flexibility.

4. **Demand Fluctuations:**

- Sudden increases or decreases in customer orders due to external economic factors.

6.2. ANALYZING STRESS TEST RESULTS: OPERATIONAL, SUSTAINABILITY & CIRCULARITY IMPACT

The RSCST will process stress test data to evaluate KPIs reported in D2.1 including the following:

Key Performance Indicators (KPIs) Monitored:

- Operational Metrics: Lead times, throughput, supply chain response time, order fulfilment rates.
- Resilience Metrics: Time to recover from disruption, availability of backup resources.
- Sustainability Impact: CO_2 emissions due to logistics delays, waste generation from inefficiencies.
- Circularity Indicators: Resource reuse, waste reduction, alternative material sourcing strategies.

Human-Expert Interaction with the RSCST:

- The RSCST will visualize real-time stress test results.
- Experts would be able to compare different recovery strategies, evaluate trade-offs, and optimize contingency plans.
- Open-source OpenLCA (www.openlca.porg) will analyse environmental datasets to integrate sustainability and circularity considerations into decision-making when interfacing the RSCST with the IMC.

6.3. DEVELOPMENT OF A PRELIMINARY RESILIENCE MITIGATION PLAN

Based on the stress test results, the RSCST will define a Resilience Mitigation Plan with AI-driven recommendations when coupled with the Resilience Digital Module (RDM) tool that will be developed in T2.1, and IMC in WPs 4 and 6 to enhance robustness.

Proposed Resilience Strategies:

1. AI-Powered Predictive Maintenance:

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- Real-time sensor analysis via the IMC toolset to prevent machine failures.
- Autonomous self-repair mechanisms via Digital Twin simulations.

2. Dynamic Supply Chain Adaptation:

- AI-based supplier risk assessment & automated supplier reallocation via the IMC.
- Multi-source procurement to mitigate dependency risks.

3. Self-Optimizing Logistics & Transportation:

- IoT-based real-time fleet tracking for predictive rerouting.
- Multimodal logistics strategies to switch between transport modes dynamically.

4. Adaptive Manufacturing:

- On-demand production models adjusting to fluctuating demand.

6.4. INDUSTRY-SPECIFIC CASE STUDY

This section integrates a customized cot manufacturing case study from pilot 1 (viz. Medwood pilot) within the NARRATE project, specifically focusing on resilience, sustainability, and circularity stress testing within a Smart Manufacturing Network. The RSCST Tool, embedded in the Intelligent Manufacturing Custodian, will assess and mitigate risks in this and the other two NARRATE pilots. In the following we shall concentrate on bespoke cot production, which is part of the Medwood pilot, to illustrate how the RSCST Tool ensures efficient, sustainable, and resilient manufacturing processes.

6.4.1 Pilot Study Overview: Smart Manufacturing for Bespoke Cot Construction

Industry Challenges in Customized Cot Manufacturing

Bespoke cot construction within an SMN involves multiple interconnected processes:

- Material Sourcing: Wood, eco-friendly paints, custom fabrics, hardware (RSCrews, hinges).
- Production: CNC machining, robotic assembly, manual craftsmanship.
- Logistics: Just-in-time (JIT) component deliveries, on-demand order fulfilment.
- Sustainability: Minimizing wood waste, optimizing energy consumption, ensuring non-toxic materials.
- Circularity: Recycling excess materials, repurposing defective parts, modular designs for extended product life.

The RSCST Tool will stress-test this SMN to assess vulnerabilities in supplier reliability, production disruptions, transportation delays, and IoT-driven failures.

6.4.2 Disruptions Modelled in the RSCST Tool

In the following we consider some typical disruptions in the Medwood pilot case study.

(A) Supply Chain Disruptions

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Scenario: Supplier Delays in Wood & Non-Toxic Paint Deliveries

- **Impact:** Production slowdown, order backlogs, increased lead times.
- **IoT Signal Source:** Supplier RFID & inventory IoT sensors detect low stock levels.
- **Resilience Strategy:**
  - Dynamic alternative supplier identification based on real-time AI risk assessment via the IMC when the RSCST toll will be coupled with other IMC components in release R1 and R2 in months 24 and 33.
  - Material substitution recommendations (e.g., Forest Stewardship Council (FRSC)-certified alternative wood).

(B) Machine Malfunctions in Smart Manufacturing

Scenario: Computer Numerical Control (CNC) Router Fails During Wood Cutting

- **Impact:** Halts in precision cutting, production bottlenecks, scrap waste.
- **IoT Signal Source:** Vibration, heat, and motor current anomalies detected by machine sensors.
- **Resilience Strategy:**
  - AI-powered predictive maintenance alerts triggered before critical failures.
  - Autonomous load balancing across alternative CNC machines in the SMN.
  - Real-time Digital Twin simulation to test fallback manufacturing strategies.

(C) Logistics & Transportation Delays

Scenario: Shipping Disruptions for Hardware Components (RSCrews, Hinges)

- **Impact:** Assembly delays, final product shipment backlog.
- **IoT Signal Source:** GPS-based tracking data from logistics partners detects route congestion.
- **Resilience Strategy:**
  - AI-driven real-time supplier reallocation for critical components when the RSCST toll will be coupled with other IMC components in release R1 and R2 in months 24 and 33.
  - Multimodal transport shift (e.g., switching from road to rail freight).
  - Localized micro-factories (3D-printing certain components on demand).

