EU-CIRCLE

A pan-European framework for strengthening Critical Infrastructure resilience to climate change

D4.3 EU-CIRCLE RESILIENCE FRAMEWORK – FINAL VERSION

Contractual Delivery Date: 05/2017	**Actual Delivery Date**: 09/2017
Type: Report	**Version**: v0.6

Dissemination Level : Public Deliverable

Statement

This report is the final technical report for the EU CIRCLE Resilience Framework Deliverables 4.1 and 4.3. It is based on the comprehensive review of frameworks done in D4.1 and the novel 4 layered approach that introduced the 5 resilience capacities (Anticipative, Restorative, Coping, Absorbing and Adaptive resilience capacities called AARCA) which can be used to measure resilience. This report seeks to build on the output of other WPs and deliverables that have developed a risk resilience framework (D3.4), a resilience prioritization module (4.2), resilience indicators and capacities (D4.5) and the adaptation module (D4.6) to form an integrated framework. D4.3 looks at approaches to modelling resilience and proposes a systems approach to quantify resilience based on the resilience capacities for use in scenario modelling of different preventative measures and mitigation options. Towards this end, D4.3 develops an analytical framework that operationalizes the layered approach using a conceptual system dynamics model of CI asset resilience. The model can be scaled to include networks and network of networks and can extended to include spatial analysis in the future.

EU-CIRCLE is a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653824. Please see http://www.EU-CIRCLE.eu/for more information

Preparation Slip			
	Name	Partner	Date
From			
Reviewer	Open Review		
Reviewer	Open Review		
For delivery			

Document Log			
Issue	Date	Comment	Author / Organization
TOC-D4.3	23/03/2017	TOC of D4.3 final resilience framework for comments	USAL
V0.1	24/04/2017	Final Resilience framework; Objectives: approaches to measuring resilience	Chaminda Pathirage / Hisham Tariq / USAL
V0.2	22/05/2017	Analytical framework; Links to other deliverables	Chaminda Pathirage / Hisham Tariq / USAL
V0.3	25/06/2017	Resilience indicators/Capacities; Comments on the overall report	Nenad/UGV
V.03	7/07/2017	Contribution from WP2, WP3 and WP4; Comments on the overall report	Loiuza EUC
V.03	7/07/2017	Contribution from WP2; Comments on the overall report	Thanasis NCRSD
V.03	7/07/2017	Contribution from WP3 and WP4; Comments on the overall report	Midori and colleagues/ARTELIA Ralf/Fhr
V.03	16/07/2017	Adaptation Framework; Comments on the overall report	Jean/ ARTELIA
V0.4	26/07/2017	Section 1, 2 and 3 draft	Chaminda Pathirage / Hisham Tariq / USAL
V0.4	27/07/2017	Resilience Assessment Model and Tool final version; Comments on the overall report	Nenad/UGV
V0.5	21/08/2017	Review	Ralf/Fhr
V0.6	31/08/2017	Incorporating feedback/comments	Chaminda Pathirage / Hisham Tariq / USAL
		List here the changes and their rational for each release	

Executive Summary

The main purpose of D4.3 is to present the final version of the resilience framework for critical infrastructure in the context of EU-CIRCLE and to develop/propose an analytical framework and a conceptual model for critical infrastructure resilience to disaster impacts, in the short run, and climate change, in the long run. This deliverable is based on D4.1, which provides the scientific background for the development of both the definition used in this report and the framework. D4.1 provided a comprehensive review and synthesis of literature associated with disaster resilience and critical infrastructure. Additional deliverables like D1.5: Report on Detailed Methodological Framework, D3.1: Registry with CI assets and Interconnections, D3.4A: Holistic CI Climate Hazard Risk Assessment Framework, D4.2: EU-CIRCLE Resilience Prioritization Module, D4.5: Resilience Indicators and D4.6: Adaptation module, along with others, have all contributed to the theoretical and methodological underpinnings of the analytical framework detailed in this report.

As such, development of the framework was based on back and forth contributions from other work packages and deliverables of the EU-CIRLCE project. The framework has 4 layers based on the contributions of the different WPs. These layers are both independent and interdependent such as; Climatic hazards, including current and future climate change (WP2); critical infrastructure, their networks and interdependencies (WP3); disaster risks and impacts (WP3); and capacity of critical infrastructure (WP4) are the four layers that form the EU CIRCLE resilience framework.

The objectives of this technical report are: (i) to present a systems framework for quantifying resilience and to introduce a novel CI resilience measure; (ii) to present the theory behind the resilience capacities and indicators; and (iii) to introduce the conceptual SD simulation model at the CI asset level and develop an example.

By using this framework, in combination with D4.5 Resilience indicators, CI asset stakeholders, operators and/or service providers can: (i) quantitatively compare different hazard response strategies for the same CI asset; (ii) compare the system performance of different CI assets to similar hazard events; and (iii) support decision making.

The analytical resilience framework presented in this report addresses the following key questions:

1) How short term (or long term) choices in resilience capacities makes an asset or network more resilient;
2) How these choices can minimize system performance loss when shocks occur;
3) How operational (short term) and strategic (long term) choices can minimize the time taken for an asset (or network) to recover and minimize the total loss of system performance

This report uses a system dynamics (SD) simulation modelling approach to better understand the behaviour of complex infrastructure systems to natural hazards in the short run and climate change impacts over the long run. SD simulation modelling was chosen in order to observe the dynamic nature of hazards and their impacts on system performance of CI assets and networks. The approach is suited to capture the feedback between resilience capacities and the disaster impact through simulation modelling.

Contents

EXECUTIVE SUMMARY 3
CONTENTS 4
1 INTRODUCTION 8
1.1 Background 8
1.2 Purpose 8
1.3 Methodology 9
1.4 Links to other deliverables 10
1.5 Incorporating feedback 11
2 THE INITIAL EU CIRCLE CI RESILIENCE FRAMEWORK 13
2.1 EU CIRCLE definition of CI resilience 13
2.2 Components of the resilience framework 14
2.3 Resilience for what (Layer 1) 16
2.4 Resilience of what (Layer 2) 21
2.5 Disaster risks and impacts (Layer 3) 24
2.6 Capacities of Critical Infrastructure (Layer 4) 26
2.7 Asset properties associated with Critical Infrastructure and Climate Hazards (Layers 1, 2, & 3) 27
2.8 Resilience parameters (Layer 3 and 4) 28
3 ANALYTICAL FRAMEWORK 30
3.1 Introduction 30
3.2 Application of the systems approach to understanding CI resilience 33
3.3 Formal definition of system performance of CI asset, network or NoN 35
3.4 The RAMTs measurement and CI Resilience framework 38
3.5 Resilience Assessment Model and Tools (RAMTs) 40
3.6 Resilience Capacities and RAMTs 42
3.7 Assigning weights to capacities 45
3.8 The conceptual resilience framework in the model 46
3.9 The Prototype Model of CI resilience 51
3.10 Running the conceptual model 55
3.11 Resilience computation for single CI asset 67
3.12 Resilience computation for CI assets in a Network 68
3.13 Interpreting the SP Curves/Shocks 71
4 THE RISK RESILIENCE FRAMEWORK 74
5 FUTURE WORK 76
6 CONCLUSIONS 77
7 APPENDIX A: CONTEXT OF THE REPORT 78
7.1 Infrastructure as Complex systems 78
7.2 The Sendai Framework for Disaster Risk Reduction 2015-2030 79

7.3 Perspectives to Resilience .... **Error! Bookmark not defined.**
7.4 Systems approach to CI Resilience 80
7.5 Multiple modelling approaches 82
7.6 The SD simulation approach 82
7.6.1 CIP/DSS, US 84
7.6.2 CIR/DSS for highways using HAZUS MH, US 87
7.6.3 CRISADMIN, EU 90
7.6.4 RESILSim, Canada 94
8 REFERENCES: 1

Table of Figures

Figure 1. EU CIRCLE resilience framework with contributions from different WPs and deliverables. 10
Figure 2. Adaptation module – the resilience framework provides a mechanism for comparing adaptation options and will feed into a decision support tool, together with cost effectiveness analytical module. 11
Figure 3. The layered approach in EU CIRLCE resilience framework 14
Figure 4. Example of using Layer 1 data to develop a river water level diagram for flood simulation (Simonovic, 2011). 18
Figure 5. Dimensions for describing infrastructure interdependencies (from pg. 34 D3.4: Holistic CI Climate Hazard Risk Assessment Framework). 24
Figure 6. Functional analysis approach (Giles, 2016) 34
Figure 7. Schematic of the function-based approach to the identification of critical assets used in D3.1 35
Figure 8. Conceptual resilience triangle for EU CIRCLE definition adapted from Bruneau and Reinhorn (2007). 36
Figure 9. Shock profile: system performance measures after a hazard event or shock (Peck and Simonovic, 2013) 37
Figure 10. The Resilience Assessment Model and Tool (RAMT) and the calculation of resilience capacities as indicated in D4.1 and D4.5. Adapted from Hughes and Healy (2014). 40
Figure 11. The analytical framework using a system dynamics simulation approach 47
Figure 12. The analytical framework conceptualizing resilience as a stock for use in simulation modelling adapted from (Peck and Simonovic, 2013) 48
Figure 13. The layers combined in a stock and flow model of the final risk-resilience framework 49
Figure 14. Interpreting the curve of system performance in the conceptual model. 50
Figure 15. The conceptual model of a single CI asset in STELLA, a SD modelling software.. 51
Figure 16. The Graphic User Interface (GUI) for the conceptual CI resilience model. 52
Figure 17. Graphical Input screen for Damage/Shock curve of event. Note numerical data could be entered instead of drawing a curve representing data generated by a climate model. 57
Figure 18. Hypothetical damage/shock curve drawn by user representing the impact of climate event (short term) or stress (long term). 57
Figure 19. Projected organisational performance response to disruption with variation in resilience: weekly performance levels 61
Figure 20. Projected organisational performance response to disruption with application of a resilience improvement plan: weekly performance 62
Figure 21. Weights input page 63
Figure 22. The General User Interface developed by the researcher for use by participants at the validation workshop. 64
Figure 23. Baseline Resilience score as determined by the participants 64
Figure 24 – Close up of the input table with baseline RAMTs score 65
Figure 25. A new resilience plan to be implemented investing in newer more resilient production facilities and hence a higher RAMTs score in Production. 65
Figure 26. Projected organisational performance response to disruption with application of a resilience improvement plan: weekly performance 65

Figure 27. Example of generic sector level models. 70
Figure 28. Understanding the impact of damage curve/profile on system performance adapted from Gotangco et al. (2016). 71
Figure 29. The link between risk and system performance (denoted here as critical functionality) adapted from Linkov et al. (2014). 71
Figure 30. Impact of differing levels of risk-resilience on system performance (denoted here as critical functionality of the system) adapted from Linkov et al. (2014). 72
Figure 31. Impact of preventative measures on system performance (Peck and Simonovic, 2013) 72
Figure 32. Combined risk resilience framework 74
Figure 33. Integrating spatial analysis into the conceptual model. 76
Figure 34 . Methods of Complexity 82
Figure 35. SD simulation model of CI interdependencies 87
Figure 36. Systems dynamics diagram for Critical Infrastructure Resilience Decision Support System used in HAZUS-MH . Source: Croope (2013) 89
Figure 37. CRISADMIN theoretical framework 91
Figure 38. CRISADMIN HV Energy production simulation model 92
Figure 39. CRISADMIN ILE architecture (source) 93
Figure 40. User Interface 96

List of Tables

Table 1. List of climate drivers and hazards (adapted from D4.1) 16
Table 2. Climate data processing in the framework of EU-CIRCLE Risk model with worked examples 17
Table 3. Context and approach to conceptualizing resilience adapted from Hughes and Healy (2014) 20
Table 4. Characterizing a system of interdependent CIs as specified in D3.4 and adapted from Rinaldi et al. (2001). 23
Table 5. Layer 2 contextual them of scale of analysis of CI 23
Table 6. Generic resilience indicators developed in D4.5 29
Table 7. Contextual themes for resilience assessment model and tool. 41
Table 8. Summary of resilience capacities with indicators 43
Table 9. Excel sheet example of the RAMTs tool (source D4.5) 44
Table 10. Overall resilience score in RAMTs (source D4.5) 44
Table 11. Hypothetical participant inputs to model to determine baseline resilience score. 56
Table 12. Changes in resilience capacities due to measures taken 58
Table 13. Number of variables in each CI sector in the CP/DSS model 85

ABREVIATIONS

AARCA	Anticipative, Restorative, Coping, Absorbing and Adaptive resilience capacities
CC	Climate Change
CH	Climate hazard
CI	Critical Infrastructure
CIPDSS	Critical Infrastructure Protection Decision Support System
CIRP	Critical Infrastructure Resilience Platform
CS	Climate Stress
DFID	Department for International Development
EC	European Commission
EU	European Union
GMB	Group Model Building
GUI	Graphical user interface
ICT	Information and Communication Technology
ILE	Integrated Learning Environment
MCEER	Multidisciplinary Centre for Earthquake Engineering Research
NoN	Network of Networks
RAMTs	Resilience Assessment Model and Tools
RC	Resilience capacity (whole system)
RF	Resilience framework
RL	Resilience Loss
SD	System Dynamics
SP	System Performance
WP	Work Package in project (followed by number)

1 Introduction

1.1 Background

The EU's capacity to maintain and improve infrastructure systems and assuring continuous critical infrastructure (CI) services is increasingly important as it seeks to promote economic prosperity and well-being within its membership particularly in the current economic environment. The European Commission, in Directive 2008/114/EC, has defined CI as "an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact on a Member State as a result of the failure to maintain those functions (Council Directive, 2008)." These assets are now increasingly interconnected and form part of large complex CI networks. Hence, CI interdependencies have become increasingly complex and difficult to understand and plan for. This complexity requires a 'system of systems' approach to properly assess and understand the nature of impact resulting in failure and cascading effects on to other related infrastructures.

To minimise such impacts and reduce risk, it is vital to identify vulnerabilities and improve the resilience capacities of critical infrastructures through developing CI strategies. To address this complex problem of CI resilience the EU CIRCLE Horizon 2020 project is developing tools for implementation in to the Critical Infrastructure Resilience Platform (CIRP), a decision support system for local governments, CI service providers and operators. The main strategic objective of EU-CIRCLE is to move towards an infrastructure network(s) that is resilient to today's natural hazards and prepared for the future changing climate.

EU-CIRCLE has developed in this report a holistic resilience framework, the purpose of which is to explain what constitutes resilience in the context of critical infrastructure and how it can be operationalized or conceptualized to help CI stakeholders better understand their resilience for effective decision making. The EU resilience framework has been delivered in two stages:

- Stage 1: Initial Framework (Technical Report) in M12
- Stage 2: Final Framework (Operational framework supplemented by a report)

The final report, which is based on the foundation laid in technical report D4.1: Initial framework, is for the purpose of establishing the operational/conceptual basis of the EU resilience framework and to provide a step by step guide towards its implementation. Furthermore, it is based on the feedback by consortium members on D4.1 and through other meetings, workshops and teleconference calls across Work Packages (WP) which indicated a need for an approach that could be operationalized.

1.2 Purpose

Accordingly, the objective of this report is to develop an operational approach to the resilience framework identified in D4.1 by;

i) presenting the theory behind the resilience framework, capacities and indicators;

ii) presenting a systems approach for measuring resilience and introducing the link between CI resilience capacities and indicators;

iii) introducing the conceptual SD simulation model at the CI asset level and develop an example of a prototype model;

A systems approach can aid researchers in better understanding hazard impacts, both on the CI system as well as society, through interactions across the physical, social and built environments. The system approach to CI resilience also seeks to address a growing need to better understand the costs of disruptions and shocks to CI systems across their complex interdependencies. Understanding these impacts are essential when responding to events, setting policies and determining protective investments. According to EU CIRCLE objectives the proposed approach should address the following questions as well:

1) How measures (short and long term related to operational or strategic issues, respectively) make a network more resilient.
2) How investing in these measures can reduce service loss when disruptive events occur.
3) How these measures can minimize the time taken for a network to recover and, thus, minimize the total cumulative loss of services.

1.3 Methodology

As indicated previously in D4.1, a number of steps were followed in the development of the resilience framework. The first step was to define the term resilience from the EU-CIRCLE point of view. The main approach used for this purpose was to analyse several existing definitions for resilience, most of which have been gathered from the EU-CIRCLE taxonomy (D1.1). The key terms were identified within each definition and have been combined under four main classifications. The terminologies associated with resilience and their interconnections were also reviewed.

