# D3.4

# Validated STT3 methodology & toolkit

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## Abstract

This deliverable presents the Stress Test Tier 3 (SST3) methodology developed within the AGILE project, focusing on the quantitative analysis of cascading failure dynamics in complex socio-technical systems under High Impact Low Probability (HILP) events. The methodology integrates three converging theoretical traditions, resilience stress testing, multilayer network science, and agent-based modelling, into a structured, transparent, and adaptable framework for examining how direct infrastructure disruptions propagate across interdependent systems and generate consequences for critical services, accessibility, and exposed populations. The document describes the conceptual foundations, implementation steps, tools, and evaluation criteria of SST3, including its relationship to the preceding tiers of the AGILE methodology. The framework is designed to remain applicable across different territorial scales, data environments, and governance settings, provided that system definition, stakeholder engagement, and assumption documentation are managed rigorously. Preliminary development-stage findings suggest that the methodology is analytically sound, practically implementable, and capable of generating decision-relevant insights when implementation is calibrated to the available data and stakeholder context.


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**Nature of the deliverable**[1] **R**

## Dissemination level

| | | |
|---|---|---|
| **PU** | Public, fully open. e.g., website | ✓ |
| **SEN** | Sensitive, limited under the conditions of the Grant Agreement | |
| **CL** | Classified information under the Commission Decision No2015/444 | |

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[1] Deliverable types:

R: document, report (excluding periodic and final reports).

DEM: demonstrator, pilot, prototype, plan designs.

DEC: websites, patent filings, press and media actions, videos, etc.

OTHER: software, technical diagrams, etc.

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# Abbreviations

| | |
|---|---|
| **ABM** | Agent-based-modeling |
| **AI** | Artificial Intelligence |
| **HILP** | High Impact Low Probability |
| **CI** | Critical Infrastructure |
| **ST0** | Stress Test Tier 0 |
| **STT1** | Stress Test Tier 1 |
| **STT2** | Stress Test Tier 2 |
| **STT3** | Stress Test Tier 3 |
| **ODD+D** | Overview, Design Concepts and Details + Decision-making |
| **VVE** | Verification, Validation, and Evaluation approach |
| **TAM** | Technology Acceptance Model |
| **DRL** | Deep Reinforcement Learning |

**Glossary of Network Science terminology**

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|---|---|
| **Node (Vertex):** | A fundamental unit of a network, representing an entity (e.g., an actor, infrastructure component, or spatial unit) connected to others via edges. |
| **Edge (Link):** | A connection between two nodes, representing a relationship or interaction. Edges can be directed or undirected, and weighted or unweighted. |
| **Degree:** | The number of edges connected to a node. In directed networks, distinguished as *in-degree* and *out-degree*. |
| **Betweenness Centrality:** | A measure of a node's importance based on how frequently it lies on the shortest paths between all pairs of other nodes in the network. Nodes with high betweenness act as critical bridges or bottlenecks for information or flow propagation. |
| **Closeness Centrality:** | A measure of how quickly a node can reach all other nodes in the network, computed as the inverse of the average shortest path length to all other nodes. Nodes with high closeness can disseminate information or impacts rapidly across the network. |
| **Clustering Coefficient:** | A measure of the degree to which a node's neighbours are also connected to each other, indicating the local cohesiveness or redundancy around that node. A high clustering coefficient suggests the presence of tightly-knit local communities. |
| **Hub Node:** | A node with a significantly higher degree than average. Hubs are structurally influential and their failure can rapidly fragment the network (see also: *scale-free networks*). |
| **High-Closeness, High-Hub Node:** | A node that combines both high closeness centrality and hub characteristics — meaning it is both well-connected (many direct links) and centrally positioned (short paths to all others). Such nodes are particularly critical for network resilience, as their disruption can simultaneously isolate large portions of the network and slow system-wide propagation. |

# Executive summary


- This deliverable presents the AGILE Stress Test Tier 3 (SST3) methodology and toolkit. The present document focuses specifically on the quantitative STT3 component and on how it builds on earlier scoping, qualitative, and semi-quantitative tiers. SST3 provides a structured way to analyse how extreme stress conditions may propagate through complex socio-technical systems via direct disruption, interdependency-driven cascading effects, and resulting consequences for services, accessibility, and exposed populations.
- Validation draws on the application of the methodology in applied stress test settings, iterative exchanges with stakeholders and infrastructure experts, and the progressive formalisation of the approach from qualitative elicitation to semi-quantitative dependency analysis and finally to a quantitative computational modelling. The results show that the tiered structure is methodologically coherent, practically usable, and capable of producing decision-relevant insights at different levels of data availability and analytical maturity.
- Overall, the methodology is sufficiently mature for structured application in diverse systems from organizations to local, regional and national contexts, provided that implementation is calibrated to the purpose of the analysis, the availability of data, and the level of stakeholder engagement that can be mobilised.

# 1. Introduction & Scope

The AGILE project develops a novel and scalable methodology for tiered risk and resilience stress tests, co-developed with disaster risk management practitioners and other key stakeholders. Within this broader framework, stress testing is used to examine how complex socio-economic systems behave under High Impact Low Probability (HILP) events, with particular attention to critical infrastructure interdependencies, cascading effects, and the resilience of societal functions.

The methodology adopts a tiered approach that combines breadth, flexibility, and increasing analytical depth within a coherent stress-testing framework. In AGILE, the tiers support qualitative, semi-quantitative, and advanced quantitative analyses of socio-technical systems across different governance levels, sectors, and application settings. They are not alternative methods, but progressively more formalised levels of analysis, differing in purpose, data requirements, stakeholder involvement, and outputs, while remaining aligned through common principles of system focus, threat-agnosticism, and resilience (Linkov et al., 2018, 2022).

The original rationale behind the tiered approach is that, in real-world decision-making contexts, it is rarely feasible to invest the same level of analytical effort, data collection, modelling capacity, and stakeholder time in all systems, sectors, or locations. The tiers therefore serve both a diagnostic and a prioritisation function. They provide a reasonable initial assessment of the system and help determine whether, given the available resources, the relevance of the system, and the severity or complexity of the identified vulnerabilities, a more specific and detailed analysis is justified. For this reason, STT3 is not conceived as a pure isolated modelling exercise, but as the most advanced stage of a process that should normally be preceded by STT1 and STT2 or similar scoping activities. These earlier tiers help define whether a quantitative model is needed, what it should focus on, and which interdependencies, failure pathways, and stakeholder concerns should be represented. STT3 can be implemented without previous tiers, but the initial steps of the methodology are likely to include a more extensive data collection phase and system characterization, to make up for the missing elements belonging to previous stress STT.

0. Pre-ST or STT0 provides the preparatory scoping of the system. It defines the system boundary, identifies relevant elements and stakeholders, and clarifies the critical functions, organisations, governance components, and technologies that need to be considered. It provides the initial information base for subsequent stress-testing activities.
1. STT1 is a qualitative scoping study. In line with the AGILE stress test design, it uses extreme high-impact, low-probability scenarios to expose vulnerabilities, challenge existing plans, and support out-of-the-box reflection on possible system-wide breakdowns. It is typically implemented as an interactive one-day tabletop exercise, using a serious card game format.
2. STT2 is a semi-quantitative interdependency analysis. It provides a more structured understanding of perceived physical interdependencies between Critical Infrastructures and decision interdependencies between organisations and infrastructures. In AGILE, it is framed as a more detailed tabletop exercise combining semi-quantitative methods, stakeholder knowledge, and interdependency analysis to support integrated resilience planning across sectors and organisations.
3. STT3 is the advanced quantitative tier. It uses modelling tools such as network science, Artificial Intelligence (AI), and agent-based modelling (ABM) to explore risk dynamics, simulate cascading failures across interconnected domains, and test possible interventions under natural, climate-related, and human-induced hazards. STT3 is

developed through collaboration between local stakeholders, including public authorities, Critical Infrastructure managers, and researchers, in order to build a digital network model of the system. The aim of this model is to represent how impacts may spread across interconnected infrastructure layers and how they may affect population groups, service availability, accessibility, and critical functions under extreme stress conditions.

Deliverable 3.4 focuses on the STT3 Risk and Resilience Stress Testing Methodology. STT3 is informed by the outputs of the preceding tiers. STT0 supports the definition of the system boundary, relevant sectors, and critical functions. STT1 identifies plausible stress conditions, vulnerability patterns, and candidate failure pathways that may not be visible from infrastructure data alone. STT2 provides structured dependency maps and bottleneck analyses, which form the starting point for the quantitative representation of the system.

Compared with the previous tiers, STT3 introduces a stronger geospatial and computational dimension. It represents infrastructure asset locations, hazard impact areas, accessibility constraints, and the spatial distribution of exposed populations and resources. It also provides a more explicit representation of intra- and inter-infrastructure dependencies, operational rules, service constraints, and outputs related to service availability, accessibility, population exposure, and resource allocation.

Stakeholder contribution remains essential in STT3, but its role becomes more targeted. While STT1 and STT2 mainly support broad exploration, shared understanding, and interdependency mapping, stakeholder knowledge in STT3 is used to refine assumptions, check plausibility, validate dependencies and operational rules, and ensure that model outputs remain interpretable and decision-relevant. Coordinating preparatory activities, including data-sharing agreements, expert interviews, and validation sessions, is therefore a fundamental component of the methodology, especially when multiple organisations contribute knowledge or data under different confidentiality constraints.

STT3 is intended to support systematic scenario exploration rather than deterministic prediction. It allows analysts to examine how different assumptions, direct impact configurations, dependency structures, and response rules may produce different systemic consequences. In particular, it enables the explicit representation of cascading failures across sectors, the interaction between infrastructure disruption and mobility constraints, and the resulting implications for population safety, service access, and reallocation needs.

For this reason, STT3 does not replace the earlier tiers. It requires substantially more data, analytical preparation, modelling effort, and validation than STT1 or STT2, and its effectiveness depends on the quality of the preceding scoping and interdependency analysis. The qualitative and semi-quantitative insights generated in STT1 and STT2 are essential for defining the scope of the model, identifying critical interdependencies, selecting relevant disruption mechanisms, and ensuring that the quantitative representation remains grounded in stakeholder knowledge and system understanding.

The final output of STT3 is a documented, scenario-based modelling framework that supports the structured exploration of cascading impacts, service disruption, accessibility loss, and consequences for the population under extreme stress conditions. In line with the AGILE STT3 concept, the framework is intended not only to simulate disruption pathways, but also to evaluate alternative resilience strategies and possible interventions through a transparent and reproducible analytical tool.

# 2. Conceptual Foundations

## 2.1. Theoretical foundations of the STT3 methodology

Modern societies depend on complex and interconnected socio-technical systems, in which infrastructures, services, institutions and populations interact across multiple spatial and functional scales. These interdependencies support efficiency, coordination and service continuity under normal operating conditions. At the same time, they also create systemic vulnerabilities: disruptions affecting one component may propagate across sectors, generate cascading or compounding effects, and compromise the ability of the system to maintain essential functions (Linkov et al., 2018).

Conventional approaches to safety and risk assessment are only partly suited to this type of problem. They typically evaluate infrastructure components in isolation, under predefined hazard scenarios, and measure performance against expected failure thresholds. This component-level and hazard-specific logic is useful for well-characterised risks, but it becomes insufficient when applied to large interdependent systems. In particular, it does not adequately capture how failures propagate across infrastructure layers, how indirect consequences accumulate, or how systems adapt and recover under stress (Linkov et al, 2022).

The STT3 methodology developed within AGILE addresses this limitation by combining a set of methodological principles with scientific approaches for systemic analysis. Its methodological principles are system focus, threat-agnosticism and a resilience perspective. These principles define the object of analysis, the way disruptions are conceptualised, and the evaluative logic of the stress test. They are operationalised through two complementary modelling approaches: multilayer network science, which represents infrastructure interdependencies and cascading propagation, and agent-based modelling, which represents heterogeneous behaviours, adaptation and time-dependent system response.