6.5. IMPLEMENTATION OF THE SUSTAINABILITY & CIRCULARITY STRESS TESTING TOOL

The RSCST Tool will be embedded into the IMC's Digital Twin & the IMC's AI decision-making framework, enabling real-time resilience assessments.

6.5.1 RSCST Tool Functionality

1. **Real-Time Stress Testing with Digital Twin Integration**

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- Simulating disruptions across the entire supply and production network.
- Monitoring IoT signals to detect vulnerabilities before failures occur.
- Analysing risk RSCenarios for operational, sustainability, and circularity impact.

2. **Automated Sustainability & Circularity Optimization**

- Life Cycle Assessment (LCA) with OpenLCA to calculate CO_2 emissions, energy use, and material waste.
- AI-driven recommendations via the IMC to enhance circularity (e.g., upcycling offcuts into new furniture components).

3. **AI-Powered Predictive & PreRSCriptive Analytics using the IMC**

- Real-time decision support for human operators.
- Autonomous SMN reconfiguration to dynamically reroute supply and production processes.
- Closed-loop optimization integrating AI, IoT, and Digital Twin insights for self-adaptive manufacturing.

6.5.2 Next Steps

(A) RSCST Prototype Development & Digital Twin Integration

Objective: Build a prototype of the RSCST Tool, integrating it with the Digital Twin of the SMN.

Key Actions

1. **Digital Twin Development for Stress Testing**

- Model customized cot production workflows in the virtual blueprint frame environment in WP-3.
- Simulate real-world disruptions: supplier delays, machine failures, logistics disruptions, and IoT sensor faults, extending the functionality of the Digital Twin blueprint frames in D3.2.

2. **IoT Data Collection & Integration with the RSCST**

- Connect real-time sensor data from factory machinery (e.g., CNC machines).
- Integrate GPS tracking & warehouse inventory data to assess supply chain disruptions.

3. **Algorithm Development for Stress Testing & Resilience Analysis**

- Train AI models for predicting supply chain vulnerabilities & production bottlenecks when the RSCST tool will be coupled with other IMC components in release R1 and R2 in months 24 and 33.
- Implement prescriptive analytics to suggest dynamic mitigation strategies.

4. **Circularity Optimization Module Implementation**

- Develop AI-driven material reuse and waste reduction strategies.
- Integrate OpenLCA for real-time sustainability impact calculations.

5. **RSCST Tool Prototype Deployment in a Controlled Environment**

- Test the prototype in a virtual simulation before pilot deployment.

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- Validate its accuracy in predicting and mitigating disruptions.

(B) Pilot Deployment

Objective: Deploy the RSCST Tool in a selected factory manufacturing bespoke cots, running live tests and other NARRATE pilot live tests.

Key Actions

1. **Factory Selection & Testbed Deployment**
   - Choose IoT-enabled production lines for pilot testing.
   - Install RSCST software in the IMC and connect with factory systems in release R2.
2. **Live Stress Testing & Data Collection**
   - Conduct real-world stress tests based on historical disruptions (e.g., past machine breakdowns, supply shortages).
   - Collect real-time feedback on RSCST tool performance.
3. **Resilience & Circularity Mitigation Implementation**
   - Apply RSCST-driven recommendations for supplier diversification, predictive maintenance, and inventory optimization.
   - Optimize circular economy workflows, such as for instance reusing wood RSCraps in production in the Medwood pilot.
4. **Continuous Refinement & AI Model Optimization**
   - Improve AI models that interconnect the RSCST tool functionality with the IMC toolset based on live pilot data.
   - Adjust resilience thresholds and response times to better fit industry needs as specified in the three pilots in WP-5.

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7. CONCLUSIONS AND FUTURE WORK

Deliverable D4.1 serves as a foundational framework for advancing resilience, sustainability, and circularity testing in the upcoming phases of the project. Specifically, the RSCST Tool will act as a key enabler for integrating IoT-driven risk detection, AI-powered decision-making, and Digital Twin-enabled simulations, transforming the Smart Manufacturing Network into a self-adaptive, disruption-resistant ecosystem.

By combining IoT, Digital Twin technology, AI-driven analytics, and circular economy principles, the RSCST Tool will empower manufacturers to:

- **MINIMIZE OPERATIONAL DISRUPTIONS** through AI-driven predictive analytics and proactive mitigation strategies.
- **REDUCE ENVIRONMENTAL** impact by optimizing resource consumption, energy efficiency, and emissions.
- **ENHANCE CIRCULARITY** by facilitating the use of recyclable materials, remanufacturing processes, and digital waste tracking.
- **ENABLE REAL-TIME DECISION-MAKING** for dynamic supply chain reconfiguration and disaster recovery.

This preliminary design remains a dynamic and evolving framework, continuously refined to ensure precise and effective implementation in the subsequent project phases. It will undergo ongoing evaluation and enhancement through close collaboration with pilot stakeholders and technical teams.

Moving forward, the next steps will focus on:

- Expanding the RSCST Tool with AI models for predictive analytics.
- Integrating OpenLCA for comprehensive sustainability scoring.
- Refining Digital Twin-based simulations for enhanced accuracy and real-world applicability.

These advancements will further solidify the RSCST Tool's role in driving resilience, sustainability, and circularity within the SMN.

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