Based on this comprehensive review of definitions in D4.1, the term resilience in the context of critical infrastructure for EU-CIRCLE has been defined as the **ability of a CI system to prevent, withstand, recover and adapt from the effects of climate hazards and climate change**.

The next step, in D4.1, was to review existing resilience frameworks. The main purpose was to analyse the rationale and components of existing resilience models in order to identify the appropriate components that can be used for the EU-CIRCLE resilience framework. 16 different frameworks were analysed and compared, with the frameworks analysed having either a national, regional or international focus. The factors influencing critical infrastructure were thus identified. Both the resilience framework analysis together with the factors influencing critical infrastructure helped to develop the necessary components for the EU-CIRCLE resilience framework presented in D4.1.

This initial framework was then presented to potential stakeholders at the EU CIRCLE Consolidated Workshop in Milan, in order to obtain their feedback which was included in D4.1. Subsequent feedback from discussions with other WP leaders and members has also now been integrated in this report, D4.3, as well as crucial contributions from the deliverables completed during this period – details of the links to these deliverables can be found below in section 1.4. These comments and feedback on the initial framework as well as participating in the workshops held in Exeter, Cyprus and Dubrovnik have been incorporated to form the basis for an analytical framework using a systems approach to better understand CI resilience.

In summary:

1 – Extensive literature review of resilience definitions and frameworks (D4.1)

2- Development of hierarchy of levels for prioritization or ranking (assigning weights) to resilience capacities, components or assets in a network, and the protective measures (D4.2)

2 – Development of a systems framework (D4.3) and assessment tool (D4.5), which is practical and feasible to implement

3 – Combining to form a final resilience framework (D4.3) for implementation in case studies

4 – Incorporating partners, stakeholders and reviewers feedback/comments into the final version

1.4 Links to other deliverables

This analytical approach has been developed with inputs from different work packages and deliverables across the project. **Figure 1** below indicates some of the key inputs that have contributed to the development of this report. This report incorporates these contributions particularly from the following: D1.5 with regards to the methodology in general and the findings of D3.1, D3.4, D4.2, D4.5 and D4.6 in order to complete this report on the final analytical framework for critical infrastructure resilience.

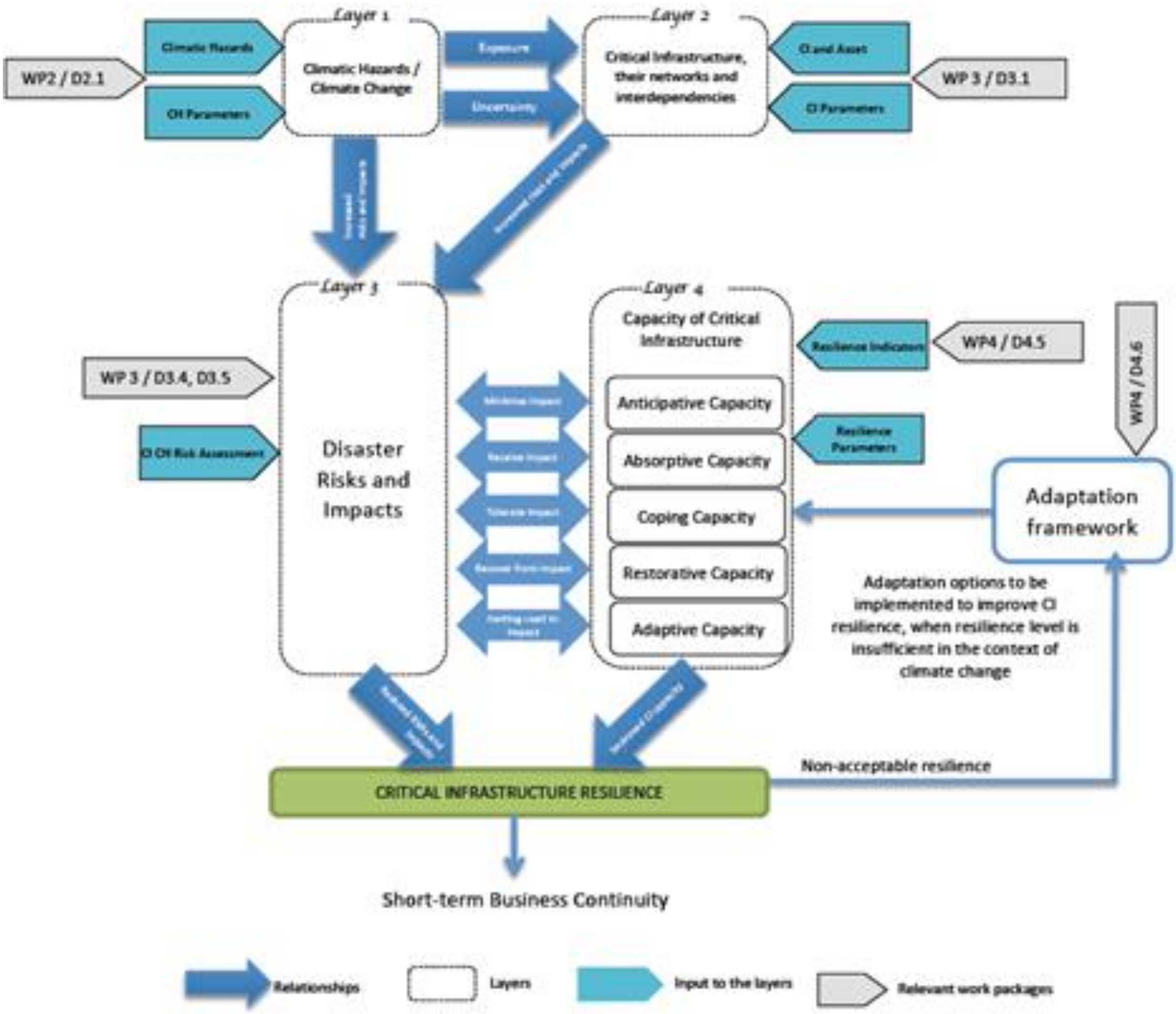


Figure 1. EU CIRCLE resilience framework with contributions from different WPs and deliverables.

By using this framework, in combination with D4.2 prioritization module and D4.5 Resilience indicators, CI asset stakeholders like CI operators and service providers can: (i) quantitatively compare different hazard response strategies for the same CI asset; (ii) compare the system performance of different CI assets to similar hazard events; and (iii) support decision making.

For the purpose of prioritizing resilience across critical functions, assets and networks, D4.2 EU CIRCLE Prioritization module has provided a detailed methodology of ranking at three different levels within the resilience framework:

1) Elicitation of relative importance of *resilience capacities*, parameters and indicators,

2) Assessment of resilience of *network assets* (or alternatively: network parts) and

3) Comparison of *protective measures*.

This allows expert feedback to be incorporated into the conceptual model through the application of methods like Analytical Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT) and the sensitivity analysis that can be conducted with simulation modelling approach – particularly system dynamics simulation modelling. For more information on these approaches please see D4.2 EU CIRCLE Prioritization module and for its application in this report see section 3.8.

Figure 2. Adaptation module – the resilience framework provides a mechanism for comparing adaptation options and will feed into a decision support tool, together with cost effectiveness analytical module.

Developing a simulation approach to modelling impacts from shocks like hazard events is increasingly important for choosing the most effective strategy for investing in protective measures if a shock happens. Although many preventative measures may look to be cost-effective in certain conditions, decision makers need tools to help them rank resilience options or choices to efficiently allocate limited budgets. This has been clearly indicated in D1.5 and D4.6 Adaptation module as an essential tool in EU CIRCLE. Preventative measures to improve resilience of CI are discussed in section 3.9.

The resilience framework in this report also provides an outline of how business continuity can be considered especially through the preventative measures and adaptation options being considered in the model – again for an application in this report see section 3.9 for more details. This will be further developed in D4.7 Business continuity module as it provides a more complete framework to consider the different options required to increase/maintain resilience in the face of events. Similarly, the resilience framework provides an outline of how costs can be calculated for the different preventative options considered in the model although a more complete review of how this will be done will be done in D4.8 Cost/Benefit module which provides a framework to compare and contrast a change in resilience capacities with respect to the costs of damages or the costs of adaptation options.

1.5 Incorporating feedback

As mentioned above, there have been many opportunities throughout the project timeline where the research team received crucial feedback on D4.1 from a number of sources including workshops, conferences, seminars, project review meetings, and telephone conferences. This has resulted in interactions at varying levels with a number of consortium members, CI stakeholders, EU scientists and other relevant stakeholders. Where possible the feedback has been incorporated into D4.3 and the research team are grateful for the contributions of all such participants.

Some of the questions raised during the feedback and being directly addressed in D4.3 were those raised by the reviewers in the informative face to face meeting in Cyprus where the following questions were discussed:

1) What is the meaning of elasticity with respect to resilience when it is seldom linear or elastic?

   This has been answered in general when discussing the need to adopt a system approach to understanding resilience and hazard impacts. By definition, a systems approach seeks to look at complex situations and these are almost always non-linear – this is explained further in the sections on systems approaches and particularly in the section on system dynamics as one of the approaches researchers have found to be well suited to incorporate non-linearity and the plasticity of resilience in its analysis.

2) The debate on whether resilience has originated in mechanics or ecology?

   The important aspect of this debate is that they both contributed to the multi-dimensional nature of resilience where both the material “restoring shape” and the biological “bouncing back” capture essential components of the resilience definition (see definition in section 2.1 and 3.1 for more details). In general the word resilience of course goes back to its origin in Latin and its first recorded use in early 1600s to discuss properties of materials in medieval scientific literature (Manyena, 2009).

3) How to derive a unique resilience measure from the “multi-layer” framework?

   This has been explained in section 3.5-8, where the resilience assessment model and tools are used to derive a unique resilience score that is then incorporated in the conceptual model. Section 3 provides the overall explanation of how and from where this measure is generated and how it can be used in a conceptual model for CI resilience as well as for use in the adaptation module later.

2 The Initial EU CIRCLE CI resilience framework

2.1 EU CIRCLE definition of CI resilience

Over the last decade, resilience has been considered as the primary objective of hazard mitigation in a number of disciplines dealing with disaster risk management and response (Coppola, 2015). The term has evolved across a number of disciplines ranging from applied mechanics to ecology to human psychology (Manyena, 2009). Regardless of the origin of the specific word, the literature has identified particular components of resilience of interest to critical infrastructure protection as D4.1 conducted an exhaustive review of these definitions and reported that the interpretation of resilience implies four concepts, though the boundaries between them are blurred:

- PREVENT - ability to predict and resist the impact – prepare for / anticipate / resist / prevent / preservation
- WITHSTAND - ability to sustain the damage – absorb / withstand / accommodate / robustness
- RECOVER - damage can occur but the system will be able to recover – respond to / recover / rapidity
- ADAPT - modifications to system – change / adapt / restoration / improvement / learn

In line with the analysis from D4.1 these definitions include elements such as the following: (i) preventing the impacts from climatic hazards by minimising the exposure of critical infrastructure to hazards; (ii) withstanding the impacts from climatic hazards and climate change by reducing the magnitude and number of impacts; (iii) recovering from the effects of climate hazards and climate change; and (iv) adapting through modification and improvements to the CI system.

As such our definition of resilience will include the capacity of a system to prevent, withstand, recover and adapt from the effects of climate hazards and climate change. The resilience framework's goal is to measure the present capacity of CI "to cope and bounce back from shocks" (Rogers et al., 2012); in other words, to assess if CI resilience level is acceptable or not to face climate hazards in a climate change context.

Critical Infrastructure systems do not act alone as they are interdependent on many other systems at multiple levels and are deeply embedded within social systems in communities in member countries. Therefore, a disruption in one system will create cascading impacts and consequences to the networked infrastructure system. This nature of interdependency of infrastructure demands a focus also on the resilience of networks when defining critical infrastructure resilience. Previous research on infrastructure networks (Murray et al., 2007, Zio and and Kroger, 2009, Turnquist and Vugrin, 2013) focused mainly on elements such as vulnerability, reliability and recovery. Vulnerability assessment focused on identifying the network links whose failure would cause the most disruption in the functioning of the network; reliability-based analyses typically focused on the degree to which a network can withstand certain types of disruptions; and recovery analysis was about system recovery in infrastructure networks following a disruptive event.

According to Turnquist and Vugrin (2013), increasing network resilience involves three related capabilities—providing absorptive capacity so that the network can withstand disruptions; providing adaptive capacity so that flows through the network can be accommodated via alternate paths; and providing restorative capacity so that the recovery of the network from a disruptive event can be accomplished quickly and at minimum cost. It is clearly evident that these three capabilities (withstand, recover and adapt) are also the essential elements in defining resilience – please see D4.1 for an extended discussion and review.

2.2 Components of the resilience framework

The review of several existing resilience frameworks in D4.1 indicated that hazards, risks and vulnerability should essentially be part of the resilience framework. The other component is the capacity of the system to deal with the disaster in order to improve its resilience. The Department for International Development (DFID, 2011) framework focuses on the 'resilience of what' and 'resilience for what' questions, and this highlights the importance of these components as we intend to develop the resilience framework for a particular system. As such, the focus of the proposed framework should be specifically given for the resilience of critical infrastructures (resilience of what) for climate hazards (resilience for what). The frameworks on city resilience all have infrastructure as one of their components. Another observation noted within some of the frameworks is the multi-dimensional approach. The critical infrastructure system could involve more than one resilience parameter and therefore the framework could possibly take a multi-dimensional form. Taking into account the nature and incorporation of multidimensional components within a resilience framework, a layered approach is chosen as it has the flexibility to modify each layer (each component) independently and yet the collective output will be based on the interconnection between the layers. Particularly as the framework is to be used within the Critical Infrastructure Resilience Platform (CIRP) under EU-CIRCLE, a layered system is easier to debug and modify as the changes might affect only limited portions of the code, and a programmer does not have to know the details of the other layers (Goldstein and Bobrow, 1980). In summary, the EU CIRCLE resilience framework will have multi-dimensional components, incorporating risks and capacities with the focus on critical infrastructure and climate hazards. These layers and components are illustrated in **Figure 3** below.

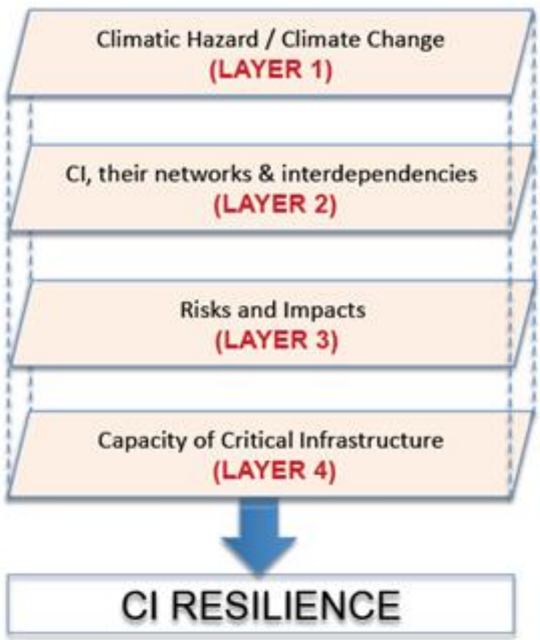


Figure 3. The layered approach in EU CIRLCE resilience framework

The EU-CIRCLE resilience framework will help to determine what constitutes resilience for critical infrastructure assets and networks. The framework has incorporated several components, which are listed below. These components are further expanded in the subsequent sections.

1. Resilience for what – the disturbance which is Climatic Hazard (CH), including current and future climate change (Layer 1)
2. Resilience of what – the context which is Critical Infrastructure (CI), their networks and interdependencies (Layer 2)
3. Disaster risks and impacts (Layer 3)
4. Capacities of critical infrastructure (Layer 4)
5. Asset properties associated with Critical Infrastructure and Climate Hazards (contributes to Layers 1, 2 and 3)
6. Resilience parameters (Contributes to Layer 3 and 4)

These layers contribute to development of a systems approach to CI resilience as they consider the different elements of each layer and how those elements have an impact on the overall CI resilience. These components are discussed in detail below.

2.3 Resilience for what (Layer 1)

The climate hazards identified in this section are obtained from EU-CIRCLE D1.3: Report on EU-CIRCLE Strategic Context. To ensure consistency across the project this section will be derived from WP2 (Climatic Data capture and processing).

The framework will address resilience of critical infrastructure to the climate hazards listed below and how climate change will affect the frequency and severity of these hazards.