Stress testing originates in fields such as medicine, engineering and material science, where increasing levels of pressure are applied to a system in order to observe its response and identify critical thresholds. When extended to socio-technical systems, stress testing shifts the focus from the probability of a specific hazard to the behaviour of the system under degraded conditions. Rather than asking whether an individual component fails under a given threat, resilience stress testing asks how the system as a whole absorbs disruption, maintains critical functions, reorganises and recovers (Linkov & Trump, 2019; Hollnagel et al., 2017).

This perspective is particularly relevant for High Impact Low Probability events, which often exceed historical experience, design assumptions and conventional planning scenarios (Pescaroli et al., 2025). In such events, the most severe consequences may arise not only from direct physical damage, but from indirect, cascading and compounding effects across infrastructure and social systems (Alexander & Pescaroli, 2019; Helbing, 2013). For this reason, a resilience stress-testing approach is better suited than a purely risk-based approach to explore the systemic consequences of extreme disruption.

Accordingly, the STT3 methodology does not aim to forecast the probability of a specific hazard, nor to reproduce a single historical event. Instead, it evaluates the structural and functional behaviour of the system under alternative degraded conditions. This is consistent with the

resilience stress-testing framework advanced by Linkov et al., (2018, 2022) and Trump et al., (2025), and provides the conceptual basis for the methodological principles and modelling approaches described below.

### 2.1.1. System focus

A core principle of the methodology is its explicit system focus. The object of analysis is not a single infrastructure, organization, or hazard, but the broader system in which critical functions arise through the interaction of multiple components. These components may include physical infrastructures, institutional actors, emergency functions, service providers, environmental constraints, and population groups. The methodology therefore treats disruption as a system-level phenomenon and examines how impacts emerge through interdependencies, bottlenecks, substitutions, and failures of coordination.

This system focus is particularly important in stress testing for HILP events for two compounding reasons. First, the increasing interconnectedness of modern infrastructure systems means that the exposure surface to cascading failure has grown substantially: as Helbing, (2013) argues, today's strongly connected global networks have produced highly interdependent systems that are vulnerable to failure at all scales, even in the absence of external shocks, and whose complexity makes cascade dynamics difficult to anticipate or control. Second, and as a direct consequence, the most severe consequences of HILP events often arise not from direct damage but from indirect and cross-sectoral effects that propagate through these interdependencies (Alexander & Pescaroli, 2019). A road closure may affect emergency access, supply chains, workforce mobility, and utility restoration; power loss may affect water, communications, health services, and public order; and governance failures may amplify otherwise manageable disruptions (Pescaroli et al., 2018). The methodology is designed to make such interactions visible and analysable.

Operationally, the system focus is implemented through explicit system definition, identification of relevant sectors and actors, mapping dependencies, and analysis of how disruptions propagate between functions. This approach avoids narrow sectoral assessments and supports a more realistic understanding of systemic vulnerability, criticality, and resilience.

### 2.1.2. Threat-agnosticism

A second defining principle of the STT3 methodology is threat-agnosticism. The stress test does not rely on a single hazard-specific logic. Instead, it represents a wide range of possible disruptions in terms of their consequences for system functioning. Examples include loss of accessibility to critical assets, service interruption, loss of infrastructure operativity, reduced availability of emergency functions, or inability to protect exposed populations. The purpose of the methodology is to examine how such consequences could emerge under different extreme conditions. This does not mean that hazards are ignored. Rather, hazards are treated as scenario triggers or external perturbations that activate structural weaknesses and interdependencies already present in the system. As Linkov et al., (2022) argue, resilience analytics favours a threat-agnostic approach because it focuses on how the structure and interdependencies of a system perform under degraded conditions. By avoiding reliance on narrowly predefined hazard scenarios, the methodology can explore novel threat combinations and the dynamic evolution of risks over time (Trump et al., 2025).

This principle is especially relevant for HILP events, where uncertainty is high and historical experience may provide only limited guidance (Pescaroli et al., 2025). In such contexts, the exact

threat type, timing, intensity or combination of hazards cannot be predicted with confidence. A threat-agnostic approach therefore allows the analysis to focus on the capacities and weaknesses of the system itself, rather than on the probability of a specific initiating event.

By including hazards as inputs rather than as the organising logic of the model, the STT3 analytical framework can be applied to different combinations of natural, technological, hybrid or cascading shocks without requiring a separate conceptual model for each case. This encourages decision-makers to focus on robustness, adaptability and systemic resilience rather than preparing only for previously experienced or narrowly defined hazards (Trump et al., 2025).

### 2.1.3. Resilience perspective

The third methodological principle is the resilience perspective. In this context, resilience is understood not only as the ability to resist or absorb disruption, but also as the ability to adapt, maintain critical functions, reorganise under stress and recover in ways that preserve or improve essential system performance (Folke, 2006; Linkov et al., 2018). This perspective broadens the analysis beyond failure detection and enables consideration of coping capacity, substitutes, fallback arrangements, governance responses and recovery pathways.

A resilience perspective is particularly valuable for stress testing because extreme events often exceed design assumptions and invalidate normal operating procedures (Hollnagel et al., 2017). Under such conditions, the key analytical question is not only what fails, but also what continues to function, what can be reconfigured, where adaptive capacity exists, and which interventions could reduce systemic consequences. The methodology therefore pays attention not only to vulnerabilities and points of failure, but also to redundancies, protective capacities, alternative pathways and coordination mechanisms (Linkov et al., 2022).

This perspective also supports decision relevance. By identifying both weaknesses and leverage points for strengthening the system, the stress test becomes a tool for resilience-oriented planning rather than a purely diagnostic exercise (Trump et al., 2025). It can therefore inform preparedness, contingency planning, investment prioritisation and cross-sectoral coordination.

### 2.1.4. Scientific methodologies used to perform systemic analysis

The methodological principles described above require analytical approaches capable of representing both interdependencies and system dynamics. The shift in the unit of analysis from individual components to the system as a whole cannot be supported by component-level assessment alone. It requires frameworks that can capture how infrastructures are connected, how disruptions propagate across these connections, and how heterogeneous actors and functions respond over time. In STT3, this is achieved through the integration of multilayer network science and agent-based modelling.

Graph-theoretic representations of infrastructure systems have a long theoretical tradition (Rinaldi et al., 2001), and their extension to multilayer and interdependent network models has substantially advanced the formal understanding of systemic fragility. The theoretical significance of this approach lies in a fundamental insight: the vulnerability of a system is determined not by the properties of its individual components, but by the topology of their interdependencies (Buldyrev et al., 2010; Valdez et al., 2020). This has been demonstrated formally in the theory of cascading failures in interdependent networks, showing that systems individually robust to single-node failures can undergo abrupt, total collapse when failures propagate across layers, a phenomenon with no analogue in single-layer network theory (Buldyrev et al., 2010; Gao et al.,

2012; Green, 2023). Network topology metrics provide the analytical vocabulary for identifying which nodes and links govern systemic fragility, how rapidly disruptions propagate, and where the system is most sensitive to cascading collapse (Casali & Heinimann, 2019). In the multilayer formulation adopted by STT3, consistent with Linkov et al., (2024), each node can sustain both intra-network dependencies with other nodes in the same layer and inter-network dependencies with nodes in other layers, producing a representational structure capable of encoding the full complexity of modern Critical Infrastructure interdependencies, and its impacts on larger systems. Network topology metrics provide an analytical vocabulary for identifying which nodes and links govern systemic fragility, how disruptions may propagate, and where the system is most sensitive to cascading effects (Casali & Heinimann, 2019). In the multilayer formulation adopted by STT3, consistent with Linkov et al. (2024), each node can sustain both intra-network dependencies with other nodes in the same layer and inter-network dependencies with nodes in other layers. This provides a representational structure capable of encoding the complexity of modern critical infrastructure interdependencies and their consequences for wider socio-technical systems.

Network science therefore provides the structural component of the STT3 methodology. It allows the model to represent infrastructure layers, dependency relations, critical nodes, connectivity constraints and possible pathways of failure propagation. However, structural representation alone is not sufficient for resilience stress testing. The key analytical questions concern not only how failures spread across a system topology, but also how the system responds over time: how populations move, how services are rerouted, how alternative destinations are selected, how exposure changes, and how consequences accumulate across different groups.

Agent-based modelling (ABM) addresses this gap by representing the system as a population of individual entities – agents – each characterised by its own properties, states, and behavioural rules, embedded in an environment with which they interact (Ouyang, 2014). The theoretical advantage of ABM lies in its capacity to generate emergent system-level behaviour from local interactions: phenomena that are not derivable from the properties of individual components but arise from their collective dynamics (Bonabeau, 2002). This makes ABM particularly suited to the study of HILP events, which may produce system states with limited or no historical precedent and cannot be adequately represented by approaches that only extrapolate from observed behaviour. As Ouyang (2014) shows in his taxonomy of modelling approaches for interdependent critical infrastructure systems, ABM is particularly useful for representing heterogeneous component behaviours and their mutual interactions under stress. The integration of temporal network perspectives further extends this capacity by introducing a chronological dimension to agent interactions, enabling the representation of time-sequenced failure propagation, adaptation and recovery dynamics (Cimellaro et al., 2024)

The integration of multilayer network science and agent-based modelling therefore provides STT3 with both structural precision and dynamic capacity. Network science supports the representation of interdependencies and cascading propagation across infrastructure layers. Agent-based modelling supports the representation of heterogeneous behaviours, adaptive responses and population-level consequences. Together, they operationalise the system focus, threat-agnosticism and resilience perspective that define the STT3 methodology. The following section explains how this theoretical foundation is translated into the operational methodology.

## 2.2. Relevance and application of the theoretical foundations

The theoretical foundations introduced in the preceding section are relevant to the STT3 methodology because they are the base of both its conceptual orientation and its analytical implementation. The methodological principles of system focus, threat-agnosticism and resilience

orientation define what the stress test is intended to analyse, how disruption is conceptualised, and how system performance is evaluated under degraded conditions. Multilayer network science and agent-based modelling provide the scientific and computational approaches through which these principles are translated into an operational model.

These foundations do not operate as separate or parallel components. Their relevance lies in their integration. A system focus requires the explicit representation of relations between infrastructures, services, institutions, environmental constraints and exposed populations. A threat-agnostic approach requires the ability to impose different forms of disruption without redesigning the model around each specific hazard. A resilience perspective requires the analysis of what continues to function, what can be reconfigured, where adaptive capacity exists, and how consequences evolve across time and across affected groups.

In STT3, these requirements are operationalised through three analytical functions. First, the methodology must represent systemic interdependence, making explicit how different infrastructure layers, service functions and population groups depend on one another. Second, it must propagate cascading failures, so that the indirect consequences of disruption can be traced across connected systems rather than being limited to directly affected assets. Third, it must simulate dynamic responses, including changes in accessibility, service availability, population exposure, destination choice and support needs under degraded conditions.

These three functions provide the bridge between the theoretical foundations of STT3 and its practical application. They explain how abstract concepts such as systemic vulnerability, threat-agnostic stress testing and resilience-oriented assessment are translated into a model structure that can be applied to concrete case studies.

### 2.2.1. Representing systemic interdependence

The first analytical challenge is representational: the methodology must encode the structure of interdependencies across infrastructure systems in a form that is both theoretically rigorous and practically usable. This is the role of the multilayer network framework. It allows infrastructures and services to be represented not as isolated assets, but as connected layers whose behaviour depends on internal connections and cross-layer dependencies.

The relevance of this approach becomes clear when applied to systems of realistic complexity. Linkov et al. (2024), for example, show how a multilayer network representation can be used to analyse the Late Bronze Age Collapse of 1200–1100 BCE as an interdependent trade and political network spanning major Eastern Mediterranean polities. Their analysis demonstrates a principle that is directly relevant to contemporary infrastructure systems: robustness at the level of individual components does not necessarily imply resilience at the level of the system. A network may remain stable when individual nodes fail, but become highly fragile when multiple critical nodes fail concurrently and trigger cascading effects across layers.