Climate drivers	Climate hazards
Temperature	Heat waves, cold snaps
Precipitation (rain / snowfall) - humidity	Floods / costal floods
Winds	Forest Fires
Cloud / fog	Droughts
Solar radiation	Earth movement caused by climate drivers such as rain (landslide, erosion, avalanches, rock fall, soil subsidence, liquefaction, etc.)
Sea level rise	Storms
Ice, frost, permafrost	Add other hazards
Storm surges, waves	
Lightning / thunderstorm	
Ocean currents	
Pressure	

Table 1. List of climate drivers and hazards (adapted from D4.1)

Layer 1 contributes to the framework by indicating the type, magnitude and duration of the disturbance or shock to a CI asset(s) or system due to a climate hazard event or climate change stress. As shown above in Table 1, there is a wide range climate drivers and hazard types that can affect a given asset of CI both in the long and short runs. For a complete risk resilience assessment, Layer 1 provides the scientific basis for including hazard impact and stress data onto the other layers such as the asset registry mentioned in the next section. The analysis from this layer can be used to develop the magnitude of the hazard event and then provide values for scenario analysis by the various mechanisms outlined in D1.3 and covered in WP2. WP2 indicates how climate data can be captured and processed to produce the required climate scenarios and models that can indicate the levels of disturbance or shock and WP3 looks at how CI assets and networks can get impacted by climate hazards and stresses.

Table 2 provides an example of how the risk framework developed in D3.4 uses climate data for analysis and this is also similarly adopted here in the resilience framework to form the basis of the simulation modelling approach chosen to operationalise the framework in D4.3 in section 3.

Table 2. Climate data processing in the framework of EU-CIRCLE Risk model with worked examples

	Example: Forest Fires	**Example: Heat Waves**
Collection of climate data from existing databases Collection from available databases climate historical or predicted or processed data, depending on the problem to solve, that are used to calculate the appropriate indices for a certain period and place of interest. **Databases:** ECA&D, CORDEX, CMIP5, etc. **Models and Tools:** GCM, RCM, ESD, etc.	Temperature Rainfall Wind Relative humidity	Temperature Humidity
Indicators Indicators measure the actual status of the environment before, during or after an event and serve as a reference status or as a signal for environmental/climate change over time (qualitative or quantitative). Indicators are referring directly to climate parameters related to the risks or to climate indices that give measure of a risk appearing or not.	Fire Weather Index (FWI)	Temperature Heat Index - Humidex
Thresholds Represent quantitative critical values derived from the examined scenario. So it is important to identify where there is a likelihood of unsustainable trends of certain indicators related to environmental issues that show threshold phenomena. These thresholds may be related not only with extreme phenomena (floods, fires, extreme weather events), but to mean climate values, standard deviation of a variable etc., depending on the assessed scenario.	FWI > 150 at least 10 days	HI > 54 °C
Return period / Probability of occurrence Based on the threshold and the indicators that have been specified, and also the processed data, we calculate the probability of occurrence of the risk scenario or its return period. A Return level with a return period of T = 1/p years is a high threshold x(p) whose probability of exceedance is p (likelihood of rare events).	1:100 yr or p=0.01%	1:200 yr
Classification The levels of Likelihood are defined by the internationally accepted descriptive terms, classified into a set of five categories.	Very Low –Very rare Low Medium High Very high-Very Likely	Very Low –Very rare Low Medium High Very high-Very Likely
Climate variables/ Secondary hazard model Collection of climate variables per case study for further processing or as input data in the secondary hazard model (fire, flood model etc.)	Fire Spreading Model	Temperature Humidity
Impact Input of above previous processed data for the impact model	Fire-line intensity	Temperature Humidity

	Fire Temperature Radiative force	

As indicated above, Layer 1 is based on outputs from WP1 and WP2 especially where data from climatic hazards and climate change can be converted to output that is usable in the proposed analytical/simulation modelling framework in the next chapter 3.

For a resilience assessment (as shown in subsequent sections – see section 3.5-7), Layer 1 data provides the basis of using the scientific analysis of climate data in two ways; 1) it could provide the climate hazard data that can be directly modelled into a separate hazard simulation model (using the appropriate simulation method) and its impact on the CI asset or network in consideration; or 2) previous climatic analysis could provide the basis for developing scenarios that represent different threshold levels of the hazard event based on inputs from meteorological sources, historical data or hypothetical worse case scenarios.

It is important to realize that both approaches generate inputs into the conceptual model of understanding hazard impacts on CI assets but the first approach of developing a hazard simulation model allows for feedback analysis dynamically as the hazard event progresses which may be useful for certain types of assessments. For example, a system dynamics simulation model of flood water level and essential CI services can be developed based on historical data and stakeholder assessment which has inputs from various climate sources such as precipitation level, upstream snowfall melt, surface water runoff from urban surfaces and other factors that influence river water level in the system being modelled as shown in **Figure 4** below. The model explores the underlying inputs into the rise in river level and can develop insights into how rising water levels can impact different CI assets in a city – in **Figure 4** below this is shown by the arrows towards failure states of multiple CI assets such as economic and physical assets at the bottom of the figure.

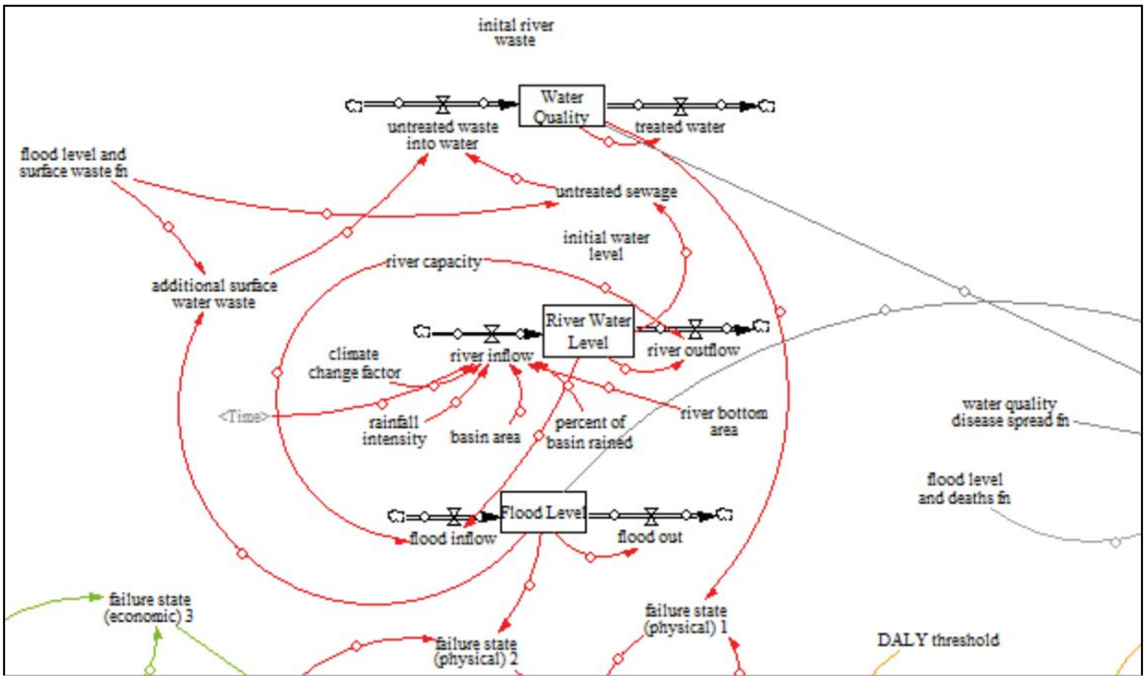


Figure 4. Example of using Layer 1 data to develop a river water level diagram for flood simulation (Simonovic, 2011).

When considering the longer term such as the impact of climate change, different considerations need to be taken with regards to the appropriate level and time frames. For instance, in the above example climate change impacts might have an impact over the long run on the magnitude, duration or frequency of the shock events which can be modelled at the same level indicating additional extreme scenarios with greater frequency of the event for the same model. For considering longer term climate change stress models, the model could be expanded or adapted to include the impact of long run issues such as rising sea levels in coastal areas, heat waves and water scarcity issues or excessive snow melt and how those additional factors impact on the resilience of a CI asset. Climate change stresses such as higher temperature can result in other types of impacts such as greater use of energy resulting in heavier loads on power networks or other ancillary effects like overheating of asset components (due to loads or due to surrounding temperature) – this can be modelled at different scales depending on the stress or event being modelled.

These models provide a systems understanding of the hazard event and can be used to link climate hazards with impacts across different systems including the CI and social sectors that are of interest to EU CIRCLE. The simulation model can provide insight into these systems by capturing the feedback that might exist between the hazard, the infrastructure and the resultant social processes that impact society overall (Peck and Simonovic, 2013, Gotangco et al., 2016).

Alternatively, as developing hazard simulation models are time consuming and require model building expertise, the entry point of climate analysis into the resilience framework could be based on the development of scenarios derived from meteorological analysis conducted by climate scientists, historical data, expert opinion or standards/regulations where threshold levels of an asset could be used. For example, in the same flooding case as above, scenarios could be generated for rise in water levels for 1m, 5m and 8m representing certain technical thresholds or based on probability of occurrences such as 1 in 5, 1 in 100 and 1 in 1000-year flood maps established after conductive extensive risk assessments as detailed in **Table 2** above.

Analysis like those based on the processes outlined above, can generate proxy values which can be used as model parameters of how a disturbance or shock can be modelled on the service delivery or performance of an asset. This allows us not to model the hazard but rather the impact of the hazard on the functions of a system.

To help conceptualize CI asset resilience for researchers/users at the initial stage of a resilience assessment, the EU CIRCLE framework provides some guidelines to clearly specify which contextual theme or approach they plan to take regarding the resilience of a CI asset. The approach adopted will depend on a number of factors such as the context, the unit of analysis, the scope and other factors such as time and cost of analysis. These contextual themes will be discussed in some of the sections below where required.

Each layer needs to contribute to the basic context and in each section we have specified this requirement as shown in Table 3 below.

Contextual theme	Discussion
Shock event or stress event	The framework will be able to evaluate both short-term shock events (e.g. earthquakes and floods) and longer-term stress events (e.g. climate change related). Stress events should be considered as part of a hazard-specific assessment (see above) and if required, a risk-assessment could be

	undertaken as well to understand likelihood and consequence of occurrence.
All Hazards/specific hazard approach	The assessment can be undertaken in one of two ways: 1 An all-hazards assessment – based on an event due to any (unspecified) hazard/failure, which could be either known or unknown. The event could be regional, local, societal or distal. 2 A hazard-specific assessment could be undertaken. This would involve identifying the relevant known hazard types and assessing the resilience to each.

Table 3. Context and approach to conceptualizing resilience adapted from Hughes and Healy (2014)

After specifying which type of analysis is required, the users then have to consider the requirements of the CI resilience assessment and the hazard event or shock. For conducting an analysis from an all-hazards perspective it is possible to use scenarios generated by the climate analysis used in Layer 1 and to focus on the impacts of the hazard on the asset service delivery or performance. The approach of focusing on the operating performance of the CI asset or network is explained in detail in following sections 3.1. Using the operating system performance of the asset or network allows us to consider the impact of a single hazard or multiple hazards as their impacts are converted into service loss or deterioration.

On the other hand, if a hazard specific approach is preferred than there is justification for the greater time and effort required to model the hazard event for insight into the crucial feedback between the hazard event and the CI system. Developing such models can provide invaluable insight into the hazard event and it socio-economic impact across sectors.

After indicating the approach, it is also useful to define the scope and size of climate hazard event or climate change stress. This can be classified according to the type of the climatic event for example using the following classifications (Hughes and Healy, 2014):

Regional Event: Such as significant physical damage to CI, coupled with severe disruptions to other lifeline services such as electricity, water and telecommunications. Example: major earthquake or flood.

Localised Event: This is a CI asset-specific incident resulting in loss of life, severe disruption to normal operations and reputation impacts. The intense focus of media and regulatory agencies requires the organisation to focus on managing stakeholder perception as well as the physical response and recovery from the event. Examples may be a collapse of a transport structure, or a hazardous spill affecting the immediate locality.

Societal event: Societal events which may cause unexpected impacts or demand on Cis, for example on the transport system. In this case, all physical infrastructures are intact; however, the system is unable to cope with demand. Examples may include: 1) a surge in traffic demand due to a specific event, or a major gathering of people, 2) growth in demand over time, 3) growth in public transport demand due to, say, fuel price rises, 4) an illness pandemic (eg influenza or SARS), meaning operational staff are unavailable.

Distal event: These could impact CI operators through key suppliers or interdependencies not based in the same region. This consequence scenario can identify the ways the CI system and related organisations may be affected through its networks of inter-organisational relationships. Examples may be the failure of a key dependent utility (power, telecommunications, water), failure of a key supplier, or an international shortage of key resources.

Climate change stress impacts can result in multiple hazard events across the spectrum of those events defined above – the can have an impact on the magnitude, duration and frequency of those events. It may be necessary to include additional variables when considering climate change impacts across larger scale of networks and longer time frames.

As mentioned above, Layer 1 can be incorporated into the framework either using a simulation model of a climate event or stress directly linked to the resilience model or through a separate climate analysis that generates threshold levels that could be used for setting scenarios. In this report, Layer 1 is conceptually incorporated into the analytical framework in section 3.8 where we consider the impacts of climate events and stresses into the conceptual resilience model – please see **Figure 13**. In section 3.8, it is incorporated into the conceptual model through proxy by the hypothetical data generated by the user - either through drawing a damage curve directly into the application or entering numerical time series data into the application in table form – see **Figure 17** for the user interface. Note this input data could take the form of scenarios or threshold levels identified in a separate climate analysis earlier and entered as scenarios - **Figure 18** demonstrates a hypothetical damage/shock curve of a long and prolonged event or stress.

2.4 Resilience of what (Layer 2)

The CI and assets provided in this section are obtained from EU-CIRCLE D1.2: State of the art review and Taxonomy. To ensure consistency across the project this section will be derived from D3.1 – Registry of CI assets and interconnections.

D3.1 has identified and collated the assets of each CI within the scope of the EU CIRCLE, for inclusion in a registry. The information in the registry will then feed into the Climate Infrastructure Resilience Platform (CIRP). For the purposes of the EU CIRCLE registry in D3.1 and here in this framework as well we use the following definitions:

Critical Infrastructure Asset is a physical long-lived resource, item, or entity that is operated as a system or network e.g. Airports, ports, coal powered plant, wastewater treatment plant, oil extraction platform etc. Critical Infrastructures within the scope of EU-CIRCLE include the following:

- Energy infrastructure
- Information and Communication Technology (ICT) infrastructure
- Water infrastructure
- Transport infrastructure
- Chemical industry infrastructure
- Health Sector
- Public Sector infrastructure

The registry will thus collect the assets of the CI sectors identified above in two steps:

1. The critical services of each CI sector will be identified, followed by subsequent identification of the assets that are required to provide these critical services, and described exhaustively in D 3.1. Once each asset has been identified, the key interdependencies and other crucial information such as the characteristics/attributes that describe the asset e.g. size of asset, age of asset, materials of asset, capacity of asset, etc. will be filled in directly by the users/stakeholders through stakeholder engagement or as data into CIRP.
2. Identification of damage functions for each asset. This will be done jointly with D3.3.

Hence the framework will focus on the resilience of critical infrastructure and their assets also taking into account the interdependencies of their networks. The main sectors of critical infrastructure and assets addressed by EU-CRICLE are set out below.

- Energy production & distribution systems
    - Electric power generation & transmission
    - Thermal power generation & transmission
    - Oil plants
    - Natural gas
    - Renewable energy plants
    - Underground mining and open pits
- Chemical Industry
    - Basic Chemical manufacturing facilities
    - Petrochemical manufacturing facilities
    - Pharmaceutical manufacturing facilities
    - Consumer product manufacturing facilities
    - Agricultural manufacturing facilities
    - Chemical storage and warehousing facilities
- Water Systems
    - Groundwater
    - Surface water
    - Sea water
    - Drinking water
    - Technical water (industry and maintenance)
    - Water for agriculture (irrigation)
    - Wastewater
    - Storm water
    - Dams
    - Water works
- Transportation
    - Road network
    - Railway network
    - Aviation
    - Maritime
    - Inland waterway transport (river transport)
    - Space transport
- ICT Networks
    - Telecommunication network
    - SCADA
    - Information Systems
- Public Sector
    - Civil Protection-Emergency responders
    - Public Health Protection

Layer 2 contributes a number of crucial dimensions to the analysis of resilience at the asset, network and NoNs level such as: the infrastructure system environment, the types of interdependencies, the coupling and response behaviour within the system, the characteristics of the infrastructure and, finally, the state of operation of an infrastructure as specified in D3.4. These dimensions allow us to better understand the CI system and systems of systems in place and are further explained in the table below:

Dimensions	Definition	Factors/variables	WP/Deliverables
Infrastructure characteristics	To characterize organization, causality and finality, types of interactions	- Scale (asset, network, NoN) - Infrastructure dynamics - Operational factors - Organizational considerations	D3.1 Registry of assets Directly by CI operator/service provider Mention in Indicators D4.5
State of operation of an infrastructure	It refers to the conditions under which an infrastructure is operating and exhibits different behaviours	- Normal operating conditions (from peak to off-peak conditions) - Times of severe stress or disruptions - Time when repair and restoration activities are initiated	Directly by CI operator/service provider UGV Indicators D4.5
Types of Interdependencies	Interdependencies and resultant infrastructure topologies	- Physical - Cyber -Geographic -Logical	D3.4 pg. 82 Directly by CI operator/service provider D3.1 Registry of assets

Table 4. Characterizing a system of interdependent CIs as specified in D3.4 and adapted from Rinaldi et al. (2001).

The framework differentiates the analysis at the initial stage by determining the scale of analysis required – this could also be aligned to the type of events considered for analysis in the discussion above but this might not always be the case. The scale of resilience assessment needs to be determined either at the asset, network or NoNs level. Once the level of assessment is determined then the resilience assessment model and tools (see section 3.5-6) can be used to measure the resilience of the asset, network or NoNs. D4.5 provides a more in depth look at how the resilience assessments can be done at the different levels.

Contextual theme	Discussion
Scale of resilience assessment	The framework will allow assessment at various scales: asset, network or NoN. The capacities measures in each case need to include additional indicators at each scale and the user can filter the questions accordingly (need to check with D4.5). Regional assessments could be aggregated to a national indicator for CIRP purposes (discuss with partners). The scale also depends on the event which could be regional, local, societal or distal – see section 2.3 above.

Table 5. Layer 2 contextual them of scale of analysis of CI

Layer 2 provides the infrastructure characteristics as indicated by the CI registry developed in D3.1. D3.1 provides the asset and network level information that can be used for conducting the required resilience assessment indicated in the next sections below. The other characteristics necessary for analysis are for example, states of operation of the CI asset or network, the types of interdependencies between them (pg. 82, D3.4), coupling and response behaviour, failure states and others. These are covered in detail on pg.34 of D3.4 in section 2.6.1 on interconnected networks and for clarity is shown here in **Figure 5** below.

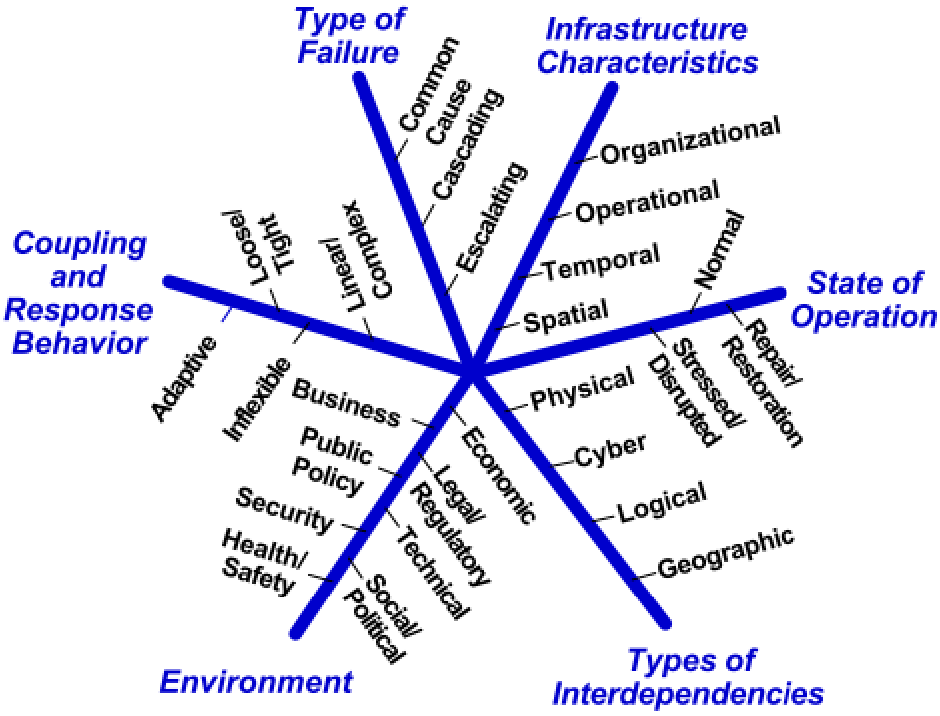


Figure 5. Dimensions for describing infrastructure interdependencies (from pg. 34 D3.4: Holistic CI Climate Hazard Risk Assessment Framework).

Layer 2 is incorporated into the analytical framework by considering the characteristics of the asset or asset properties as defined in D3.1: Asset Registry that help define the asset and is used to generate the baseline resilience score in the resilience assessment tool – please see section 3.6 for more details. Additionally, for illustrating how layer 2 is integrated into the resilience framework and the conceptual model please see Figure 13 in section 3.8 where Layer 2 is incorporated through a stock and flow diagram.

2.5 Disaster risks and impacts (Layer 3)

The broadly accepted definition of "risk" is that risk is a product (or another mathematic operator such as the maximum) of two aspects: The first are the consequences of a hazard, the second is the likelihood of the occurrence. AS/NZS 4360 defines "consequences" as "the outcome of an event expressed qualitatively or quantitatively, being a loss, injury, disadvantage or gain (AS/NZS, 2009). There may be a range of possible outcomes associated with an event". Likelihood is defined as used as a "qualitative description of probability or frequency".

Climate hazards, including the nature of uncertainty of current and future climate change, will increase the disaster risks and impacts on critical infrastructure, especially when they are exposed to such climatic conditions. As such, the level of vulnerability of critical infrastructure to climate hazards and climate change will positively correlate with the level of risk of the climate hazard and its impact(s) on critical infrastructure. The level of risk and its impacts are also influenced by the various capacities of critical infrastructure. Hence, in order to achieve resilience the risk level and the various capacity levels must be maintained at an optimum level. Risks and impacts are discussed in detail in WP3, and in particular deliverables 3.4 and 3.5.

The EU-CIRCLE process of risk management is discussed in detail in D3.4: Holistic CI Climate Hazard Risk Assessment Framework **which forms the basis of how the resilience framework integrates the risk process in Layer 3 – for more details see Figure 32. Combined risk resilience framework.** The six working steps of the National Infrastructure Protection Plan (DHS, 2013), identified in D3.4, provide the frame of reference for the EU-CIRCLE risk management framework into the resilience framework in this report, which has been modified according to the project's scope and objectives. The following steps make up the EU-CIRCLE risk management process:

1. Establishment of CI (or regional) climate change resilience policy, or specific business orient decision that will be addressed within the proposed framework
2. Identification, collection and processing of climate related data and secondary hazards
3. Identification of assets, systems, networks, and functions
4. **Assessment and evaluation of risks**
5. **Selection and implementation of protective programmes including adaptation options**
6. **Measurement of effectiveness**

D4.3 resilience framework interacts with D3.4 Risk framework by using steps 4, 5 and 6 to complete the analysis in layers 2 and 3 as specified in section 2 above. Step 4 uses the Consequence based risk approach for assessing and evaluating risks and is used in the conceptual model across to determine a baseline scenario from which other changes can be compared using the Anticipative, Restorative, Coping, Absorbing and Adaptive (AARCA) resilience capacities and the CI assets corresponding resilience assessment model and tool scores discussed in section 3.6. Step 5 looks at how protective programs and adaptation options can change AARCA resilience capacities by reducing the likelihood of occurrence, reducing the impacts / consequences, transferring in full or partly the risk and/or to avoid risk. These changes can result in different scores after the RAMs assessment and will differ from the baseline scenario defined in the previous step. Step 6 look at the measurement of effectiveness by comparing impacts on system performance of different RAMs scores as done through steps 4-5 by adding either a cost benefit analysis or conducting an analysis of based on the desired outcome of a decision criteria. These could be for example:

(i) The maximum resilience value (MRV): the level of system performance achieved when the physical characteristics of the disturbed system return to pre-disturbance state (end of simulation period). According to this criterion the higher value of MRV is preferred.

(ii) Time to fastest recovery value (TFRV) of system performance: the time required by the system under the impact of a disaster to reach the resilience value of one. According to this criterion the shortest time TFRV is preferred.

(iii) Lowest resilience value (LRV): the maximum loss of system performance due to the disturbance over the simulation period. According to this criterion the higher value of LRV is preferred indicating the smaller loss of system performance.

The disaster risk and impacts layer plays a crucial role in the risk assessment process to generate the correct resilience indicators (RAMs) for the conceptual model. **Figure 13** in section 3.8 discuss how Layer 3 is incorporated into the conceptual model along with the other layers. Layer 3 contributes to both the asset properties side and the CI impact side through the resilience parameters/indicators as indicated in section 2.7 and 2.8 below.

2.6 Capacities of Critical Infrastructure (Layer 4)

The capacities of critical infrastructure is one of the main ingredients for infrastructure resilience. An improved capacity will reduce the risks and impacts. This section presents the different types of capacities. At any one point the critical infrastructure can either have one or a combination of more than one type of capacity. The level of each type of capacity can vary even within a single critical infrastructure against a particular type of hazard. For example, a railway network along the coast can have a good level of anticipative capacity through an early warning system for a storm (leading to a storm surge and coastal flooding), but might have a poor level of absorptive and coping capacity. In such an instance, it can minimise the damages only by avoiding the disasters rather than facing it. Therefore, it is crucial to determine the level of each type of capacity for an infrastructure in order to understand its level of resilience against climatic hazards. The different types of capacities, called AARCA, are discussed below.

Anticipatory capacity: is the ability of a system to anticipate and reduce the impact of climate variability and extremes through preparedness and planning (Bahadur et al., 2015). This is considered as a proactive action before a foreseen event to avoid disturbance, either by avoiding or reducing exposure or by minimising vulnerability to specific hazards (Kellett and Peters, 2014). As such it has close links to vulnerability, hazards and prevention.

Absorptive capacity: is the ability of a system to buffer, bear and endure the impacts of climate extremes in the short term and avoid collapse (death, debilitation and destruction of livelihoods) (Wisner et al., 2004, Folke et al., 2010, Béné et al., 2012). This is the first line of defence (Biringer et al., 2013).

Coping capacity: is the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters (UNISDR, 2009). This is similar to absorptive capacity. The absorptive is immediately after a disaster whereas coping can be for a comparatively longer period.

Restorative capacity: is the ability of a system to be repaired easily and efficiently (Biringer et al., 2013). This capacity is associated with recovery too. In the context of critical infrastructure, system repair is the distinguishing feature of restorative capacity and it has been claimed as the final line of defence that requires the greatest amount of effort. Biringer et al. (2013) state that restorative capacity is not usually used unless either the absorptive and adaptive capacities are not able maintain an acceptable level of performance or the system is completely broken and unable to perform.

Adaptive capacity: is the combination of assets, skills, technologies and confidence to make changes and adapt effectively to the challenges posed by long term trends, such as future climate change (UNISDR, 2009). One of the distinguishing features of this capacity is the reorganisation and change of standard operating procedures where Biringer et al. (2013) claim this as the second line of defence.

All these different types of capacities discussed above are included within the EU-CIRCLE resilience framework as depicted in Figure 1 at the beginning of this section. For how they are incorporated into the resilience assessment model and tool please see Figure 10.

2.7 Asset properties associated with Critical Infrastructure and Climate Hazards (Layers 1, 2, & 3)

The establishment of a threshold level of risks and vulnerability for each critical infrastructure can be achieved through coupling each asset against each type of climate hazard. This determination can be based on the Critical Infrastructure (CI) capacities, which were discussed in Section 2.6 and 3.4, and the Climatic Hazard (CH), both current and future, parameters. These CI and CH parameters feed into the EU-CIRCLE resilience framework as shown in **Figure 1**.

Some of the features that can be built within the resilience framework and are discussed in the sections above are summarised below

- Critical Infrastructure parameters/asset properties
  - Lifecycle
  - Age of infrastructure
  - Location of infrastructure
  - State of maintenance
  - Level of interdependencies

- Climatic hazards parameters
  - Frequency of the event (historically)
  - Magnitude of the event
  - Anticipated level of impact on CI
  - Future climate change projections (for X time periods e.g. for the next 50 years and X regions etc.) (WP2)
  - Nature of uncertainties

2.8 Resilience parameters (Layer 3 and 4)

In order to put resilience into practice, we want to know what properties indicate resilience, how to measure or assess their resilience, and how to manage for resilience. There are several dimensions to resilience that need to be taken into consideration when trying to achieve a holistic approach for infrastructure resilience. One of the components of EU-CIRCLE resilience framework will be the resilience parameters that are related to critical infrastructures and their capacities.

The EU-CIRCLE resilience framework recognises five types of generic resilience parameters. These parameters correspond to the critical infrastructure capacities outlined in section 2.6 Capacities of Critical Infrastructure above and are a way of quantifying these capacities. These parameters are as follows:

1. Anticipation,
2. Absorption,
3. Coping,
4. Restoration, and
5. Adaptation.

Resilience indicators have been developed and further analysed for each parameter and each type of critical infrastructure as a part of *D4.5 Resilience Indicators*. Possible generic indicators are shown in **Table 6** below. The list of generic indicators is not final and will be changed in accordance with the results of further research. These generic indicators will be further developed in a several levels, e.g. specific indicators, sub-indicators, indicator variables, etc.

The resilience indicators can be qualitative, quantitative or binary according to the type of data they utilize and may be absolute (e.g., speed of critical infrastructure failure) or relative (e.g., recovery/loss ratio) (Prior, 2014).

Quantitative indicators (e.g. the average annual temperature, the number of projects developed in response to a policy, or the number of bridges constructed) are often preferred for monitoring and evaluation. Quantitative resilience indicators might be most appropriate for technical features of infrastructure. Where quantitative data is not available, and the issue is still considered important for monitoring purposes, qualitative or binary indicators may be utilized.

Qualitative indicators provide narrative or summary information regarding an item of concern. Qualitative indicators may be most appropriate when examining the quality of infrastructure organisation, operation, maintenance or management, or when assessing users interactions with infrastructure. Adaptation indicators, because they relate to processes, are more likely to be qualitative than climate change or climate impact indicators.

Binary indicators have a yes/no answer. Several indicators appropriate for climate adaptation could be binary, e.g. early warning systems in place (yes/no).

In principle, the strategy for measuring resilience is to quantify the difference between the ability of a critical infrastructure to provide services prior to the occurrence of an event and the expected ability of that infrastructure to perform after an event (Bruneau et al., 2003). This discussed in further details in section 3 below.

Phillips and Tompkins (2014) define good metrics with the following properties:

– Comprehensive,
– Understandable,
– Practical,
– Non-redundant, and
– Minimal.

The above create defensible, transparent and repeatable metrics and have been used as guidelines to developing these indicators in D4.5.

Table 6. Generic resilience indicators developed in D4.5

Resilience parameters	Generic resilience indicators
Anticipation	1. Probability of failure 2. Quality of infrastructure 3. Pre-event functionality of the infrastructure 4. Quality/extent of mitigating features 5. Quality of disturbance planning/response 6. Quality of crisis communication/information sharing 7. Learnability
Absorption	1. Systems failure (Unavailability of assets) 2. Severity of failure 3. Just in time delivery - Reliability 4. Post-event functionality 5. Resistance 6. Robustness
Coping	1. Withstanding 2. Redundancy 3. Resourcefulness 4. Response 5. Economic sustainability 6. Interoperability
Restoration	1. Post-event damage assessment 2. Recovery time post-event 3. Recovery/loss ratio 4. Cost of reinstating functionality post-event
Adaptation	1. Substitutability (replacement of service) 2. Adaptability / flexibility 3. Impact reducing availability 4. Consequences reducing availability

3 Analytical Framework

3.1 Introduction

This section presents a conceptualization of the resilience framework as defined and detailed in D4.1 and the sections above. D4.3 proposes to use a simulation modelling approach to better understand the behaviour of complex infrastructure systems to natural hazards in the short run and climate change impacts over the long run. System dynamics (SD) simulation modelling is proposed as an approach to CI resilience modelling as it captures the complexity of hazard events and climate stress and their impacts on CI assets and networks. The approach is suited to capture the feedback between the layers detailed in the previous section and uses the resilience capacities introduced in section 2.8 above and proposes a proxy for disaster impact through simulation modelling of CI system performance. This section will introduce the theory behind the conceptual model and define the capacities and their respective resilience indicators as developed in D4.5 and how they can be used to conceptualize CI resilience at the asset, network and NoN levels. The proposed approach forms the foundation on which the D4.1 initial resilience framework will be operationalized. The computational definitions denoted here in this section are based on some of the literature covered previously in D3.1, D3.4, D4.1, D4.5 and D4.6.