This insight is central to the STT3 methodology. The vulnerability of an interconnected system is determined not only by the intrinsic fragility of individual components, but also by the topology of their dependencies. The position of an asset within a network, the number and type of services depending on it, and its role in connecting otherwise separate parts of the system may determine whether a local disruption remains contained or becomes systemic. For this reason, STT3 requires the explicit mapping of both intra-network and inter-network dependencies across infrastructure layers as a precondition for subsequent analysis (Buldyrev et al., 2010; Rinaldi et al., 2001).

In operational terms, representing systemic interdependence means defining the relevant infrastructure layers, identifying the entities within each layer, specifying the dependency relations between them, and linking these structures to the services and population groups that may be affected. This provides the structural basis for analysing how disruption can move from one part of the system to another.

### 2.2.2. Propagating cascading failures

Once interdependencies have been represented, the second analytical challenge is to trace how disruptions propagate through the system. The objective is not only to identify which components are directly affected by an initial perturbation, but also to reveal indirect, higher-order and cross-sectoral consequences that conventional component-level assessments may miss.

Network topology provides the analytical basis for this task. As Casali & Heinimann, (2019) argue, the topology of the network influences how rapidly and how widely a failure spreads. Nodes with high betweenness centrality (e.g., a bridge node) may act as bottlenecks whose removal fragments the network. An example of high-betweenness centrality node is a major highway interchange connecting two otherwise poorly linked urban districts exemplifies a high-betweenness node. Even if the interchange serves relatively few direct users compared to a city-centre road, its closure forces all cross-district traffic through long detours or severs connectivity entirely. In infrastructure stress testing, such nodes are prime candidates for triggering cascade failures across transport and logistics chains.

Nodes with high closeness centrality may be reached more quickly by propagating disruptions. Highly connected or strategically positioned nodes may therefore generate consequences that are disproportionate to their physical size or apparent sectoral importance. An example of this can be a regional electricity substation that distributes power to multiple municipalities illustrates high closeness centrality. Because it sits at short topological distance from a large share of the network, any disruption originating at, or reaching, this node propagates quickly and broadly across the system, with little time or buffer for downstream operators to react.

Arosio et al., (2020) operationalise this logic in a procedure directly applicable to infrastructure stress testing, iteratively removing directly impacted nodes and re-evaluating the connectivity of the remaining graph at successive orders of impact. Their results show that indirect impacts – transmitted through severed service links – can ultimately affect a far larger share of the system than the initial hazard footprint would suggest, precisely because certain high-hub nodes serve as critical intermediaries whose failure simultaneously cuts off service supply to large numbers of downstream receivers. An example is a wastewater treatment plant receiving inputs from dozens of municipal collection networks and discharging into a shared water body represents a high-hub node. Its simultaneous connections to many upstream suppliers and downstream receivers mean that its failure does not affect one link in isolation: it simultaneously cuts service to all connected municipalities and may trigger regulatory or environmental consequences across the receiving environment. This non-linear amplification is one of the central reasons why HILP events cannot be assessed only through direct damage estimates. Their consequences must be traced through the full propagation dynamics of the interdependent system (Pescaroli & Alexander, 2018).

In the STT3 methodology, this propagation logic acts as the analytical engine through which local failures are translated into system-level impacts. A directly disrupted electricity asset may affect water infrastructure, transport operations, emergency facilities or shelters. A road closure may

alter accessibility to services, constrain evacuation routes, delay emergency response or isolate population groups. A disruption in one layer may therefore modify the functioning of other layers, producing cascading effects that unfold through the system's dependency structure.

This approach is consistent with the threat-agnostic orientation of STT3. The model does not need to be redesigned for each hazard type. Instead, different hazards can be represented as different configurations of direct impacts, such as inaccessible roads, non-operative infrastructure nodes, service interruptions, flooded areas or reduced facility availability. The propagation mechanism then traces how these initial disruptions generate wider systemic consequences.

### 2.2.3. Simulating dynamic responses

Representing interdependencies and propagating failures through network topology captures the structural dimension of cascading disruption. However, this is not sufficient for resilience stress testing. Resilience is not only a property of network structure; it also depends on how the system responds over time. Infrastructure operators may adapt, services may be rerouted, emergency functions may be reallocated, and population groups may change their behaviour in response to evolving conditions.

This is where agent-based modelling becomes analytically important. ABM represents the system as a set of entities with their own states, properties and behavioural rules, interacting with one another and with the environment. This makes it possible to represent heterogeneous actors and functions rather than assuming that all components behave in the same way. In the context of STT3, this is essential because infrastructure components, shelters, service points and population groups do not simply fail or remain functional; they may change state, depend on other components, become unavailable, receive demand, or trigger reallocation needs.

Carramiñana et al., (2024) conceptualise the city as a complex adaptive system in which infrastructure networks can be represented as interacting node-agents, each operating according to internal logic and reactive rules, while links represent the dynamic exchange of resources and services. This hybrid framing is closely aligned with the logic of STT3. It combines the structural precision of network science with the behavioural and temporal granularity of ABM, allowing local changes to generate emergent system-level consequences.

The temporal dimension is also essential. As Cimellaro et al., (2024) argue through temporal network theory, the order and timing of interactions matter for understanding failure propagation and recovery dynamics. In STT3, this allows disruptions to be represented not only as static damage states, but as evolving conditions. Direct impacts may occur at different moments, cascading effects may propagate through dependencies, and population outcomes may depend on the state of accessibility and services at the time decisions are made.

In practical terms, this means that STT3 can simulate how infrastructure degradation affects exposed populations over time. For example, the model can evaluate whether residents or visitors can still reach accommodation, shelters, gateways or other safe destinations; whether these destinations remain accessible and operative; whether services such as electricity and water are available; and which groups may become stranded or require support. This dynamic response capacity is what allows STT3 to move beyond static vulnerability mapping and towards resilience-oriented stress testing.

### 2.2.4. Towards an integrated analytical framework

Together, the three analytical functions of representing interdependence, propagating failures and simulating responses constitute the applied architecture of the STT3 methodology. Each function corresponds to a specific methodological need. Systemic interdependence must be represented because modern socio-technical systems cannot be understood as isolated components. Cascading failures must be propagated because the most severe consequences of extreme events often emerge indirectly. Dynamic responses must be simulated because resilience depends on adaptation, reconfiguration and time-dependent system behaviour.

No single theoretical or modelling approach provides all of these capabilities on its own. Network science provides the representational structure and the propagation logic, but it must be complemented by dynamic modelling to capture behavioural and temporal responses. Agent-based modelling provides this dynamic capacity, but it requires a structured representation of the system and its interdependencies as its substrate. Resilience stress testing provides the evaluative framework that gives the analysis its purpose: assessing not only whether systems fail, but how they function, degrade, adapt and recover under extreme stress.

The STT3 methodology therefore integrates these approaches into a single analytical framework. It uses network-based representations to encode infrastructure dependencies and accessibility constraints; propagation rules to translate direct impacts into cascading consequences; and agent-based simulation to represent heterogeneous responses, exposure, accessibility, service availability and support needs.

### 2.2.5. Tiered approach and differentiation between the tiers

The rationale behind the tiered structure is practical as much as methodological. In real-world decision-making contexts, it is rarely feasible to invest the same level of analytical effort, data collection, modelling capacity, and stakeholder time across all systems, sectors, or locations. The tiers therefore serve two complementary functions: they provide a reasonable diagnostic of the system under examination, and they help determine whether, given the available resources and the importance of the system, a more specific and detailed level of analysis is warranted. This is why, in the ideal application of the methodology, all STT3 implementations are preceded by STT1 and STT2 processes.

Crucially, however, the tiers are not sequentially dependent in a strict sense. Completing an earlier tier strengthens the analytical foundation of the next, but it is not a prerequisite. Each tier can be applied independently, with appropriate adjustments to the scoping and data collection effort required to compensate for missing prior outputs. The value of progression lies not in obligation but in cumulative analytical gain: earlier tiers surface system knowledge, stakeholder insights, and interdependency patterns that would otherwise need to be reconstructed from scratch at a later stage.

STT0 occupies a particular position in this structure. As a preparatory scoping phase rather than a stress test tier in its own right, it does not produce stress-testing outputs but establishes the informational and relational conditions under which all subsequent tiers operate more effectively. Its contributions, i.e. system boundary definition, stakeholder mapping, and preliminary data gathering, provide a foundational layer that informs subsequent analytical choices across the full tiered sequence.

In practice, the degree to which tiers can be completed sequentially depends on project timelines, stakeholder availability, and data access conditions that are rarely fully controllable.

Where STT1 and STT2 outputs are available prior to STT3 development, they provide a more grounded system representation and a more targeted modelling scope. Where this sequential progression is not fully achieved, the methodology remains applicable, but the preparatory burden of STT3 increases accordingly and assumptions must be documented with greater care. Future applications of the methodology will be well positioned to test and consolidate the full sequential logic of the tiered approach under more controlled implementation conditions.

## 2.3. Assumptions and constraints

STT3 is designed to support the most detailed and explicit level of analysis within the tiered methodology. In principle, it can incorporate highly granular and infrastructure-specific information, including detailed asset locations, operational dependencies, service areas, failure thresholds, response rules, and population distributions. The objective of the tier is therefore not to simplify the system because detailed information is unnecessary, but to provide a modelling framework capable of using such information when it is available.

In real-world applications, however, the information required for this level of representation may be only partially available, heterogeneous in quality, or unevenly accessible across stakeholders and sectors. Under these conditions, the methodology can still be applied by using proxies, simplifying assumptions, or expert-informed approximations, provided that these are explicitly documented and treated as assumptions rather than as direct observations.

Open data availability is often limited, especially for Critical Infrastructure assets, dependency relations, operational procedures, and emergency resources. As Schotten et al., (2024) demonstrate for Critical Infrastructure network, a recurring challenge across all complex system modelling approaches is the availability and accessibility of sufficiently high-quality input and validation data. The resulting gaps frequently require modellers to assume specific technical parameters, functional relationships, and system behaviours, introducing uncertainties that are often poorly understood and difficult to capture. Even where open data exist, they may be spatially incomplete, temporally outdated, or insufficiently representative for stress-testing purposes; where more detailed data are available, they are often withheld due to confidentiality concerns related to infrastructure protection (Larsson & Große, 2023). The methodology therefore combines public datasets with stakeholder inputs where possible, while maintaining explicit documentation of assumptions and uncertainties.

The selection of infrastructures and critical functions to include in STT3 is based on the findings of previous Tiers, and is guided by analytical relevance, stakeholder engagement, and difficulty of data access. In practice, it is rarely possible to model all system components at the same level of detail. A scoping decision, based on the previous STTs findings and discussion with the case study partners, is therefore required to prioritise those sectors, interdependencies, and societal functions that are most relevant for the stress-testing objectives.

Co-design with multiple stakeholders improves realism, legitimacy, and contextual relevance, but also creates trade-offs. The framing of these trade-offs is itself shaped by the institutional perspective of the stress test owner, the organisation or governance body commissioning the analysis, whose priorities influence the definition of critical functions, the delineation of the system boundary, and the objectives the methodology is expected to serve. Making this framing explicit is therefore a precondition for meaningful multi-stakeholder co-design. Different organisations may have different priorities, levels of technical detail, and constraints on data sharing. The methodology therefore seeks a balance between technical specificity and cross-sectoral usability, recognising that a fully exhaustive representation is neither feasible nor always desirable. STT3

uses previous STT results and bilateral discussion between involved entities to define clear objectives, so that the end product of the analysis can respond to the interests and needs of the participants.