The CI resilience framework conceptualizes CI resilience as a dynamic behaviour of a system over time which can be used for the comparison of various alternate strategies for system performance improvement and support decision making processes within those stakeholder organizations tasked with operating CI assets and networks. The methodology developed in this report can be implemented by various CI stakeholders such as asset operators, service providers and other public/private sector organizations to quantify and compare different hazard response strategies. The conceptual framework develops a model that can be used by these stakeholders to compare the performance of a CI asset under different hazard conditions (for example, comparison of the performance of a power generation unit under hazard conditions like a flood compared with the impact from a forest fire) or to compare different CI assets under similar hazard conditions (for example, a flood impacting a power generation unit and its distribution network of assets).

Therefore, this section then develops a generic system dynamics simulation model as an analytical tool in the EU CIRCLE Resilience Framework that can be used as a basis for quantification of critical infrastructure asset resilience by: (i) introducing the analytical CI Resilience framework as a method of quantifying/conceptualizing hazard impact (i.e. in terms of shock to performance); (ii) defining both the hazard and resilience as dynamic (i.e. changing over time); (iii) proposing an analytical framework for integrating the layered approach and the resilience capacities (i.e. the AARCA resilience capacities); and (iv) presenting a conceptual framework for integration of impacts on a CI asset, a network of CI assets or a network of networks.

Deterministic vs Probabilistic approaches

As indicated in Part A section 1.4 above, the preference among consortium members was for a modelling approach that combines the strengths of the consortium, the availability of data sources (and willingness to share access) with the requirements of stakeholders hence the need for using an integrated approach. After considerable consideration the deterministic approach to modelling hazard impacts was decided upon and the conceptual framework developed in this section seeks to continue in that direction. A deterministic approach is differentiated from a probabilistic one on the basis of not including uncertainty in the analysis. Probabilistic methods consider the stochasticity involved with the behaviour in the system. These methods try to overcome the issue of lack of historical data and "develop" historical data by replicating the physics of the phenomenon and producing a large number of simulated events through climate modelling and other meteorological analysis (Hosseini et al., 2016).

Deterministic methods, on the other hand, begin the analysis with the probability of an event as a given and finite. This approach typically models scenarios, where the input values are known and the outcome is observed. They can be used effectively in combination and are not necessarily mutually exclusive. For example, probabilistic modelling (i.e. running multiple scenarios at different probabilities of occurrence) can be used to generate a range of deterministic scenarios that can be used to developed a number of scenarios that might include (OECD, 2012):

- **Worst-case** e.g. the maximum losses
- **Best-case** e.g. the losses that can be absorbed
- **Most "likely"** e.g. the losses that are most likely to occur

Although, there are pros and cons of using both approaches, for the EU CIRCLE and CIRP, members felt a deterministic approach would best suit the analysis of CI resilience as it suited the inputs generated from the contributing work packages as detailed above in the layered approach. The feedback from partners also highlighted its value in generating comparative scenarios for disaster risk reduction and resilience building which suited stakeholder's needs. Although there are some of limitations of the approach such as it does not consider the full range of possible outcomes, and does not quantify the likelihood of each of these outcomes this may be, to certain extent, addressed with the adoption of the appropriate simulation modelling method (Ouyang, 2014).

Both Ouyang (2014) and (Hosseini et al., 2016) have reviewed the different methodologies that could be adopted for understanding the impact of climate hazard events and climate change stresses on CI. From these approaches, Francis and Bekera (2014) have strongly advocated a quantitative approach to developing resilience metrics that can aid in decision making. D4.3 uses this approach to quantification of resilience, as developed in detail in D4.5, to determine the effect of preventative measures and adaptation options on CI resilience with respect to hazard events and climate stresses. This report seeks to provide the framework for integrating these metrics developed in D4.5 into the resilience framework developed in D4.1. Although there are a large number of resilience frameworks as indicated in the extensive review in D4.1, in the literature the majority of these frameworks are qualitative in nature (Twigg, 2009, Tyler et al., 2014). Bhamra (2015) has noted that among those few quantitative approaches proposed in the literature even fewer have been validated through applications in relevant case studies indicating a need for developing quantitative tools that can be applied in case contexts (Bhamra, 2015).

Despite this difficulty a number of well-known studies like Bruneau and Reinhorn (2007), Cutter et al. (2010), and Irwin et al. (2016) have proposed conceptual frameworks for measuring resilience that have been applied in case studies but these have largely used a static indicator that is a single value calculated over the duration of the disaster (Beccari, 2016, Simonovic, 2016). Beccari (2016), in his extensive review of resilience frameworks and indicators, has drawn attention to two key limitations of these frameworks: (1) that they have a low use of direct measures of disaster resilience and largely depend on indirect measures, and (2) the low use of sensitivity and uncertainty analysis in their results limiting the explanatory power of these tools (Beccari, 2016).

The multi-layer approach proposed in D4.1 and expanded in this report, D4.3, seek to address some of these criticisms by closely integrating the four layers which include many direct measures of disaster resilience in terms of data from climate modelled scenarios, damage curves, asset properties, risk assessment tools and the capacity scores. The use of system dynamics and a systems approach to quantifying resilience addresses the second point of using simulation modelling to test sensitivity and uncertainty analysis through stakeholder involvement throughout the stages of the resilience assessment process and to determine the validity and reliability of these tools. Therefore, the resilience framework proposed here can be used as the basis for a tool in the decision support system like CIRP that innovatively uses the multi-layered approach to compute resilience capacities which can be compared across temporal and spatial dimensions.

As mentioned earlier, a number of modelling approaches in the literature offer a quantitative means to assess resilience, and from these the systems approach has been identified as an appropriate tool for the quantification of CI resilience as well as integration into the output of other deliverables and work packages in the EU CIRCLE project. The use of system dynamics simulation modelling allows for the integration of the quantification of resilience (as developed in D4.5) with the multi-layers as explained in this report. This report proposes using a conceptual system dynamics (SD) model of a CI asset system, measuring its resilience capacities and then comparing its system performance to the impact of a hazard event. The model uses system performance as a proxy for the whole structure of the CI asset or the network. System dynamics has been used in a number of key studies in CI protection, particularly used in considering interconnectedness between CI assets and networks. SD simulation modelling has been used in large scale CI sector level analysis like in the CIP/DSS project, as a smaller module for asset network analysis in a DSS like the HAZUS-MH, both used by the department of Homeland Security (DHS) in the United States (Min et al., 2007, Ouyang, 2014). In the EU, the CRISADMIN project has used SD methods to define and understand how impacts can cascade across different CI networks (Armenia et al., 2014). Another project within the EU that uses SD for assessing CI resilience is the Smart Mature Resilience (SMR) project which looks at developing a resilience maturity model of a city across different resilience metrics ((Hanania and G., 2017).

In Canada, researchers have developed ResilSIM an innovative SD simulation modelling tool for an online DSS that integrates a dynamic quantitative resilience measure into the SD simulation modelling framework of cascading impacts thus developing a unique novel method of measuring resilience and the impacts of hazards across CI networks in urban areas in one functional tool (Simonovic, 2016). The ResilSIM interface allows users to consider preventative measures and adaptation options and can input those directly into the simulation model as parameters allowing for a comparison of different measures over time (Irwin et al., 2016). The value of modelling cascading impacts across CI networks using SD has been validated in numerous published reports and documents - for a brief summary of these applications see the appendix at the end of this report.

The SD simulation modelling approach developed in this report utilizes a similar systems approach, as in the research mentioned above, to understanding CI asset performance and hence looks at system behaviour overall to assess impacts. These measures determine resilience of a system by comparing before and after a hazard event or shock without concentrating on the need to model extensively the system specific characteristics (unless those are necessary for the analysis). This report uses resilience capacities (as developed in D4.1) to conduct a resilience assessment of CI assets (as developed in D4.5) and then use the metric developed to aid decision making.

Building on emergency planning experience, Levine (2014) has identified the following criteria to provide a sound basis for developing policy-relevant resilience measures that are more fit-for-purpose for end users and which can help establish impact monitoring to inform the management of interventions and policy by developing a set of measures:

1) that could aid in choosing between investments in competing policies or interventions;
2) that could help in better understanding the determinants of resilience to various threats in different situations, and

3) that could support making a political or advocacy case for investment in resilience.

Therefore, this report develops an approach that can be used as one of the set of tools to be used in a decision support system based on the concept of resilience capacities which can be compared for CI assets across time and space to allow for both a dynamic (and spatial analysis if required).

This technical report develops a conceptual system dynamics simulation model as analytical tool in the EU CIRCLE Resilience Framework for use in quantification of Critical Infrastructure Asset resilience.

1. To develop a method to assess the level of resilience of Critical Infrastructure for natural hazards;
2. To identify and understand the elements contributing to CI resilience;
3. To enhance the capacity of CI assets and networks to cope and then to adapt with Climate Change impacts.

To once again repeat from section 2, the definition of resilience in the context of critical infrastructure is given as the **ability of a CI system to prevent, withstand, recover and adapt from the effects of climate hazards and climate change**. Following this definition of CI resilience, the next section looks at a systems understanding of CI resilience and how it can be conceptualized within the EU CIRCLE framework forming the analytical basis for measuring and comparing capacities for CI resilience for a single asset, a network and the case of NoNs.

3.2 Application of the systems approach to understanding CI resilience

A system is defined as a "a group of independent but interrelated elements comprising a unified whole" and "is a set of parts coordinated to accomplish a set of goals" (McManus, 2008). The definition of a CI system can be extended to include "any organized assembly of resources and procedures united and regulated by interaction or interdependence to accomplish a set of specific functions or a collection of personnel, equipment, and methods organized to accomplish a set of specific functions" (Bouchon, 2006). For example, if applied to the electricity sector the definition can be specified as: "…an integrated combination of generation, transmission and distribution of electricity or natural gas that may be used by a utility or a group of utilities through a power pool or an operator that manages services for more than one system (Bouchon, 2006)."

Building on this definition Bouchon (2006) uses the broader definition to include: "A set of actors or entities bound together by a set of rules and relationships into a unified whole. A system's health is dependent on the health of the whole pattern, which can sometimes be reflected (and thus measured) in the status of a key part of the system."

In summary building on the broader definition above, D4.3 defines a system as *an organized ensemble of sub-systems or components and of interacting processes, which is coherent enough to keep a relative degree of autonomy and performs a function or possesses a structure (Simonovic, 2011).*

Functional approach to systems resilience

The systems approach relies on the analysis of what the whole system is, the environment in which it exists or operates, what its objectives are, and how it is supported by the activities of the parts. According to systems scientists there are two complementary ways of analysing a system (Simonovic, 2011):

1- The structural approach answers the question: “what is the system made of?”

2- The functional approach answers the question: “how is it working?”

The ***structural analysis*** approach consists of identifying the boundary between the system and its environment and then recognising the elements (components, sub-systems or black boxes) of the system. Since systems are always embedded in larger systems, the concept of element does not refer here to a single component but is relative to the whole it is part of. These elements are themselves systems (and therefore sub-systems). The level of analysis, and then the boundaries must be defined as a function of the scope of the analysis, so that accurate boundaries of the system and subsystems can be identified. The most common boundary of systems used in analysis could be organizations but for CI systems might be individual assets, whole networks or even NoN, such as sectors.

The ***functional analysis approach*** (**Figure 6**) is based on the analysis of the function of a system rather than the list of elements or components that make up the system. In this approach, the task is to first identify the system’s objectives: they refer to the goal and the services a given system has to fulfill or provide - here in our report we use the term system performance. The performances of the system can be measured, with respect to the required level of expected output or service and this can be defined with the owners or operators of the service on the supply side or users if considering demand side (Giles, 2016).

Studies using functional approaches can also be called *input-output approaches* or efficiency approaches. These are generally used for identifying the trouble spots within a system especially places where there is waste and then proceed to remove the inefficiency – more about this approach is covered in section 2.6.3 of D3.4 Pg. 37. The input-output approach counts on the principle that a system is an entity into which various types of resources are imputed and out of which comes an output in terms of a product or a service – providing a benchmark to gauge system performance. For urban resilience, CI is a crucial system for the function of larger systems like communities and cities, so its system performance requires special emphasis. The system performance thus defined of each component and their contribution to the performance of the overall system can be used to assess the baseline working capacity of a CI asset, network or even a Network of Networks.

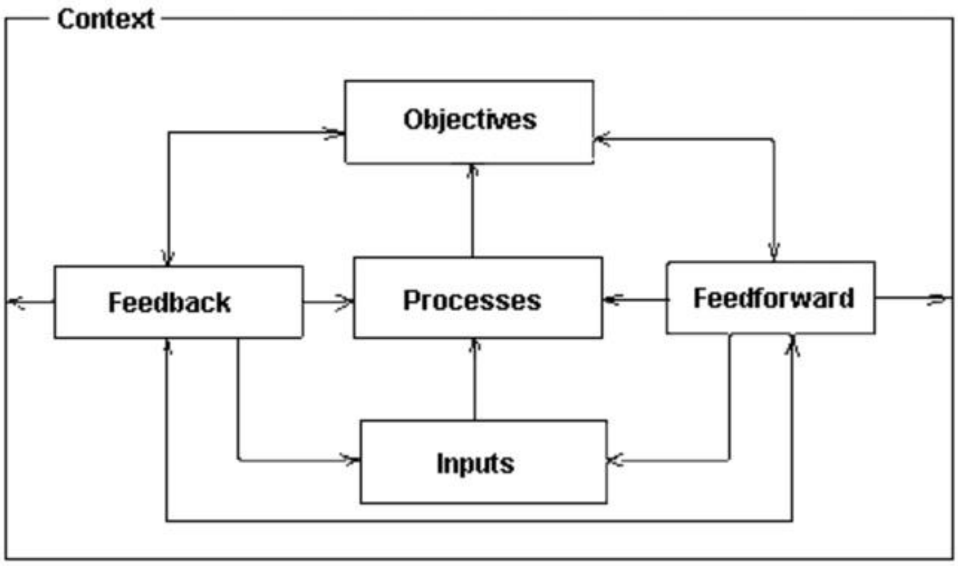


Figure 6. Functional analysis approach (Giles, 2016)

The EU CIRCLE CI resilience framework utilizes this understanding of functional analysis of a system to conceptualize and define the system performance of a CI asset, network or NoNs. The approach emphasises the need for understanding flows in the system particularly regarding the feedback and feed-forward flows in the system being considered. The functional analysis approach is also one of the approaches used in D3.1 to build registries of assets. Figure 7 below demonstrates how the information collected can prove useful for analysis in the resilience framework.

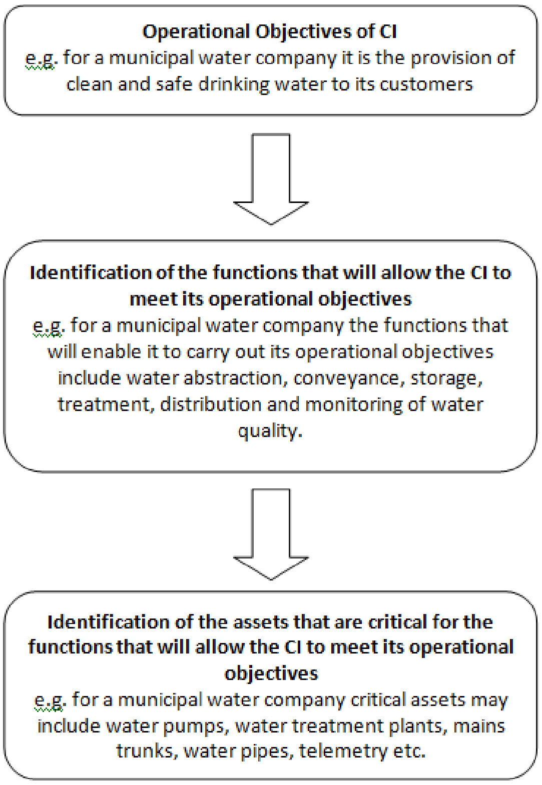


Figure 7. Schematic of the function-based approach to the identification of critical assets used in D3.1

The resilience framework uses this approach to identification of CI assets to define a system performance curve as a proxy for the operations of the asset, network or NoN. The conceptual model then proposes to use these curves as functions which can then be impacted in different ways through the application of degradation curves or shock curves as covered in more detail in the subsequent sections below. The following section introduces the formal definition and how it integrates into our analysis.

3.3 Formal definition of system performance of CI asset, network or NoN

The conceptual basis for the definition of system performance here is taken from the literature that uses an approach developed over a decade of use by several researchers but was pioneered experts based at the Multidisciplinary Centre for Earthquake Engineering Research (MCEER) University of Buffalo (Bruneau et al., 2003, Bruneau and Reinhorn, 2007, Cimellaro et al., 2010). Bruneau et al. (2003), first proposed a quantitative metric for measuring the loss of resilience of a community to an earthquake and developed a framework for seismic resilience measures that could be used to compare resilience of structures over time and over communities. Subsequently, Sheffi and Rice Jr. (2005) used this conceptualization to develop a qualitative disruption profile which could be used to look at impacts at the enterprise level indicating that it can be adapted for use in many similar applications requiring a functional approach to understanding a system as described above.

The MCEER resilience framework defined the impact of an earthquake event on a physical structure such as a building as a function of its system performance. For example, a hospital is a physical structure with a function and a shock such as an earthquake would affect both its physical structure and its function as a key part of the response infrastructure (Bruneau et al., 2003). The study conceptualized the resilience triangle, as shown in Figure 8 below, which could be used to represent the loss occurring from a disruption or disaster event regarding service delivery or system performance as a composite of both hard and soft systems within the structure. Hence in the diagram below, system performance can range from 0% to 100%, where 100% means no impact on service and 0% means no service available (Bruneau et al., 2003, Bruneau and Reinhorn, 2007, Cimellaro et al., 2010). Note also that we can depict the four elements of the EU CIRCLE definition of resilience within the diagram to depict how and where those elements interact.

D3.4 (pg.89) also notes the use of this method in Bruneau and Reinhorn (2007), Cimellaro et al. (2010) and in Ganin et al. (2016), and how it successfully introduces the time element in the CI modelling process. D3.4 also describes it as being used by Bruneau and Reinhorn (2007) and Cimellaro et al. (2010) to indicate the period necessary to restore the functionality of a structure, and infrastructure system to a desired level that can operate or function the same, or close to, or better than the original one. The report also indicated the use of this method to determine resileince dynamics during extreme conditions where it was shown be used for both Asset and Network levels of the CI system – see D3.4A: Holistic CI Climate Hazard Risk Assessment Framework pg. 89 for more details.

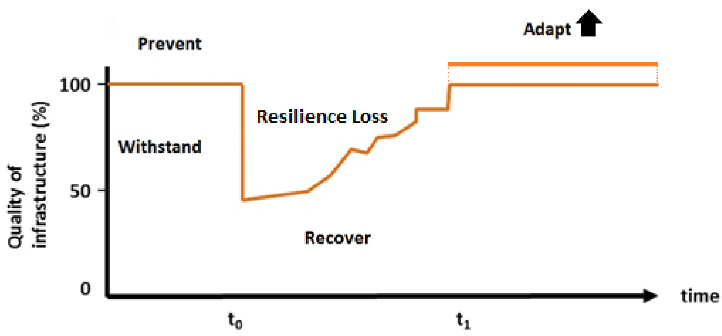


Figure 8. Conceptual resilience triangle for EU CIRCLE definition adapted from Bruneau and Reinhorn (2007).

Mathematically Bruneau et al. (2003) defined the term as follows:

$$RL = \int_{t0}^{t1} [100 - Q(t)dt$$

Where RL was resilience loss, t0 was time at which the shock occurs, and t1 as the time at which the community returns to its pre-shock state. Q(t) is the quality of the community infrastructure which could represent a composite of several different types of performance measures. Q(t) can be then compared to the as-designed pre-shock infrastructure quality, denoted by 100. Hence in this conceptualization, larger RL values indicate a lower resilience and lower RL values indicate higher resilience. A number of researchers and scientists have commented on the general applicablity of this measure and how it can be extended to a number of applications (Sheffi and Rice Jr., 2005, Peck and Simonovic, 2013, Hosseini et al., 2016).

Peck and Simonovic (2013) update the concept of the resilience triangle and adapt it in their research to indicate that the system performance (SP) of city functions (such as CI) and use it to determine CI network level resilience and the NoN or sector level. This report will use the computational definition of system performance as used by Peck and Simonovic (2013). Peck and Simonovic (2013) represent typical system performance levels at the sector level within a city, using them to develop proxy indicators for five sectors - physical, health, economic, organizational and social (PHEOS) sectors that make up overall city resilience in their framework (Peck and Simonovic, 2013) which has been validated in a number of studies (Srivastav and Simonovic, 2014a, Srivastav and Simonovic, 2014b, Gotangco et al., 2016). These studies have used the framework to scale resilience assessments down to the individual units of the sectors that make up overall city resilience in a SD simulation feedback model – see appendix 2 for an application in Resilsim (Irwin et al., 2016).

The SP of these sectors can be represented under shock and recovery in three states as shown below in **Figure 9**. The three states represent a situation where the CI asset recovers completely to its initial pre-shock level; (ii) the system recovers to below the initial pre-shock level; and (iii) the system recovers and “bounces back better” than the initial pre-shock level (Peck and Simonovic, 2013). These could be termed as the shock profile of a hazard or stress event, a shock or a disturbance to the overall function of the system as defined above.

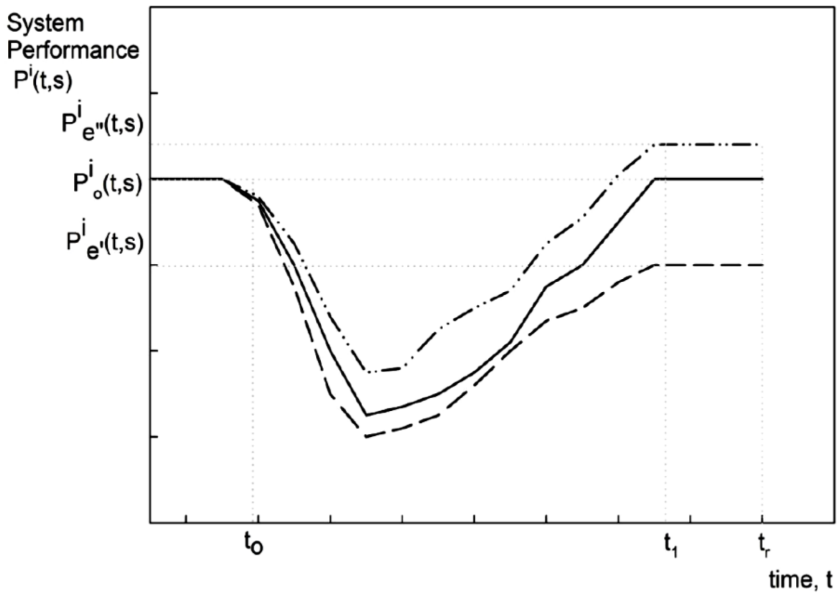


Figure 9. Shock profile: system performance measures after a hazard event or shock (Peck and Simonovic, 2013)

The approach uses the concept of SP in developing a SD simulation model of City resilience and this research adapts that approach for application to CI resilience. The system performance shock profile provides researchers with a useful framework for understanding how a disruption can potentially affect the system performance of a system of a CI asset or Network as may be the case in the project case studies. Here in our conceptual model, resilience is considered as 1) the ability of the system to prevent or withstand shocks and negative impacts and therefore mitigate the deviation from the baseline SP; and 2) the ability of the system to quickly recover from any shocks, re-establish system functioning, and 3) if possible, adapt and “build back better” and improve on the baseline SP.

This conceptualization allows us to define loss of performance in terms of the resilience triangle and in mathematical terms as the area below the line. Calculating the changes in the area under the line allows us to measure the change in total loss due to a shock or disturbance and this can be linked to the level of resilience in the system to withstand those shocks. This conceptual representation can help in understanding the chronology of events as well as the timing of response and mitigation or preventative measures that may be considered and can be used to engage with stakeholders in discussions on CI resilience. In the next section we look at how we can use this computation of system performance under shock in relation to the initial baseline resilience capacities of a CI asset, network or NoNs.

The conceptual model in SD uses the quantitative inputs from the resilience capacities and the resilience assessment model and tool (RAMTs – see section 3.5 below) and can allow for a comparison of the SP as affected by the shock or hazard with respect to an initial or baseline SP. This measure can be plotted over time at the pre-disaster, during and post-disaster stages as shown in section 3.3 above. This provides a means to track and compare system resilience under different conditions and scenarios which can be used to aid decision making among CI stakeholders.

3.4 The RAMTs measurement and CI Resilience framework

This section looks at using the resilience assessment model and tools (RAMTs) developed in D4.5: Resilience indicators and capacities and how this combines with the resilience framework as proposed here in D4.3. This section provides a summary of how the proposed conceptual framework for measuring resilience based on the capacities developed in the previous sections. Each step of the process is explained to justify the approach.

The process is described in **Figure 1.** EU CIRCLE resilience framework with contributions from different WPs and deliverables.s, which includes an initial determination of the context of resilience assessment model and tools (RAMTs). This is then followed by the description of an indicators developed in D4.5 which combine to form a resilience score from 10 (very high resilience) to 0 (very low resilience).

For example:

10 Very high resilience – meets all standards and requirements for continued service operation in the most difficult conditions

7-9 High resilience – acceptable performance in relation to capacities, some improvements can be made

4-6 Moderate resilience – less than desirable performance and specific improvements should be prioritised (based on D4.2)

1 -3 Low resilience – poor performance and specific improvements across all capacities required urgently

0 Very low resilience – resilience practically not exist, improvements required urgently, without delay

Note these are just for guidance the final categorization and description of these resilience capacities as indicators will be made in D4.5.

The values of the Resilience Indexes represent variables based on which to evaluate the opportunities and make decisions on the necessary adaptations (D4.6 Adaptation model and D4.7 Cost-effectiveness model) and ensure business continuity (D4.4 Business continuity model).

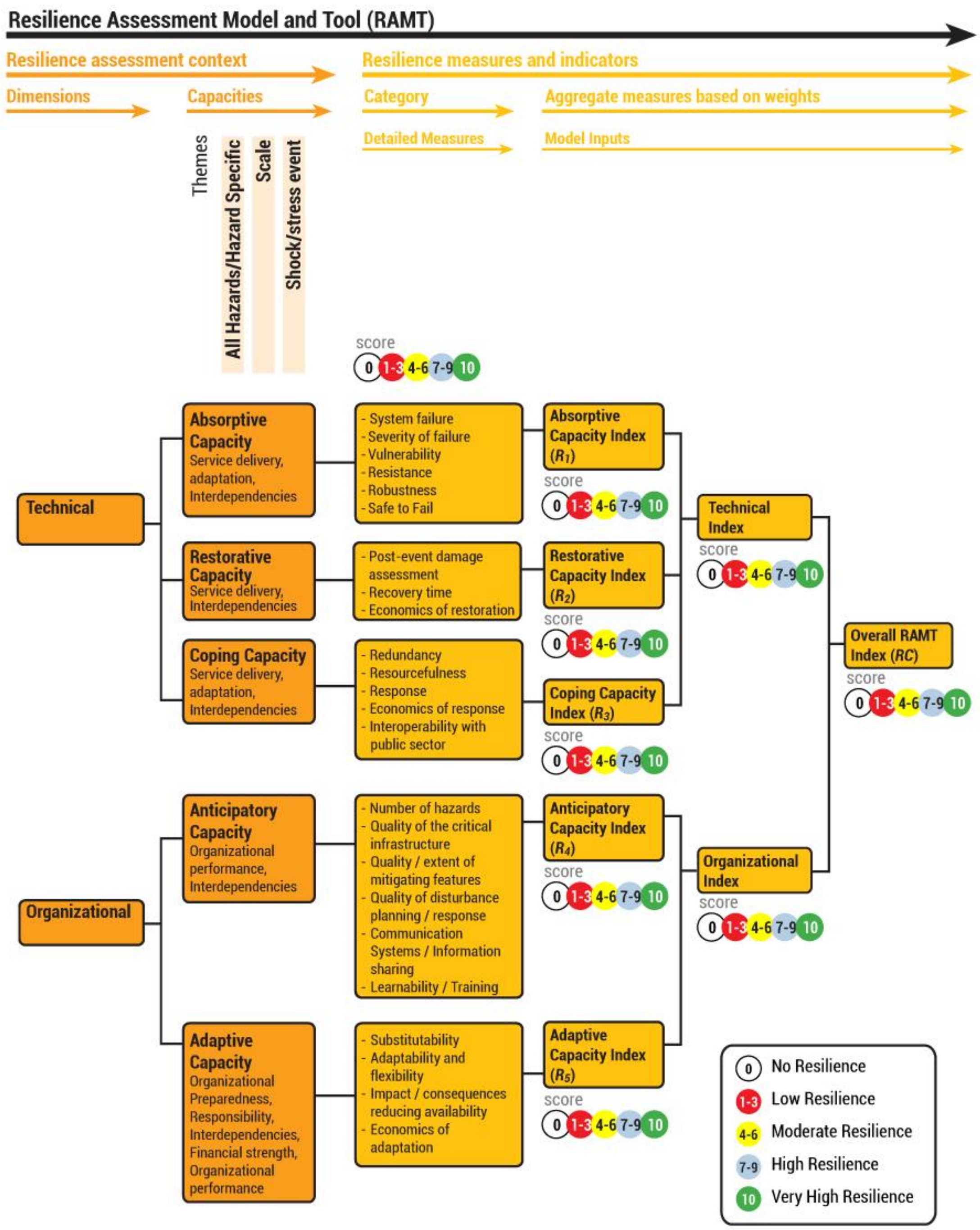


Figure 10. The Resilience Assessment Model and Tool (RAMT) and the calculation of resilience capacities as indicated in D4.1 and D4.5. Adapted from Hughes and Healy (2014).

3.5 Resilience Assessment Model and Tools (RAMTs)

The RAMTs has been developed on the basis of the ARCAA resilience capacities developed in the framework in sections 2.7-8 above. The only difference here is that they are first divided into the broad categories of Organizational Capacities (Anticipative and Adaptive) and Technical (Absorptive, Restorative and Coping). The resilience capacities are then specified into the distinct ARCAA categories of Absorptive, Restorative, Coping, Anticipative and Adaptive.

Each of these five capacities has been identified after an extensive review of the literature (D4.1) and for their specific application to CI. At this stage, it is important to draw attention to the contextual themes mentioned in section 2 above that can help indicate which set of RAMTs assessments to do and which set of questions to ask in the individual categories. These themes influence the context and approach of the RAMTs. These themes are as repeated in **Table 7** below.

Context/theme	Discussion
All Hazards/specific hazard approach	The assessment can be undertaken in one of two ways: 1 An all-hazards assessment – based on an event due to any (unspecified) hazard/failure, which could be either known or unknown. The event could be regional, local, societal or distal. 2 A hazard-specific assessment could be undertaken. This would involve identifying the relevant known hazard types and assessing the resilience to each.
Scale of resilience assessment	The framework will allow assessment at various scales: asset, network or NoN. The capacities measures in each case need to include additional indicators at each scale and the user can filter the questions accordingly (need to check with D4.5). Regional assessments could be aggregated to a national indicator for CIRP purposes (discuss with partners). The scale also depends on the event which could be regional, local, societal or distal – see section 2.3 above.
Shock event or stress event	The framework will be able to evaluate both short-term shock events (e.g. earthquakes and floods) and longer-term stress events (e.g. climate change related). Stress events should be considered as part of a hazard-specific assessment (see above) and if required, a risk-assessment could be undertaken as well to understand likelihood and consequence of occurrence.

Table 7. Contextual themes for resilience assessment model and tool.

3.6 Resilience Capacities and RAMTs

The shock or hazard impact of a disaster on overall CI service delivery shows considerable differences around time and space and are the result of the interaction between the various CI assets, networks or sectors as the various components have different capacities to absorb, recover and adapt to these diverse types of hazards. These different capacities can be defined by a range of different resilience indicators as indicated in D4.1 called the AARCA resilience capacities (absorptive, anticipatory, restorative, coping and adaptive capacities).