A further limitation concerns the availability of probabilistic fragility information at the level of individual assets. In many contexts, fragility curves or failure functions are not available, not validated for the local case, or not shareable. Empirical fragility curves tend to be scarce due to limited observational data, particularly within lower hazard intensity ranges, and where available, the majority of relationships between hazard intensity and asset damage have been derived through expert judgement approaches that may not be transferable to other regions or extrapolated to more severe events than those previously witnessed (Argyroudis et al., 2019; Karagiannakis et al., 2025). More broadly, even comprehensive fragility frameworks such as HAZUS (a GIS-based loss estimation software developed by FEMA, providing standardised fragility and damage functions for earthquakes, floods, and hurricanes) are limited to specific hazard types and asset classes, leaving many infrastructure categories and multi-hazard combinations without validated functions (Schotten et al., 2024). Where fragility information is available but held by operators or national authorities, confidentiality constraints further restrict access for analytical purposes (Larsson & Große, 2023). Where fragility data are unavailable or incomplete, the methodology responds through explicit assumptions, which are documented transparently as part of the analytical framework. Furthermore, one of the intended outputs of STT3 is precisely the identification of nodes whose systemic role justifies a more targeted and detailed individual assessment, including dedicated fragility characterisation where resources allow.

These assumptions and constraints do not invalidate the methodology, rather, they define the conditions under which it should be interpreted and applied. A central principle is therefore transparency: simplifications, data gaps, and abstraction choices should be documented clearly so that users understand both the analytical value and the boundaries of the resulting model outputs.

# 3. Objectives and Benefits

The objective of the STT3 methodology is to provide a structured, scalable, and transparent quantitative approach for systemic stress-testing in a HILP scenario. The elements of stress include different sources of disruption in complex socio-technical systems: direct impacts from hazards, cascading effects in critical infrastructure networks, resulting consequences for critical functions, infrastructure performance, availability of essential goods and services, and exposed populations. Within the broader AGILE project, this objective is consistent with the development and application of a novel, replicable, and multi-sectoral risk and resilience stress-testing methodology designed to support systemic analysis of HILP events across different geographic settings, sectors, and governance levels.

More specifically, STT3 is intended to support the design and application of a quantitative model capable of representing interdependent system components, relevant environmental and operational constraints, and the possible societal consequences of disruption under stress conditions. It is important to specify that STT3 analysis' purpose is not to provide deterministic prediction, but to support structured exploration of how different disruption patterns, dependency structures, and response assumptions may generate different systemic outcomes. In this respect, STT3 contributes to AGILE's broader ambition to strengthen risk and resilience analysis through

methods that are scientifically robust, practically applicable, and relevant to disaster risk management practice.

The methodology is intended for a range of users and decision contexts, including scientific and technical teams, public authorities, civil protection actors, infrastructure operators, and other organisations involved in preparedness, contingency planning, and resilience assessment. It is designed to support applications at local, regional, and, where appropriate, broader governance levels, provided that the system boundary, analytical priorities, and modelling scope are clearly defined. This is aligned with AGILE's overall mission of improving methodologies and tools for practical implementation and use by disaster risk management stakeholders.

Expected outputs from STT3 include structured representations of system interdependencies at asset scale, explicit descriptions of disruption pathways, scenario-based analyses of direct and cascading effects, and indicators or spatial outputs describing service disruption, accessibility constraints, and consequences for affected population groups. Depending on the application, the methodology may also support the exploration of alternative assumptions, response conditions, or resilience-enhancing interventions. This reflects AGILE's wider objective of developing stress-testing approaches that help identify vulnerabilities, analyse cascading failures, and support more effective resilience management and preparedness planning.

The main added value of the methodology lies in its ability to connect stakeholder knowledge, system understanding, and formal quantitative modelling within a common framework that remains threat-agnostic, resilience-oriented, and adaptable to different territorial and sectoral contexts. By combining structured scoping, explicit representation of interdependencies, and quantitative exploration of system behaviour under stress, STT3 provides a more detailed and analytically rigorous basis for examining systemic vulnerability than would be possible through qualitative or semi-quantitative approaches alone. At the same time, its modular design supports transferability, iterative refinement, and adaptation to different data environments and case-study conditions.

# 4. STT3 methodology

## 4.1. Method description

The methodology of STT3 can be structured as a sequence of steps progressively translating methodological concepts and findings from the previous tiers into an operational computational model. These steps may be organised through technical meetings, stakeholder exchanges, data transfers, coding phases, and validation workshops or structured interviews.

The implementation of STT3 is not conceived as a purely technical modelling exercise carried out in isolation. Rather, it includes iterative co-development and refinement with relevant stakeholders and domain experts in order to support model scoping, improve the plausibility of assumptions, refine key dependencies and operational rules, and ensure that the resulting outputs remain interpretable and decision-relevant.

The STT3 methodology is supported by two dedicated technical resources that underpin the development, documentation, and implementation of the agent-based model: the ODD+D template and the Python-based modelling environment.

**The ODD+D protocol, agent-based modelling protocol**

Agent-based models present particular challenges for transparency, replicability, and communication: their behaviour emerges from the interaction of many individually specified components whose collective dynamics are often opaque and difficult to anticipate, and early applications of ABM were widely criticised for being so poorly documented that model structures could not be understood, evaluated, or reproduced (Grimm et al., 2006). The flexibility and diversity inherent to the ABM paradigm, a source of its analytical power, simultaneously makes individual modelling studies prone to being disparate and opaque in their formulation, execution, and analysis (Daly et al., 2022). A structured documentation protocol is therefore not merely a reporting convention but a scientific necessity for model verification, validation, stakeholder communication, and iterative refinement. The STT3 ABM is documented and developed using the ODD+D protocol (Grimm et al., 2020; Müller et al., 2013), which provides a standardised framework specifically designed to address these challenges for agent-based and individual-based simulation models.

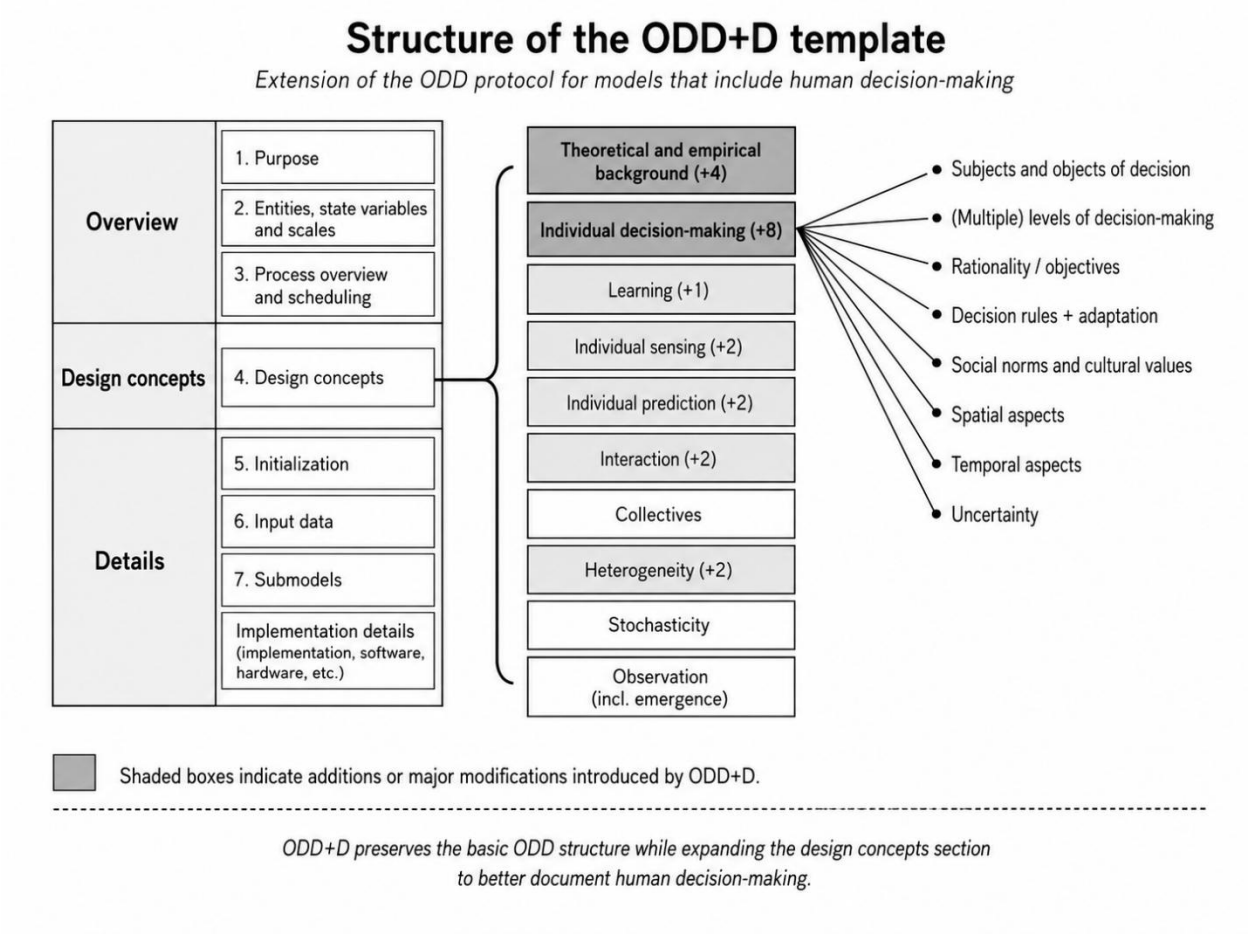


*Figure 1 Schematization of ODD+D protocol, re-elaborated from Grimm et al., (2020)*

ODD+D, standing for Overview, Design concepts, Details, plus Decision-making, builds on the ODD protocol originally developed by Grimm et al., (2006) for ecological and social-ecological simulation models, subsequently updated and consolidated in Grimm et al., (2020) to reflect advances in ABM practice across disciplines, schematized in Figure 1. The critical extension introduced by ODD+D is the explicit treatment of human decision-making: where the original ODD framework was primarily designed to describe the behaviour of non-cognitive agents in ecological

contexts, ODD+D adds a dedicated Decision-making component that captures how human and organisational agents perceive their environment, form objectives, and select actions. This extension is directly relevant to STT3, in which both technical infrastructure components and human actors (operators, emergency responders, civil protection units, and citizens) are represented as agents whose decisions shape the propagation and management of disruption.

Within the STT3 methodology, ODD+D serves a dual function. As a documentation standard, it ensures that all model components (purpose, entities, state variables, process scheduling, input data, submodels, and decision rules) are described in a clear, consistent, and auditable manner, improving traceability between conceptual assumptions, implementation choices, and analytical outputs. As a development framework, it structures the iterative dialogue between the modelling team, the host organisation, and wider stakeholders throughout the co-development and validation process: by providing a shared language for describing model behaviour, ODD+D makes it possible for non-modelling stakeholders to review, challenge, and contribute to the behavioural rules that govern agent actions, a particularly important feature given that the operational rules of infrastructure operators and emergency responders are co-developed with those actors as part of the AGILE methodology. In this sense, ODD+D supports not only the technical robustness of the model but the legitimacy and communicability of the stress-testing process as a whole.

**Python-based modelling environment**

The STT3 model is implemented in Python, which provides a flexible and widely used environment for building, testing, and documenting computational models. Python makes it possible to integrate different methodological components within a common workflow, including data preprocessing, simulation, spatial analysis, network analysis, and visualisation. In practical terms, the implementation may draw on libraries such as *Mesa* for agent-based modelling, *NetworkX* for network representation and dependency analysis, and additional packages such as *geopandas* and *rioxarray* for geospatial processing, numerical routines, and output generation. A limitation of this environment is that Python-based ABMs can become computationally demanding as model complexity and the number of agents increase, and that the absence of a single standardised ABM framework means that implementation choices, including the structure of agent classes, scheduling logic, and output routines, require explicit documentation to ensure reproducibility across teams and applications (Daly et al., 2022). The modelling environment supports transparency, reproducibility, modular refinement, and transferability across applications, and is well suited to the iterative co-development approach adopted in STT3.

### 4.1.1. Consolidation of findings from previous tiers

Consolidating the outputs of the previous tiers into a suitable form iis a pre-requisite for model development. Each tier contributes a distinct type of input, moving from qualitative scoping and stakeholder knowledge through structured dependency mapping to the quantitative formalisation that STT3 requires, and their contributions are complementary rather than redundant (Linkov et al., 2018, 2022). The objective at this stage is not yet to code the model, but to translate previously elicited knowledge into a set of explicit modelling requirements that will govern all subsequent modelling choices. If such knowledge can be obtained by previous tiers, STT3 must start by integrating the missing information.

This phase draws selectively on the contributions of each preceding tier. STT0 informs STT3 by supporting the initial definition of the system boundary, the identification of relevant stakeholders and sectors, the clarification of critical functions, and the preliminary selection of components that

are analytically meaningful to include in the model. It provides the conceptual perimeter within which all subsequent modelling choices are made. STT1 informs STT3 by surfacing plausible stress conditions, vulnerabilities, service disruptions, and cross-sectoral effects that may not be evident from infrastructure data alone. Through stakeholder engagement and qualitative scenario development, STT1 is particularly useful for identifying relevant consequences, priority stakeholder concerns, and candidate failure pathways – that is, the chains of disruption through which an initial stress event may propagate across the system – which subsequently inform the scenario configurations tested in STT3. STT2 analysis translates directly into inputs to SST3. Operating already on a network-based representation of the system, it produces a structured mapping of dependencies and bottlenecks that supports the selection of priority infrastructures, the formulation of direct impact configurations – the initial failure states from which cascading dynamics are simulated – and the formalisation of inter-network relationships to be encoded in the quantitative model.

This consolidation will produce a documented modelling specification that clarifies what the model is expected to address, which mechanisms are considered essential, what level of abstraction is appropriate for the intended analysis, and what assumptions are being made where knowledge is incomplete or uncertain. This specification provides the foundation for the first sections of the ODD+D documentation – in particular the Purpose, Entities, and State Variables components (Grimm et al., 2020; Müller et al., 2013) – and serves as the reference document against which subsequent modelling choices are reviewed and validated.

### 4.1.2. System definition and scoping

This step is, whenever possible, informed by the findings of previous tiers, and in particular of STT0. To ensure that implementation will provide valuable and sound outputs, it consists of a structured exchange between the stress test host and the modelling team to clarify the following topics:

- Purpose of the exercise and the expected outputs.
- System boundaries, including relevant decision context, available data, and the expected level of stakeholder engagement.
- Already existing frameworks and models of risk assessment and resilience.
- Definition of stakeholder strategy for data gathering and data management, especially for sensitive data.

In the case of STT3, system definition and scoping also helps determine which modelling activities can be supported directly by the host organisation, which require dedicated technical development by the modelling team, how many stakeholders should be involved in the co-development process and which kind of HILP scenarios should be prioritized.

When host and modeller are not the same entity, the scoping of the stress test should be discussed by both entities jointly. The definition of the scoping of STT3 consists in combining analytical priorities, stakeholder relevance, system criticality, data availability, and practical feasibility, which can evolve during the application of the methodology thanks to new findings about the system or due to constraints, see section 2.3 for more information about model assumptions and limitations.

Host and modellers must decide the target audience (infrastructure operators, civil protection emergency units, policymakers, ...), the objective of the test, and the level of confidentiality of the model application. Multiple system characteristic of the system boundaries should be discussed,

defining the spatial and temporal extent of the analysis, identifying the infrastructures, services, territorial units, and population categories to be included, selecting the stress conditions to be explored, and specifying all the data already available for all of the aforementioned topics. The system is then defined as a set of interdependent physical, organisational, and societal components that jointly sustain critical functions, including infrastructure assets, service providers, governance bodies, emergency organisations, and the populations that depend on them. This definition deliberately spans multiple domains, reflecting the theoretical principle established in Section 2.1 that systemic resilience cannot be assessed by examining any single infrastructure layer in isolation (Buldyrev et al., 2010). In STT3, this system definition is translated into a computational representation structured as a multilayer network of interdependent nodes and links, in which each node represents a functional component of the system and each link encodes a dependency, whether physical, organisational, service-based, or informational. The level of abstraction at which this representation is constructed is not fixed but in dialogue between the host organisation and the modelling team, as a function of the analytical objectives, the available data, and the stakeholder context. A more granular representation enables higher-fidelity simulation of localised failure dynamics but requires more detailed input data and greater computational resources; a more aggregate representation sacrifices some precision but broadens the range of scenarios that can be explored. This trade-off is one of the central scoping decisions of this phase, and its implications for model outputs are documented explicitly as part of the assumption and limitation framework described in Section 2.3.

Understanding existing information on the system also helps to define HILP events that are relevant for the purpose of application. Existing risk and resilience frameworks and models should be used to create realistic scenarios of possible impacts, which will be aggravated based on previous Tier outputs, stakeholder engagement or combining different scenarios to create high impact and low probability conditions to stress the system with.

### 4.1.3. Definition of the modelling architecture

Another major decision to be taken is the definition of the computational architecture of the STT3 model. As established in the theoretical foundations of the methodology (Section 2.1), the selected implementation approach is agent-based modelling, which provides the representational flexibility and dynamic simulation capacity required to examine cascading failure dynamics and adaptive system responses under HILP stress conditions. Under this approach, the system is represented through a population of entities – agents – each characterised by attributes, possible states, and rules governing their behaviour and interactions, operating within an environment that encodes the spatial, infrastructural, and operational conditions relevant to the stress test. A critical design decision at this step concerns the distinction between components that should be represented as agents and those more appropriately treated as environmental features, network elements, or static background constraints (Macal & North, 2010). In general, entities are most appropriately represented as agents when they possess an identifiable state, can undergo meaningful state transitions during the simulation, and play an active role in the evolution of the system through interactions, behaviours, or decision rules. Components whose primary function is to provide the physical or logical structure within which dynamics unfold – road network geometry, administrative boundaries, hazard intensity surfaces – are more appropriately represented as environmental features, unless modelling their internal dynamics is necessary to address the analytical objective. In a typical STT3 application, for example, an electricity substation would be represented as an agent with states ranging from fully operational to partially degraded to failed, and with behavioural rules governing its response to supply loss or downstream demand changes; the road network connecting it to other assets would instead form

part of the spatial environment, unless road-specific disruption dynamics are themselves an object of analysis.

The central output of this step is the dynamic architecture of the model, which defines three interdependent components. The first is the disruption mechanism: how direct impacts – the initial failure states, possibly informed by previous tiers – are introduced into the simulation and assigned to specific agents or network elements. The second is the propagation logic: how cascading effects spread through intra- and inter-network dependencies and agent interactions over time. The third is the temporal structure: how the simulation is organised into time steps or event sequences, how agent states are updated, and how the chronological dimension of disruption and recovery is represented, consistent with the temporal network theory described in Section 2.1 (Cimellaro et al., 2024).

The ODD+D protocol provides the structuring framework for documenting, in a form that is transparent, reviewable by non-modelling stakeholders and reproducible the decisions made at this step, like the definition of Entities, State Variables, Scales, and Process Overview and Scheduling components.

The definition of the modelling architecture may be refined iteratively through exchanges with stakeholders and domain experts, particularly when deciding the appropriate level of abstraction, the components to represent explicitly, and the dependency and response mechanisms to include. These exchanges are most productive when conducted with reference to the draft ODD+D documentation, which provides a shared language for discussing model structure without requiring stakeholders to engage with the underlying code.

### 4.1.4. Data collection and input structuring

This step consists of collecting, validating, and structuring the input data required to instantiate the computational model. Data collection in STT3 applications typically draws on multiple complementary sources. Publicly available datasets – including administrative geographies, population data, land use classifications, infrastructure network maps, and hazard or risk information – provide the baseline spatial and contextual layer. Stakeholder contributions, obtained through data-sharing agreements, technical interviews, or co-development sessions, are the primary source for dependency relationships, operational parameters, asset-level attributes, and emergency response resources. As discussed in Section 2.3, this reliance on stakeholder-contributed data introduces constraints that are characteristic of critical infrastructure analysis: detailed operational data are frequently withheld for confidentiality reasons, fragility information at the asset level is often unavailable or not validated for the local context, and the level of detail that infrastructure operators are willing or able to share varies significantly across sectors and institutions (Larsson & Große, 2023; Schotten et al., 2024).

The aim of this step is to produce an input structure that is internally consistent, aligned with the selected level of abstraction, and capable of supporting reproducible model construction, even where incomplete data require simplifications or approximations. Consistency checking at this stage involves verifying that datasets from different sources use compatible spatial references, temporal resolutions, and classification systems; that asset-level information can be linked across datasets; and that the dependency structure derived from stakeholder inputs is coherent with the network topology derived from geospatial data.

The two fundamental input types are geospatial data and dependency data (Rinaldi et al., 2001; Schotten et al., 2024). Main components may include, but are not limited to, critical infrastructures,

essential services, relevant spatial units, exposed population groups, and environmental conditions.

Geospatial data encompasses three levels of information. The first is a general characterisation of the system context: geography, administrative units, and population distribution. The second is infrastructure-specific information, including network topology, service coverage areas, and relevant sub-units or nodes. The third covers known impact and response information within the system: hazard and risk areas, exposure maps, and existing emergency management plans.

Dependency data consists of a mapping of intra- and inter-network relationships for each critical infrastructure included in the analysis. This encompasses the vulnerability of each main asset to hazard or stress conditions, the effects of asset failure or malfunction on other assets within the same network, and the cross-network dependencies through which disruption may propagate to other systems. Where the analysis includes cascading failure dynamics, the dependency data must be sufficient to identify the assets, systems, or service components considered relevant and the pathways through which disruption travels between them.

Beyond infrastructure, two further categories of input may be required depending on the scope of the application. Where the analysis includes societal consequences, additional information is needed to represent the population groups potentially affected and the conditions relevant to their exposure, accessibility, service loss, or reallocation needs. Where the model includes emergency response resources (shelters, evacuation destinations, emergency services) further information is required on their location, availability, capacity, and the conditions under which they remain operational under stress.

Where information gaps cannot be filled through data collection, three strategies are available: the use of simplified proxy representations based on structural or functional analogues from comparable systems; the application of expert elicitation to assign plausible parameter values; or the explicit exclusion of the undocumented component from the model scope, with corresponding adjustment of the analytical objectives. In all cases, the assumptions introduced at this stage must be recorded explicitly, both in the model documentation and in the corresponding Input Data section of the ODD+D protocol (Grimm et al., 2020; Müller et al., 2013), so that their implications for model outputs can be assessed during validation and communicated transparently to stakeholders.

The quality and completeness of the inputs have a direct bearing on the reliability and interpretability of all subsequent model outputs. For this reason, this step should be treated not as a preparatory task to be completed before modelling begins, but as an iterative process that continues in parallel with model development, as new data needs become apparent and as initial model runs reveal inconsistencies or gaps in the input structure.

### 4.1.5. Coding

The model of the system is developed as a modular python code, schematized in Figure 2.