Properties of Resilience capacities

As mentioned previously CI networks are a combination of physical and social systems containing elements that can be both hard and soft systems. Any CI asset has a limited capacity to prevent, withstand and recover from a hazard event based on several factors such as the size of the hazard event, the vulnerability of the asset and resilience capacity of the asset. In the simulation framework these hazard events will be termed as shocks that have an impact on the functional or system performance of the asset (or CI network depending on the unit of analysis). The shock will impact the system performance of the CI asset in part due to the type of hazard/shock, the size and duration of exposure to that hazard/shock and will be represented in the framework as a loss to system performance.

The capacity of the CI asset to cope or deal with the shocks is called the resilience capacity of the system and is represented by the five AARCA capacities (absorptive, anticipatory, restorative, coping and adaptive capacities). The resilience capacity (RC) of the CI asset is the combined behaviour of the different components within the asset system that varies at different times both in and across temporal and spatial dimensions. It is important to note that RCs may change due to everyday processes and hence are dynamic in nature. These RCs are represented in the framework by using the five resilience capacities (AARCA) introduced in D4.1, further developed in D4.2 and, finally, specified in D4.5. The AARCA capacities are defined below as:

Anticipatory capacity ($\boldsymbol{R_1}$): is the ability of a system to anticipate and reduce the impact of climate variability and extremes through preparedness and planning.

Absorptive capacity ($\boldsymbol{R_2}$): is the ability of a system to buffer, bear and endure the impacts of climate extremes in the short term and avoid collapse (death, debilitation and destruction of livelihoods.

Restorative capacity ($\boldsymbol{R_3}$): is the ability of a system to be repaired easily and efficiently.

Coping capacity ($\boldsymbol{R_4}$): is the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters.

Adaptive capacity ($\boldsymbol{R_5}$): is the combination of assets, skills, technologies and confidence to make changes and adapt effectively to the challenges posed by long term trends, such as future climate change.

The overall resilience capacity (RC) of a CI asset system (or network) can be represented as a function in both time and space. It can be mathematically denoted as a function of the five AARCA capacities as follows:

$$RC(t,s) = f\left(R_j(t,s)\right) \quad j = 1,2,3,4,5$$

where ***RC*** is the resilience capacity of the CI asset system (or network); **f()** is the mathematical function combining the effects of the five AARCAs as ***R***'s; ***j*** is the index for each AARCA capacity; ***t*** represents the time period; and ***s*** represents the spatial location. Note that in this report the spatial component of the framework will not be elaborated on and will be considered in future work. The next section will cover the analytical framework for the CI asset resilience based on system performance and resilience capacities.

The Resilience Assessment Model and Tool (RAMTs) developed by UVG in D4.5 provide necessary resilience indicators to quantify these capacities RC as defined above and in section 3.4. D4.5 has developed RAMTs which defines a number of indicators for each of the individual five resilience capacities where each capacity generates a specific score for its category. The indicators cover a range of parameters which are mentioned here in brief only but are extensively covered in D4.5. These capacities are described in Table 8. Summary of resilience capacities with indicators below and relate to their definitions as explained earlier.

Table 8. Summary of resilience capacities with indicators

Category/Resilience Capacity	Measurement indicators	Description
Technical		
Absorptive Capacity	2.1. System failure (integrity of the CI affected) 2.2. Severity of failure (services of the CI affected) 2.3. Vulnerability 2.4. Resistance 2.5. Robustness	(R_2): is the ability of a system to buffer, bear and endure the impacts of climate extremes in the short term and avoid collapse (death, debilitation and destruction of livelihoods.
Restorative Capacity	4.1. Post-event damage assessment 4.2. Recovery time 4.3. Economics of restoration	(R_3)**:** is the ability of a system to be repaired easily and efficiently
Coping Capacity	3.1. Redundancy 3.2. Resourcefulness 3.3. Response 3.4. Economics of response 3.5. Interoperability with public sector	(R_4): is the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters.
Organizational Capacity		
Anticipatory	1.1. Number of hazards 1.2. Quality of the critical infrastructure 1.3. Quality / extent of mitigating features 1.4. Quality of disturbance planning / response 1.5. Communication Systems / Information sharing 1.6. Learnability / Training	(R_1): is the ability of a system to anticipate and reduce the impact of climate variability and extremes through preparedness and planning

Adaptive	5.1. Substitutability 5.2. Adaptability and flexibility 5.3. Impact / consequences reducing availability 5.4. Economics of adaptation	**(R_5):** is the combination of assets, skills, technologies and confidence to make changes and adapt effectively to the challenges posed by long term trends, such as future climate change.

D4.5 has developed the detailed RAMTs spreadsheet which goes into the details and describes how the indicators can be measured and generates scores on a scale of 10 (very high resilience) to 1 (very low resilience). An individual capacity score is generated in RAMTs and shown below in Table 9. The resilience index is generated for adaptive capacity for this example.

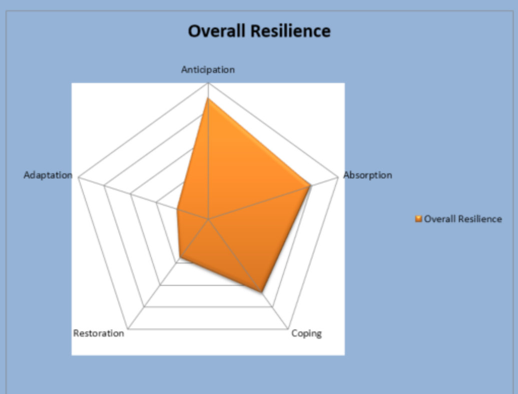
Table 9. Excel sheet example of the RAMTs tool (source D4.5)

Resilience Indicators	Resilience Categories / Subcategories	Metrics
5.1. Substitutability	5.1.1. Replacement of asset is possible	I = 0 or 10 (if both i = yes)
	5.1.1.1. Technical is possible	i = yes or no
	5.1.1.2. Financial is possible	i = yes or no
	5.1.2. Replacement of service is possible	I = 0 or 10 (if both i = yes)
	5.1.2.1. Technical is possible	i = yes or no
	5.1.2.2. Financial is possible	i = yes or no
5.2. Adaptability and flexibility	5.2.1. CI have ability to change while maintaining or improving functionality	I = 0 or 10
	5.2.2. Quick adoption of alternative strategies is possible	I = 0 or 10
	5.2.3. Responding to changing conditions in time is possible	I = 0 or 10
5.3. Impact / consequences reducing availability	5.3.1. Re-locate of facilities is possible	I = 0 or 10
	5.3.2. Building new facilities according to climate-ready standards	I = 0 or 10
	5.3.3. Protection of existing critical infrastructure	I = 0 or 10
	5.3.4. Development of flexibility of networks is possible	I = 0 or 10
5.4. Economics of adaptation	5.4.1. New investments take consider a climate change	I = 0 or 10
	5.4.2. How many new clients can be reached by improving the service / climate adaptation polices	I = (p * 2) / 10 ; (Imax = 10)
	5.4.3. Reputation is increased by implementing climate change adaptation options	I = 0 or 10
	5.4.4. Decisions on adaptation adopt due to market forces	I = 0 or 10

The overall resilience score generated by the RAMTs index is shown below from D4.5 where an example has been provided. The screen shows how cumulative score can be generated from combining each of the individual capacities to generate an overall resilience score.

Table 10. Overall resilience score in RAMTs (source D4.5)

Resilience Indicators	Resilience index R	Capacity index C	Weight C	Real C
Anticipation				
1.1. Number of hazards	1.45	6.76	1	2.23
1.2. Quality of the critical infrastructure	1.26			
1.3. Quality/extent of mitigating features	1.30			
1.4. Quality of distrubance planing/response	1.40			
1.5. Communication Systems / Information sharing	0.90			
1.6. Learnability / Training	0.45			
Absorption				
2.1. System failure (integrtity of CI affected)	2.37	7.31	2	1.97
2.2. Severity of failure (services of the CI affected)	1.67			
2.3. Vulnerability	1.50			
2.4. Resistance	1.30			
2.5. Robustnes	0.47			
Coping				
3.1. Redundancy	2.62	8.38	3	1.68
3.2. Resourcefulness	2.70			
3.3. Response	1.55			
3.4. Economics of response	0.86			
3.5. Interoperability with public sector	0.66			
Restoration				
4.1. Post-event damage assessment	3.15	6.70	4	0.87
4.2. Recovery time	2.48			
4.3. Economics of restoration	1.07			
Adaptation				
5.1. Substitutability	2.68	8.51	5	0.60
5.2. Adaptability and flexibility	3.00			
5.3. Impact / consequences reducing availability	2.00			
5.4. Economics of adaptation	0.83			



The RAMTs also generates a web diagram showing the relative scores of the five resilience capacities. It provides a summary dashboard for users to view the various scores and also has the capacity to add weights to the scores to reflect the relative importance of each capacity for the asset, network or NoN.

In summary, the approach to conducting a RAMTs assessment is as follows:

1. Determine the context of the assessment:
   a) all-hazards or specific hazards (including shock or stress event, rare events etc)
   b) scale: asset/network/NoN or sector context
   c) shock or stress event.

2. Undertake the assessment using the questions relative to the context above and select scores for each.

3. Apply weightings to the scores, as required.

This will generate resilience scores for categories, capacities and measures and a total score. As a stand-alone assessment, the RAMTs tool within this framework can be applied to generate a relative score that could be used to compare resilience across assets/networks or NoN/sectors. However, to provide additional rigour, other steps should be applied.

3.7 Assigning weights to capacities

The RAMTs tool in the framework consists of a range of questions across the capacities shown in Table 8. Once the relevant questions have been answered, weights can be applied at any of the three hierarchal levels described in D4.2 Prioritization module such as the capacities, assets or protective measures as determined by the model, data or expert opinion. These weights should be a percentage value and must add to 100% across each set of indicators considered.

The weights will allow the user to place importance to one capacity (or asset or protective measure as the case may be) over another. For example, one may determine that 'anticipative capacity' is more important than 'adaptive' and as such, the user should allocate a larger weight to that category, i.e. of 20%:20%:20%:30%:10%, to generate the correct score. It is important to note that the weights are subjective and will be based on user preference. In all instances, the individual scores for each question can be viewed and interrogated to determine reasons behind a specific principle or dimension score.

D4.2 provides us with a validated methodology for developing these weights with regards to the different hierarchy levels of consideration within the model. As mentioned in section 1.4:

In case (1), the elicitation of importance of resilience capacities, parameters and indicators, if assess only capacities, it is not needed to define criteria and indicators. The alternatives (which are in this case the resilience capacities) could be directly ranked for example by means of pairwise comparison.

In case (2), *the* assessment of resilience of network assets, the criteria are the resilience capacities. These criteria are in turn composed of sub-criteria, which are called "Generic resilience indicators" see section 2.6 of this report. The achievement of every network asset regarding each sub-criteria must be measured by an suitable indicator.

In case (3), the comparison of protective measures, the criteria are the different alternatives like preventative measures or mitigation options that could be taken and the same hierarchy of indicators, sub-criteria or criteria can be applied.

These hierarchy levels described in D4.2, guide how expert feedback is incorporated in the conceptual model at the level of the AARCA resilience capacities, or at the level of the different components or assets in the model, and at the level of the different protective measures chosen. This will be further clarified in the section 3.9 when an application in the prototype is considered.

3.8 The conceptual resilience framework in the model

The analytical framework used in this research is based on the application of the definitions covered above and uses them to form a conceptual model based on combining the different layers outlined in section 2 previously. This section provides an explanation of how the layers in section 2 can be operationalized to be used in the conceptual model. The conceptual model uses system dynamics simulation approach and terminology to explain how resilience can be conceptualized as a quantity and measured as a composite of resilience capacities that determine the impact of a shock or hazard on the system performance of a CI asset. The framework also proposes to use this conceptual approach for analysis of CI networks and NoNs/sector level resilience as well.

The conceptual model developed here can be used as an aid to the process of collecting the information and data required in the measurement of resilience capacities through the resilience assessment model and tool (RAMTs) developed in D4.5 and briefly detailed in the sections 3.4-6 above. This framework extends the D4.1 resilience framework to use the values generated from RAMTs to calculate overall CI asset resilience. The analytical framework then utilizes the results of the RAMTs by using the scores as inputs to SD simulation model. Simulating changes in RAMTs can be useful to understand how preventative measures (short run) and adaptation options (long run) can improve RAMTs scores and how that in turn can result in increased resilience for the asset to climate hazard events and climate change stresses.

System Dynamics simulation approach relies on understanding complex inter-relationships existing between different elements within a system. This is achieved by developing a model that can simulate and quantify the behaviour of the system. Simulation of the model over time is considered essential to understand the dynamics of the system (Sterman, 2000b). Understanding of the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model and simulating the model for understanding its behaviour are some of the major steps that are carried out in the development of a system dynamics simulation model (Sterman, 2006). It is relevant to point out that the central building blocks of the principles of system dynamics approach are well suited for modelling any physical system. The power of simulation is the ease of constructing “what if” scenarios and tackling big, messy, real-world problems (Hovmand, 2014). In addition, general principles upon which the system dynamics simulation tools are developed apply equally to social, natural, and physical systems. Using these tools in disaster management allows enhancement of models by adding social, economic, and ecological sectors into the model structure (Simonovic, 2016). A number of SD simulation modelling examples in CI protection literature are provided at the end of this report in the appendix and can be considered as good examples of the use of the method in the field.

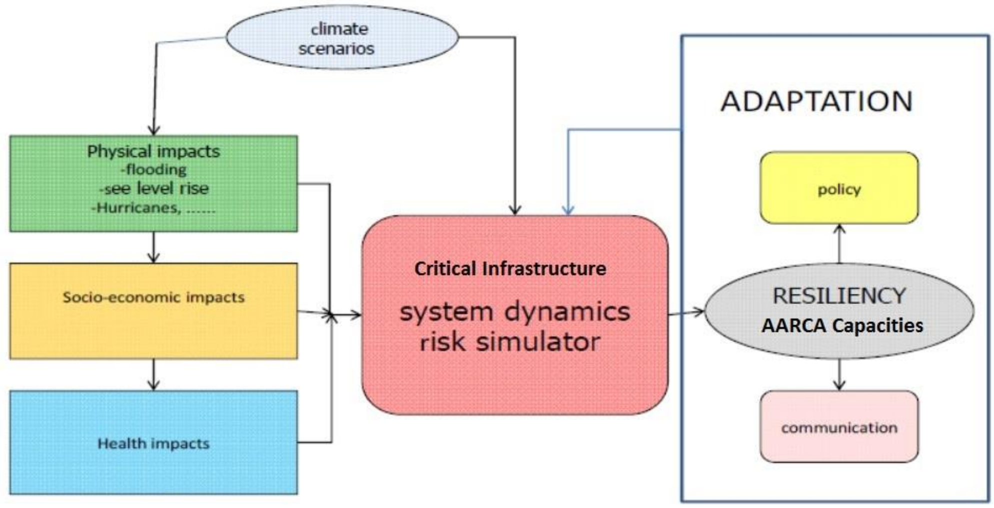


Figure 11. The analytical framework using a system dynamics simulation approach

As shown in **Figure 11** above, the analytical framework developed in this report can be used to support the decision support process by allowing stakeholders to compare alternative resilience strategies for system performance improvement. The analytical framework does this by using a system dynamics simulation modelling approach to look at CI asset behaviour under hazard conditions. Stakeholders can use the analytical framework to compare various preparedness and response plans, and performance of CI assets or networks under different types of hazard conditions. The results of the analysis can either be used for policy formulation or communication to other stakeholders for further action or advocacy.

SD approaches are designed to capture the dynamic behaviour of a system as it changes over time and are particularly helpful in understanding phenomenon where a bidirectional relationship exists between components of a system or even across systems. These relationships are known as feedback mechanisms and can be shown diagrammatically in causal loop diagrams (Sterman, 2000b). These methods are also designed to understand non-linear relationships where disproportionate responses or feedback may exist in a system, for example where threshold limits or tipping points exist before large changes within a system (Maani and Cavana, 2007). Another aspect of social phenomenon that these methods can help in understanding are time-delayed effects in the feedback process where delays in the response may cause significantly different effects than expected if the feedback was simultaneous (Mabry et al., 2008, Mabry et al., 2010).