The main parts of the code are:

- coding of the undisturbed model
- application of direct and cascading impacts

- exposed-system response logic (time steps and output)

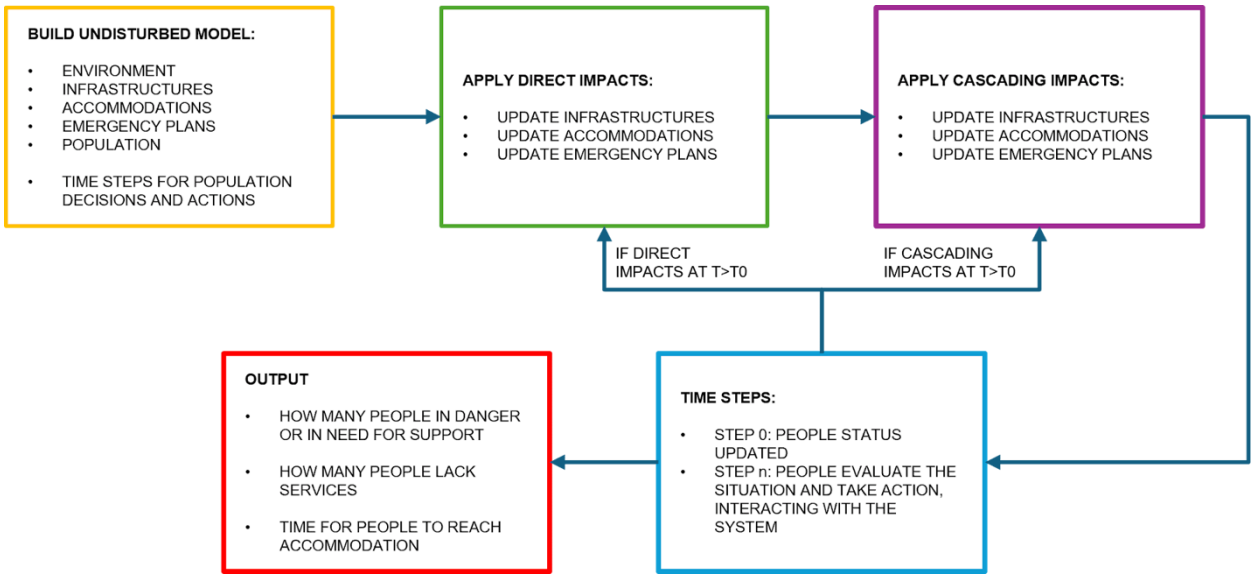


*Figure 2: Main steps of the modelling architecture*

### Coding of the undisturbed model

This step, described in the yellow box in Figure 2, consists in implementing the undisturbed system in computational form. Building on the modelling architecture and the structured inputs, this involves instantiating the selected agents and environmental components, assigning their initial attributes and operational states, and establishing the dependency relationships and interaction rules that govern baseline system behaviour.

The baseline representation serves a dual purpose. It reproduces the system configuration prior to the introduction of any stress condition, and it establishes the reference state against which all disrupted configurations are subsequently compared. The definition of impact in STT3 – whether measured in terms of service loss, connectivity degradation, population affected, or functional capacity – is therefore always relative to this baseline, making its accurate and consistent construction a precondition for the interpretability of all stress test outputs.

Once the baseline is implemented, this step includes a structured set of internal consistency and plausibility checks before any disturbance mechanisms are applied. These verify that agents are correctly instantiated and connected, that dependency relationships are coherent with the network topology, that initial states are consistent across interacting components, and that the model produces behaviourally plausible outputs under undisturbed conditions. Where possible, baseline behaviour should be validated against observed or documented system performance – such as known service coverage levels, typical accessibility conditions, or historical operational data – following the logic of pattern-oriented validation, in which the model is required to reproduce multiple known patterns of system behaviour simultaneously before it is applied to novel conditions (Grimm et al., 2006). The Initialisation component of the ODD+D protocol (Müller et

al., 2013) is populated at this stage, documenting the initial state of all agents and environmental elements and the data sources or assumptions on which that state is based.

A validated baseline is the essential precondition the following implementation, in which stress conditions are introduced and their propagation through the system is simulated.

**Coding of direct impacts and cascading logic**

These steps, described in the green and purple boxes in Figure 2, consist of implementing the disturbance logic of the model. Building on the propagation principles established in the theoretical foundations (Sections 2.1 and 2.2), this involves encoding both the direct impacts applied to the system and the cascading consequences generated through the dependency structure and agent interactions represented in the model.

Direct impacts are introduced as externally defined disturbances, possibly derived from the scenario configurations previous tiers, affecting selected agents or network elements at one or more predefined time steps. This makes it possible to represent not only single disruptive events but also sequences of impacts occurring at different moments in time, as may be required to analyse evolving, compounding, or multi-origin stress conditions characteristic of HILP events (Pescaroli et al., 2025).

Cascading impacts are generated as a downstream consequence of direct impacts propagating through the dependency structure of the model. Depending on the logic adopted, these effects may occur immediately following the triggering event or may emerge after a delay (Ouyang, 2014). Delays reflect empirically observed dynamics in which disruption does not propagate instantaneously across infrastructures and services: a power outage may take hours before affecting water treatment operations; a transport network failure may take days before disrupting supply chains or workforce availability. In the model, delays are represented through time-stepped state transitions in which the failure condition of an upstream agent is propagated to dependent downstream agents only after a defined interval, consistent with the temporal network logic described in Section 2.1 (Cimellaro et al., 2024).

The cascading logic is the most consequential modelling decision in STT3: small differences in how dependency relationships are encoded, how failure thresholds are defined, or how propagation delays are parameterised can produce substantially different system-wide outcomes (Pescaroli & Alexander, 2018). The Sub-models and Process Overview and Scheduling components of the ODD+D protocol (Grimm et al., 2020; Müller et al., 2013) are populated at this stage, providing a structured and auditable description of the disturbance and propagation mechanisms that is accessible to reviewers and non-modelling stakeholders alike.

**Coding of exposed-system response logic**

This step, described in the blue and red boxes in Figure 2, consists of implementing the behavioural or functional response routines governing how represented agents respond over time to the evolving state of the system. It may include movement rules, service-demand changes, rerouting mechanisms, operational adaptation, destination choice, or other response processes relevant to the selected system and analytical objective (Cimellaro et al., 2024).

A key design decision at this step concerns the source and structure of behavioural or operational response rules. Where empirical data on agent behaviour or operational response under stress conditions are available, such as historical evacuation records, mobility datasets, service-use data, operator logs, or emergency management documentation, these provide the basis for

calibrating agent decision rules (Pel et al., 2012). Where such data are not available, response rules may be derived from expert elicitation, relevant behavioural or operational literature, or co-development sessions with emergency management and infrastructure stakeholders, with the corresponding assumptions documented explicitly.

Equally important is the representation of heterogeneity across the agents included in the model. Different agent groups may have substantially different movement capacities, information access, physical mobility, operational roles, dependency on specific services, or vulnerability profiles, distinctions that aggregate models cannot capture but that ABM is specifically designed to represent (Bonabeau, 2002; Filatova et al., 2013; Taillandier et al., 2021). In STT3, agents may therefore be differentiated by attributes such as mobility constraints, operational function, proximity to resources, or dependence on public services, allowing the model to surface differential impacts that would be invisible in a uniform representation.

This step also populates the Sub-models component of the ODD+D protocol (Grimm et al., 2020; Müller et al., 2013) for behavioural or operational response processes, complementing the infrastructure cascading sub-models and completing the dynamic specification of the model.

This step is particularly important because it makes explicit how population consequences emerge not only from the existence of disruption, but from the interaction between infrastructure conditions, temporal dynamics, movement opportunities, and heterogeneous individual capacities within the affected system, capturing the kind of differentiated, time-dependent impact patterns that resilience stress testing is specifically designed to reveal.

### 4.1.6. Verification and validation

Assessing a model's quality and fitness for a given scenario is a fundamental challenge in the development and application of modelling approaches. A structured framework is required to ensure not only that the model is correctly implemented but also adequately represents the real system and proves useful in supporting decision-making. To this end, the ODD+D protocol (Müller et al., 2013) will be systematically applied to design and document the model, ensuring the clarity, transparency, and usefulness of its outputs.

In STT3, the assessment is organised following a structured framework inspired by the Verification, Validation, and Evaluation (VVE) approach (Ralyté et al., 2025). Verification and validation are embedded in the implementation phase and focus on ensuring the model's correctness and plausibility. Evaluation, by contrast, is treated as a distinct phase and focuses on assessing the usefulness, usability, and overall value of the model (see chapter "Evaluation").

**Model verification**

Verification will be conducted to ensure that the model has been correctly designed and specified in accordance with its formal rules and theoretical foundation. The main objective is the model's correctness and internal consistency with respect to its specification, and it also involves the method components, including the modelling procedure, notation, syntax, and semantics (Collins et al., 2024; Ralyté et al., 2025). It ensures that the computational implementation matches the intended design and its underlying logic (Crooks et al., 2008; Sargent, 2013).

In this process, the ODD+D protocol serves as the formal specification against which the model's internal consistency is measured, providing the structural blueprint for the independent code review.

To reduce the risk of systematic errors being overlooked by the modelling team, the verification process involves engaging at least two experts (different from the code developer) with relevant technical expertise to conduct an independent review of the model's code (Sargent, 2013). This review includes an examination of the code to find bugs, logical errors, and deviations from the intended model specification, as well as a check for structural inconsistencies in the model's rules, parameters, and agent behaviours (Rand & Rust, 2011; Sayyed-Alikhani et al., 2021).

**Model validation**

Model validation is performed by the host organization, and is defined as the process of ensuring a "correspondence between the implemented model and reality" (Wilensky & Rand, 2015). Effectively, validation seeks to answer whether a modelling method produces outcomes that are not only relevant but also aligned with real-world needs (Ralyté et al., 2025). Within the field of ABM, two primary validation pathways exist: empirical validation and stakeholder validation. While empirical validation – the assessment of model outputs against real-world datasets – is the most common approach (Roxburgh et al., 2021), it often requires a large amount of data (Polhill & Salt, 2017). Given the limitations of available empirical datasets for this specific context, STT3 validation efforts focusses on the stakeholder approach.

Stakeholder validation involves gathering feedback from the model's subjects or domain experts regarding the appropriateness and accuracy of design decisions. In STT3, the approach consists of three to four semi-structured interviews with key stakeholders. The aim is to ensure that the model's underlying logic aligns with the lived experience and professional knowledge of experts.

Additionally, to ensure the model accurately represents real-world conditions under normal circumstances, the model will be run without any scenario applied.

**Role of facilitators**

ST3 requires much less facilitation than STT1 and STT2, but it still benefits from structured coordination between the method developer, the host organisation, and selected domain experts. In this phase, the facilitation role is primarily technical and organisational: arranging data exchanges, structuring expert consultations, supporting validation meetings, and ensuring that modelling assumptions are discussed in a transparent and traceable way. The emphasis is therefore not on workshop moderation, but on maintaining an effective interface between model development and stakeholder knowledge.

### 4.1.7. Scenario simulations

The analytical process of STT3 unfolds across the implementation steps described above, from system scoping and model architecture through to coding, verification, and validation of the relevant system dynamics. Once the model is fully implemented and the baseline system validated, the core analytical phase consists of a structured sequence of simulation runs designed to progressively reveal the system's behaviour under increasingly severe or complex stress conditions.

The sequence typically begins with a baseline run, in which the model is executed under undisturbed conditions to confirm that the system behaves as expected and that all components are correctly instantiated and connected. This run serves as the reference configuration against which all subsequent disrupted states are compared and provides the opportunity for a final consistency check before stress conditions are introduced.

Stress scenario runs are then executed sequentially, each introducing a defined configuration of direct impacts, derived from the scenario specifications, and allowing the cascading and population response dynamics to evolve over the simulation time horizon. A typical STT3 application includes a minimum of three stress scenarios of progressively increasing severity or complexity: for example, a single-hazard disruption on one infrastructure layer (Scenario 1), a multi-hazard compound disruption on one or more infrastructure layers impacted at the same time (Scenario 2), and a compounding or cascading sequence possibly involving temporal accumulation of impacts across different infrastructure layers (Scenario 3). Additional scenarios may be introduced to test specific hypotheses, explore the sensitivity of outputs to particular dependency assumptions, or examine the effect of resilience measures such as redundancies, rerouting capacities, or emergency response activations.

Each run produces a set of outputs, that are reviewed and interpreted in relation to the baseline and to each other. The comparison across scenarios allows the analysis to identify the conditions under which the system transitions from manageable disruption to systemic failure, which components or dependencies act as critical amplifiers of cascading effects, and where adaptive capacity or redundancy is most consequential for system performance.

### 4.1.8. Output

STT3 produces both quantitative and visual outputs, designed to support the interpretation of stress test results by technical stakeholders, emergency management practitioners, and decision-makers.

Quantitative outputs include time-series data on the operational state of individual agents and infrastructure components across simulation time steps, connectivity and service coverage metrics at successive stages of disruption, estimates of the number, location, or distribution of exposed users, functions, assets, or population groups affected by service loss or inaccessibility under each scenario, and summary indicators of system-level performance, such as the proportion of the system remaining functional, the time to reach critical disruption thresholds, or the extent of cascading amplification relative to the initial impact footprint.

Visual outputs include spatial maps of direct and cascading impact (see deliverable 4.4 for examples) distributions at selected time steps, network diagrams illustrating the propagation of failures across infrastructure layers, and comparative visualisations of system state across scenarios, for example showing how exposure, service disruption, accessibility loss, or displacement evolves from Scenario 1 through Scenario 3. Where temporal dynamics are central to the analysis, animated or sequential map outputs may be produced to illustrate the time-dependent progression of disruption and recovery.

All outputs are produced in formats compatible with standard GIS environments and data analysis workflows, supporting further processing, integration with other analytical tools, and inclusion in reports or presentations to the host organisation and stakeholders.

## 4.2 Practical requirements

Within the Agile project, the resources and know-how necessary for developing STT3 can be split between host organisation and modelling team (if they do not coincide). However, if another research or administration entity would like develop a STT3 on its own, they would need to supply all the following skills.

### 4.1.9. Resources required from the host organisation

The successful implementation of STT3 requires a structured contribution from the host organisation across three areas.

1) The first is a dedicated point of contact – typically a staff member with sufficient institutional knowledge of the relevant infrastructure systems, operational procedures, and stakeholder landscape to coordinate data collection, facilitate access to internal expertise, and act as the primary interface with the modelling team throughout the process. This person does not need to have a technical modelling background, but should have the authority and availability to coordinate across internal departments and external partners.
2) The second is technical and data support. STT3 requires geospatial and dependency data as described in Section 4.1.3. The host organisation is expected to be able to provide or facilitate access to this data in open or standard formats, *GeoPackage* or equivalent vector formats being sufficient for geospatial inputs, and to have access to basic GIS viewing capabilities, such as QGIS, for reviewing and validating spatial representations of the system. No proprietary software or specialised data infrastructure is required on the host side.
3) The third is legal and administrative capacity. Where data sharing involves sensitive operational information about critical infrastructure, the host organisation will need to engage its legal or data protection function to establish appropriate data-sharing agreements before the modelling process begins. This is particularly relevant where data is contributed by third-party infrastructure operators or involves information subject to confidentiality constraints under national or EU law.

### 4.1.10. Modelling team know-how

The method developer team brings three categories of expertise that the host organisation cannot reasonably be expected to provide without significant preparation.

1) The first is modelling and coding capacity: the development, testing, and refinement of the Python-based ABM requires specialist skills in agent-based modelling, network analysis, geospatial processing, and software development that go beyond standard GIS or data analysis competencies.
2) The second is methodological and domain expertise for the design and validation phases: translating the host's knowledge of the system into modelling requirements, designing plausible stress scenarios, and validating model behaviour against known system dynamics requires experienced practitioners who combine technical modelling knowledge with familiarity with critical infrastructure resilience concepts.
3) The third is facilitation capacity: the co-development and validation sessions that punctuate the STT3 process require structured facilitation by practitioners experienced in working with heterogeneous stakeholder groups in complex institutional settings. In case of difficulties by the method developers to directly facilitate the sessions, such as language barriers, it is their responsibility to prepare and train people from the host organisation, so that the activities can still be performed in a methodologically sound way.

In the current AGILE implementations, this expertise is provided by the core methodology development team. Future replications should aim at progressive capacity transfer, reducing dependency on the original developers and enabling host organisations or trained practitioners to implement the methodology with greater autonomy.

## 4.2. Method boundaries and limitations

The following boundaries reflect limitations identified at the conceptual and modelling stage of the STT3 methodology. Limitations discovered during application are documented separately in Section 5.3.

### 4.2.1. Thematic and system scope

STT3 is designed to represent physical and organisational infrastructure systems whose components can be mapped spatially, whose dependencies can be identified and encoded, and whose operational states can be meaningfully characterised as a set of discrete conditions. Systems that operate primarily in the cyber or digital domain, including software-defined infrastructure, communication protocols, and cybersecurity dynamics, are not directly representable within the current framework, as their failure modes, propagation logic, and recovery dynamics differ fundamentally from those of physical infrastructure and are not amenable to the spatial and network-based representation on which STT3 relies (Ouyang, 2014). Where cyber dependencies are relevant, they may be represented in simplified form as logical dependencies between physical assets, but the internal dynamics of cyber systems are outside the current scope.

### 4.2.2. Temporal dynamics and event onset

The model operates through discrete time steps and is designed to represent disruption dynamics that unfold over hours to days, consistent with the temporal scale of HILP events and their cascading consequences. Very fast-onset events whose critical dynamics unfold over seconds or minutes, such as explosions, structural collapses, or instantaneous power surges, are not well-suited to the current temporal resolution of the model, as the time step granularity required to capture their dynamics would substantially increase computational demands and would require input data at a level of precision not typically available in the data environments for which STT3 is designed.

### 4.2.3. Scale

The methodology does not impose a fixed geographic scale. It is most naturally suited to bounded territorial or functional systems where infrastructure assets, dependencies, service areas, and exposed users can be represented with sufficient resolution for cascading dynamics to be analytically significant. At very large scales, the number of agents and dependency relationships may exceed practical computational limits without significant simplification of the system representation, with corresponding loss of analytical resolution. At very small scales, such as a single building or facility, the network-based representation of interdependencies may lose much of its analytical value, and other modelling approaches may be more appropriate.

### 4.2.4. Behavioural assumptions

Agent behaviour in STT3 is governed by rules that are co-developed with stakeholders, through meetings and discussions with local authorities and critical infrastructure operators, in which key actors describe their response protocols and decision logic under stress conditions. These inputs are then translated qualitatively into agent decision rules in the model and validated against known system dynamics where possible. However, under HILP conditions, by definition unprecedented, the behavioural rules of both technical and human agents may not fully capture the range of

responses that would emerge in a real event. The model is therefore an exploratory and analytical tool, not a predictive one, and its outputs should be interpreted accordingly, as indicative of the structural conditions for cascading failure and of the relative sensitivity of the system to different stress configurations, rather than as forecasts of specific outcomes (Trump et al., 2025).

### 4.2.5. Data requirements and sparsity

While STT3 is designed to remain applicable under conditions of partial data availability, there is a minimum threshold of information below which a meaningful model cannot be constructed. In highly data-sparse contexts, where neither geospatial asset data nor dependency information is available from public or stakeholder sources, the model cannot be instantiated without relying on assumptions so extensive that outputs would not be analytically meaningful. The methodology is therefore most suited to contexts where at least a basic spatial representation of the relevant infrastructure systems is available and where it is possible to have some form of stakeholder engagement to elicit dependency information.

Understanding what constitutes a sufficient data foundation requires clarity on where data typically comes from and why gaps arise. Data availability for critical infrastructure systems is characteristically limited: public datasets are frequently fragmented across institutional sources, temporally outdated, or deliberately aggregated for security reasons, while the operational and dependency information most relevant to resilience stress testing is typically held by infrastructure operators under confidentiality constraints (Larsson & Große, 2023; Schotten et al., 2024). A hybrid data procurement strategy is therefore a methodological necessity rather than a preference, combining three complementary categories of sources.

The implementation of a STT3 stress test requires a structured approach to data procurement that reflects both the methodological requirements of the model and the practical constraints of the system. As discussed in Section 2.3, data availability for critical infrastructure systems is characteristically limited and three categories of data can be analysed. These categories reflect a progression from publicly accessible to operationally sensitive information, and together define the data procurement strategy that analysts should pursue systematically before and during STT3 implementation.

The first category consists of institutional open-access repositories maintained by national, regional, or municipal authorities. These typically provide the foundational geospatial layer for the analysis (administrative boundaries, land use classifications, infrastructure network maps, and population data) and constitute the starting point for system definition and spatial representation. Their coverage, resolution, and currency vary across national contexts and infrastructure sectors, and should be assessed systematically during scoping, which can be part of STT0, when a SST3 is planned.

The second category consists of global or pan-European geospatial databases (such as OpenStreetMap, the Global Human Settlement Layer, or Eurostat's spatial datasets) which can supplement institutional sources where coverage is incomplete, provide cross-validation of locally sourced data, or offer standardised representations of population distribution and demographic characteristics relevant to exposure and vulnerability assessment. The completeness and accuracy of these sources vary by geographic context and should be verified against institutional references before integration into the model.

The third and most analytically critical category consists of data obtained through direct collaboration with infrastructure operators, public authorities, municipal authorities, and

emergency management bodies. This category provides the operational and dependency information (service coverage logic, asset-level interdependencies, failure thresholds, and emergency management protocols) that public sources cannot supply. Because detailed operational data for critical infrastructure is frequently treated as sensitive from a security perspective, institutional scientific collaboration is the primary viable route to this category of information (Schotten et al., 2024). Establishing such collaborations requires formal data governance arrangements, including data sharing agreements, confidentiality protocols, and clear definitions of permitted uses, that should be initiated during scoping of the case study when SST3 is foreseen, and confirmed before data collection begins.

Beyond data acquisition, stakeholder collaboration serves a second methodological function: it directs analytical attention toward the operational vulnerabilities and dependency relationships that are most significant in practice, many of which are not recoverable from public data alone. This makes the collaborative data procurement process an integral part of the model design, rather than a preparatory step preceding it.

Data quality and consistency are managed through a structured validation process as described in Section 4.2.3. This includes verifying topological consistency between datasets from different sources, checking that asset-level attributes are compatible with the selected level of abstraction, and documenting all assumptions introduced where information gaps cannot be resolved through data collection. All data sources, their coverage, their known limitations, and the assumptions applied in their use are recorded in the Input Data section of the ODD+D template, ensuring traceability and reproducibility across applications.

# 5. Evaluation

## 5.1. Criteria

The evaluation phase aims to determine whether the model can be effectively applied in practice and whether it provides meaningful added value for the context it is intended to support. Specifically, it will aim to determine whether the model can be applied with ease and whether the resulting models effectively improve the context they are intended to address, for instance, in terms of efficiency, usability, or return on investment (Ralyté et al., 2025).

In this sense, evaluation seeks to answer the overarching question: *Is the model worthwhile?* This includes assessing whether the approach is feasible to implement, whether it supports understanding of complex system dynamics, and whether it can effectively inform decision-making processes.

As highlighted by Ralyté et al., (2025), the VVE framework is inherently context-dependent, meaning that evaluation criteria may vary according to the model's application domain and intended purpose. In STT3, evaluation will be conducted through a questionnaire grounded in the Technology Acceptance Model (TAM) (Davis, 1989), a well-established framework for assessing the adoption of methods and artefacts based on users' perceptions and experiences. The TAM considers a combination of perceived and behavioural factors, which are operationalised in this research through the following dimensions:

- Perceived ease of use: the extent to which the modelling method is considered effortless to learn and apply.

- Perceived usefulness: the degree to which users believe that the method effectively achieves its intended objectives and contributes to improving the situation under analysis.

- Intention to use: the willingness of users to adopt and employ the method in future applications.

The dimension of actual usage, typically included in TAM to capture the extent to which a method is implemented in practice, is not assessed in STT3. This limitation is due to the experimental nature of the research, which does not allow for the observation of real-world adoption over time.

## 5.2. Methods, sources of data and evidence

The evaluation of STT3 will be conducted through a structured questionnaire grounded in the Technology Acceptance Model (TAM), to be administered to involved participants in an applied methodological context. It will be conducted in the context of the first full pilot implementation and a more detailed description of its characteristics will be provided in the final iteration of this deliverable. The questionnaire will operationalise the three TAM dimensions defined in Section 5.1, perceived ease of use, perceived usefulness, and intention to use, through a set of structured items combining Likert-scale ratings and open-ended questions. The instrument is designed to capture participants' perceptions and experiences at the conclusion of their engagement with the methodology, when they have sufficient direct experience to form an informed assessment. The questionnaire will be developed and piloted prior to the first full pilot implementation, and refined based on pilot feedback before broader administration.

**Target respondents**

The target respondents are the stakeholders and practitioners who will have actively participated in one or more phases of STT3 implementation, for example people involved during scoping sessions, previous STT, data collection meetings and review of model outputs. This population is selected because it comprises the primary intended users of the methodology: infrastructure managers, emergency management practitioners, public-sector officers, and technical experts whose adoption of the approach in future applications is the ultimate measure of its practical value. Respondents are not required to have a modelling or technical background; the questionnaire will be designed to be accessible to participants with diverse professional profiles and varying levels of familiarity with simulation methods. A minimum number of respondents per application will be defined during the piloting phase, balancing the need for analytical meaningfulness with the practical constraints of stakeholder availability in institutional settings.

**Administration**

The questionnaire will be administered at the end of the stress-testing process, following the presentation and discussion of model outputs with the host organisation and stakeholders. This timing is chosen to ensure that responses reflect a complete experience of the methodology, from initial scoping through to the interpretation of results, rather than a partial or preliminary impression. Where the implementation involves multiple stakeholder groups with different levels of engagement, separate administration may be considered to capture variation in perceptions across participant profiles. The questionnaire may be administered in written form, digitally, or as a structured interview depending on the preferences and availability of the participants.

**Complementary evidence**

Quantitative questionnaire data will be complemented by qualitative evidence gathered throughout the implementation process. This will include facilitator observations recorded during co-development and validation sessions, notes on recurring difficulties or questions raised by participants, and any structured feedback collected at intermediate stages. These qualitative sources will be used to contextualise and enrich the interpretation of questionnaire responses, particularly where quantitative ratings alone do not fully explain the pattern of results, and to capture process-level insights that a post-hoc questionnaire may not surface.

**Analysis**

Questionnaire data will be analysed descriptively, reporting the distribution of responses across items and dimensions. Results will be interpreted in relation to the specific implementation context, including the characteristics of the application settings, the stakeholder composition, and any constraints that may have affected the experience of the methodology. Open-ended responses will be analysed thematically to identify recurring observations, concerns, or suggestions that can inform the learning and improvement process described in Section 5.3. Where multiple pilot applications are completed before the final evaluation, results will be compared across contexts to assess the consistency and transferability of the methodology across different institutional and territorial settings.

## 5.3. Findings

As of June 2026, the STT3 methodology has been fully implemented in the Venice pilot case study, documented in deliverable D4.4. The Venice implementation operationalises the methodology in a spatially constrained urban system characterised by critical infrastructure interdependencies, compound hazard exposure, and a heterogeneous population of residents and visitors. It provides a reusable, code-based modelling framework that stakeholders can use to explore systemic stress-test scenarios under different disruption assumptions. The preliminary evaluation presented in Section 5 draws on insights emerging from this implementation process, including the co-development and validation activities carried out with Venice municipal authorities, infrastructure operators, and Civil Protection practitioners. A second pilot application in Iceland is currently in the data collection phase and progressing according to plan. Its outputs will provide an additional empirical basis for evaluating the methodology across a different geographic, institutional, and hazard context. Further validation sessions and scenario refinements are planned for both sites before the conclusion of the project, and will inform the final consolidated assessment of the methodology's applicability, transferability, and limitations.

The evaluation of STT3 through the TAM questionnaire described in Section 5.2 has not yet been completed at the time of writing and will be conducted in the context of the first full pilot implementation. The findings reported in this section therefore represent a preliminary, development-stage assessment based on evidence accumulated during the design, implementation, and initial testing of the methodology. They are organised according to the four analytical dimensions that will structure the formal evaluation: analytical value and effectiveness, usability and applicability, context-dependent effects, and methodological limitations.

**Analytical value and effectiveness**

Available evidence from the modelling phase suggests that STT3 can achieve a high degree of methodological soundness when the model architecture is documented clearly, dependencies are formalised explicitly, and the ODD+D description is maintained in parallel with code development. The methodology's primary analytical contribution lies in its capacity to connect

infrastructure disruption, spatial constraints, and societal consequences within a single formal computational representation, providing added value over purely qualitative or semi-quantitative approaches when the objective is to examine the internal logic of cascading effects and their population-level consequences in greater detail.

The main challenges to analytical effectiveness concern uncertainty in parameterisation, the simplifications required by missing or inaccessible data, and the difficulty of empirically validating certain cascading mechanisms where observational data on real system failures is unavailable or confidential. A critical observation is that richer and more detailed model outputs do not automatically imply higher certainty: the interpretive value of STT3 outputs remains dependent on the quality of underlying assumptions and the rigour of scenario design. This distinction between analytical granularity and epistemic certainty should be communicated explicitly to decision-makers and stakeholders when presenting results.

**Usability and applicability**

STT3 is implementable in practice, but its implementation is resource-intensive and may be challenging for host organisations without dedicated modelling support from the method developer team. As described in Section 4.3.1, the methodology requires a minimum combination of institutional data-sharing capacity, stakeholder coordination, and specialised modelling expertise that cannot reasonably be expected from a host organisation acting alone.

Applicability is generally stronger at local and regional scales, where system boundaries, stakeholder networks, and interdependencies are more clearly identifiable and manageable. Selected components of the methodology may be adapted to larger-scale applications, but scaling up introduces specific structural and computational challenges. While national-scale models can be topologically simpler, focusing on backbone infrastructures such as high-voltage transmission grids or major transport corridors, the primary bottleneck lies in data acquisition, harmonisation, and governance across heterogeneous regions and operators. Transferability to other contexts is possible but not automatic: data structures, infrastructure representations, governance arrangements, and institutional configurations often require substantial adaptation before a new application can be initiated.

A specific scalability constraint concerns the modelling of population dynamics at large scales, where simulating a realistic number of individual agents becomes computationally prohibitive. A potential mitigation strategy is the adoption of a nested modelling approach, in which macro-scale simulations capture systemic disruptions across regional or national infrastructure networks, while micro-scale models use these outputs as stress inputs to simulate localised impacts and population behaviour, such as evacuation or sheltering, at the local level. This approach has not yet been implemented in STT3 but represents a viable direction for future development.

**Context-dependent effects**

Context strongly shapes the scope, effort, and interpretive value of a STT3 application. Factors that have been identified as particularly influential include: the institutional willingness of infrastructure operators to share operational data; the maturity and accessibility of existing geospatial and dependency data systems; the geographical and administrative scale of the application; and the complexity of cross-sectoral dependencies within the system under analysis. These factors affect not only the quality of model inputs but also the degree to which the methodology can be applied with the level of fidelity described in Chapter 4, or whether significant simplifications are required. Context-dependent effects should be considered explicitly when

comparing findings across different applications, as differences in outputs may reflect differences in implementation conditions as much as differences in the systems being analysed.

Geographical specificity is a particular consideration: systems with unique physical, infrastructural, or institutional characteristics, whether due to geography, governance structures, or the nature of the population served, require tailored calibration that cannot be transferred directly from previous applications. Robust data governance frameworks and standardised data-sharing protocols are essential prerequisites for enabling consistent and comparable implementations across diverse contexts.

**Methodological limitations**

The main methodological limitations of STT3 identified at the modelling stage concern five areas. First, data dependence: the quality and scope of model outputs are directly constrained by the availability and accessibility of input data, as discussed in Section 4.3.4. Second, the limited availability of validated fragility and dependency functions at the asset level, which frequently requires the use of expert-elicited or assumed parameters whose implications for outputs are difficult to quantify. Third, the simplified treatment of human decision-making: while the ABM framework allows for the representation of heterogeneous population agents, the behavioural rules governing their responses under unprecedented HILP conditions are necessarily approximations whose validity cannot be fully verified in advance. Fourth, the need to abstract from many operational details of real infrastructure systems, which introduces a gap between the model representation and the actual behaviour of the systems being analysed. Fifth, model-building effort: constructing, testing, and validating a STT3 model requires substantial investment of time and expertise, and the resulting tool may still require expert mediation for interpretation by non-technical stakeholders.

These limitations do not negate the usefulness of STT3, but they delimit the kinds of claims that can responsibly be made from its outputs. The methodology is an exploratory and analytical tool designed to illuminate the structural conditions for cascading failure and the relative sensitivity of the system to different stress configurations, not a forecasting tool capable of predicting specific outcomes with quantified confidence. This scope must be clearly communicated in all applications.

## 5.4. Improvements

### 5.4.1. Adjustments already implemented

During the development and validation of STT3, several adjustments are typically introduced to improve clarity, robustness, and usability. These may include refinement of dependency rules, better structuring of input data, simplification of overly complex mechanisms, clearer output indicators, or improved documentation of assumptions.
Changes may concern both the model itself and the implementation process. Typical examples include revision of the system boundary, correction of network connections, restructuring of scenario inputs, improvement of scheduling logic, revision of decision rules, and clarification of reporting templates and validation procedures.
Such adjustments are generally introduced to respond to data limitations, remove technical inconsistencies, improve interpretability, or better align the computational model with stakeholder knowledge and the intended analytical purpose of the stress test.
Where these adjustments have been applied, they generally improve transparency and practical usability, even when they require a degree of simplification. The key point is not to maximise

complexity, but to preserve an interpretable representation of the most relevant system mechanisms under stress.

### 5.4.2. Planned refinements

Further refinements are expected in future applications of STT3. These should be understood as part of the normal evolution of a computational methodology, reflecting the continuous advancement of data availability, modelling techniques, and stakeholder needs.

- Potential areas for refinement include:
    - more explicit modelling of recovery and restoration processes,
    - improved behavioural representation of affected populations,
    - stronger treatment of uncertainty,
    - more systematic scenario comparison,
    - better integration of governance and emergency-management actions into the computational logic.

    In this context, the integration of Deep Reinforcement Learning (DRL) offers a promising avenue, both for supporting early-response decision-making by responsible authorities and for informing proactive planning strategies aimed at increasing network robustness and reducing vulnerability to systemic failures.

The availability of higher-quality and more consistent data will further improve the reliability and robustness of the model.
Such adjustments are typically introduced to address data limitations, resolve technical inconsistencies, enhance interpretability, and better align the computational framework with stakeholder knowledge and the intended analytical objectives of the stress-testing process.

# 6. Conclusions

The STT3 methodology provides a transparent and analytically valuable way to examine how direct disruptions and cascading effects may propagate through complex socio-technical systems under extreme stress. Its main strengths lie in its system focus, explicit treatment of interdependencies, compatibility with geospatial and network data, and capacity to connect infrastructure failures with population and accessibility consequences. Its main weaknesses concern data dependence, implementation effort, and the unavoidable simplifications required when representing uncertain and heterogeneous real-world systems.
Overall, STT3 is strongest when used as a structured exploratory tool embedded within a broader tiered methodology. Its value therefore depends on matching methodological ambition with the evidence and resources actually available.
Replication of the methodology in other contexts is feasible provided that several conditions are met: a clear system definition; access to at least a minimum set of infrastructure, spatial, and population information; involvement of knowledgeable stakeholders or experts; and sufficient modelling capacity to build, document, and validate the computational architecture. The use of ODD+D is particularly important for replication because it supports consistent transfer of the model logic across teams and case studies.
Looking ahead, further implementations should focus on expanding the empirical basis for validation, improving integration with other AGILE outputs, and strengthening guidance for adaptation to different scales and governance settings. The present deliverable should therefore be seen as both a validated methodological reference for STT3 and a foundation for subsequent refinement, application, and integration within the broader AGILE project.

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