According to EU CIRCLE objectives highlighted in section 1, by using a SD simulation approach in the framework developed here in D4.3 and in combination with the resilience assessment model and tools used for the quantification of the capacities developed in D4.5 Resilience indicators and the use of adaptation options and their impacts to be developed in D4.6: the Adaptation framework, the proposed approach could allow CI asset stakeholders to address the following questions as well:

1) How measures (short and long term related to operational or strategic issues, respectively) make a network more resilient.
2) How investing in these measures can reduce service loss when disruptive events occur.
3) How these measures can minimize the time taken for a network to recover and, thus, minimize the total cumulative loss of services.

A number of critical infrastructure decision support systems use system dynamics as one of the primary simulation methods in their analysis. The appendix of this report briefly introduces the most successful or popular examples from the literature that have been either implemented and still in use or have been validated through multiple case studies and are coming into implementation.

The SD simulation approach depends on developing an understanding of the complex interrelationships that exist between different elements within a system - such as those that may exist in a CI asset or network. Here we develop a conceptual model that can simulate and quantify the behaviour of the system and hence give us a better understanding of the CI resilience to climate hazards. The major steps in any SD model development are 1) understanding the system and its boundaries, 2) identifying the key variables, 3) describing the interactions between variables through mathematical relationships, 4) mapping the structure of the model, and 5) simulating the model for understanding its behaviour (Maani and Cavana, 2007).

The analytical framework uses the definitions and concepts covered above in sections 3.1-3 to develop a conceptual model that combines the components of resilience as shown in the layered approach in section 2. The resilience framework is converted into the conceptual SD model using the diagram shown below in **Figure 12**. In SD, stocks are variables that accumulate over time, represented by a box, while flows are represented by arrows with "spigots". The flows are connected to stocks and can either add to or take away from stocks over time at a controlled rate. Other texts and arrows provide additional information and connections between variables. **Figure 12** can also be scaled up to conceptually denote the resilience of a network or a Network of Networks.

Figure 12 illustrates how resilience can be conceptualized as a stock over time (yellow box) with flows coming in to denote the level of resilience at this point in time (t1). The "spigot" on the incoming flow represents the contribution to overall resilience of the scores generated from the RAMTs process indicating that the overall resilience is a function of RAMTs. The "flow out" show how the size of shocks or impact of a hazard event is related to the level of resilience present at (ti) in the system.

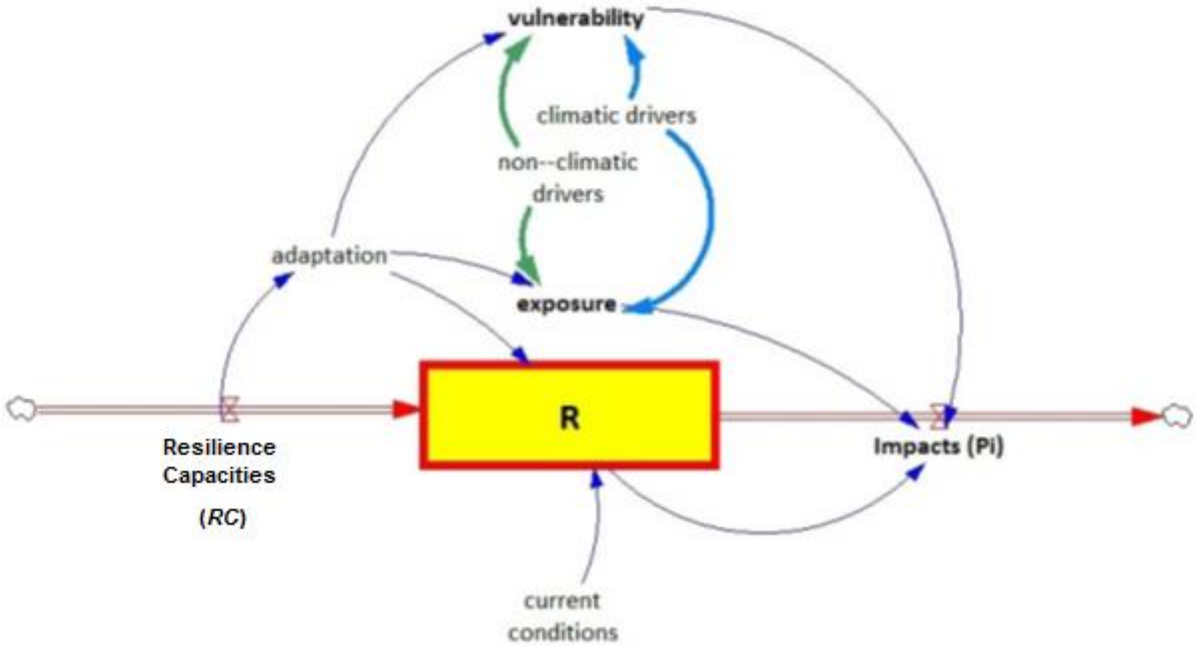


Figure 12. The analytical framework conceptualizing resilience as a stock for use in simulation modelling adapted from Peck and Simonovic (2013).

In **Figure 12.** The analytical framework conceptualizing resilience as a stock for use in simulation modelling adapted from Peck and Simonovic (2013). In their model they have developed a detailed flood model resulting in a key stock the flood water level (see section 2.3 for an example) and the changes in this stock are quantified through the interaction between the components of layers, for example in Layer 1 - the hazard, exposure and vulnerability factors indicated in the figure above (Peck and Simonovic, 2013). This method of conceptualizing resilience has been used in a number of case studies where it has been successfully applied to community or city resilience (Peck and Simonovic, 2013, Srivastav and Simonovic, 2014b, Gotangco et al., 2016, Irwin et al., 2016) For consideration in our conceptual model for CI resilience, and also for addressing the key problem of lack of data on damage functions in general, the SD model combines the three (hazard, exposure and vulnerability) into a damage profile identified by the user (see section 3.7).

As shown in section 2 the resilience framework indicates that the impacts are related to the preventative measures and the mitigation or adaptation options taken compared to the level of vulnerability of the asset as shown in **Figure 12**, hence the higher the resilience the lower the impact (Pi) on SP (and vice versa) on the system as a whole. For the simple demonstration of the conceptual model, a simple one stock model is enough to show how RC can affect the level of overall resilience in the face of a shock.

For the analytical framework as a whole, where several layers are combined for analysis, we will need to use a two stock model that can demonstrate the feedback present in the system and also demonstrate the ability of SD simulation methods to capture CI interdependencies as well. Here we introduce the feedback and interaction between resilience and system performance that interact across the 4 layers indicated in the framework in section 2.

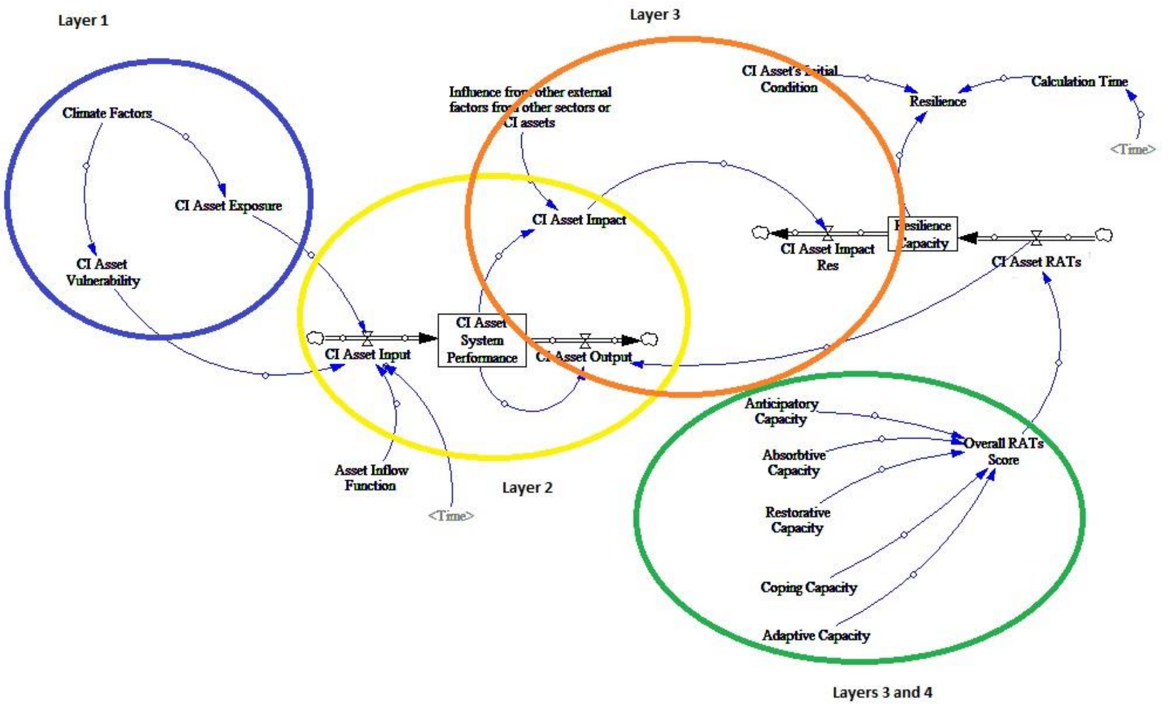


Figure 13. The layers combined in a stock and flow model of the final resilience framework

Figure 12 initially showed how resilience can theoretically be conceptualized using stock and flow diagrams that are commonly used in the systems approach. This diagram can be used to intuitively explain the SD simulation modelling approach to stakeholders and to start the discussion on how resilience may be conceptualized by them within the system through participatory methods such as group model building sessions. The purpose of using such simplifications is to engage stakeholders in understanding the resilience of CI from their perspectives – for more details on perspectives see appendix section 7.3.

Figure 13 on the hand, shows in slightly more detail how the conceptual model is made operational by utilizing the different components in section 2 that make up the layered approach. In **Figure 13**, the SD simulation model incorporates layer 1 : Climate data (in blue) by indicating how or rather what climate hazards or climate change stresses are impacting the CI asset or network. In our conceptual framework, we have asked the stakeholders or users to define a degradation or damage function that can be used to calculate the impact of the hazard on SP as a proxy for a fully developed climate model as shown in section 2 previously. Layer 2 in yellow indicates the asset or network information and characteristics that form the baseline parameters or asset properties of the model as developed in D3.1 – the asset registry. The orange circle denotes layer 3, the risk level and the impact of the hazard on the system's system performance as well as resilience. Finally, the green circle incorporates the data from both layers 3 and 4 to derive a measure of resilience (through the RAMTs) that can determine the ability of the system to prevent, withstand, recover and adapt to the shock or disturbance being modelled.

It is also worth considering that one challenge identified early on in the project has been the issue of lack of access to consistent impact data over time to develop and validate mathematical functions related to exposure (to hazard events such as flooding and wild fires) called damage functions which has been highlighted by EU CIRCLE consortium members repeatedly in conversations and meetings during the workshops. The SD simulation method allows analysis even with limited availability of data as long as experts can provide an indication of what sort of impact is expected resulting in using hypothetical data for use in a simulation model. This data is validated by observing the overall behaviour of the system and ensuring it is consistent to observed behaviour in the past.

This hypothetical damage profile is calculated arbitrarily at this stage but can be based on scenarios generated from separate climate analysis, an estimation based on expert opinion or be based on historical data (if available). The approach adopted here for defining the damage or degradation curve or shock for the conceptual model does not necessarily indicate that this will be the approach used for the case studies. It is preferred for the case studies that a hazard specific SD model be developed which incorporates feedback between the hazard impacts and the resilience (vulnerability) of the CI asset. An example of this approach to modelling a full hazard model is shown in section 2.4 above.

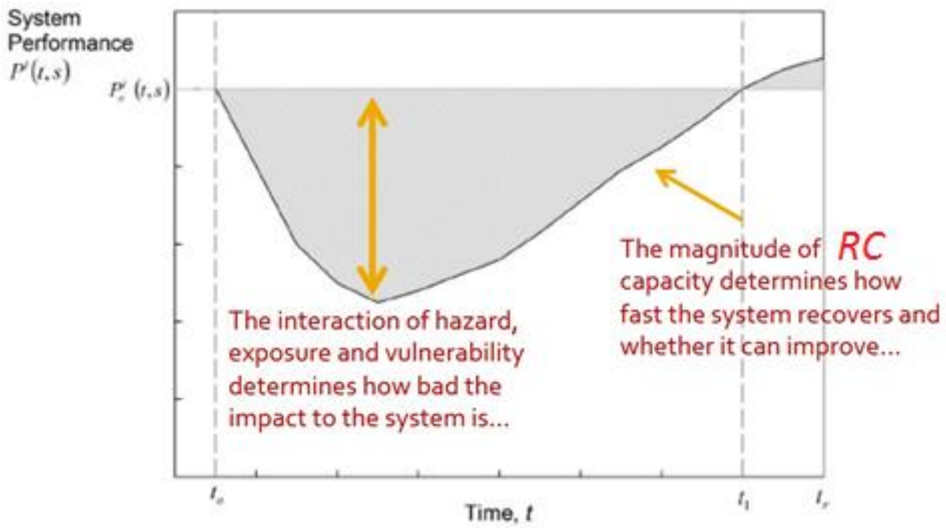
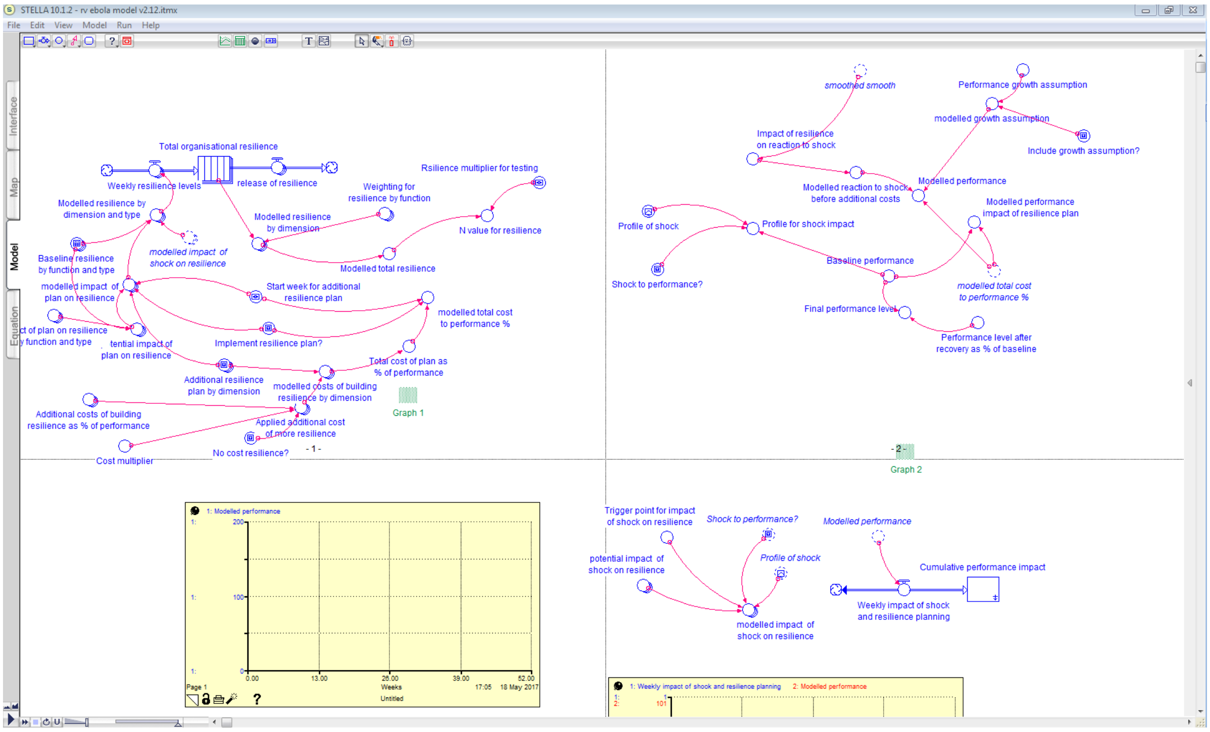


Figure 14. Interpreting the curve of system performance in the conceptual model.

The slope of the curve of SP can be interpreted as shown in **Figure 14** where larger the hazard and the greater the exposure and vulnerability of the system the greater the size of the fall in SP which is directly offset by the value of the resilience capacities. **Figure 14** shows that the higher the value of the resilience capacities, the faster the system recovers while the framework can indicate “building back better” by showing a return of system performance to a higher level – this is discussed in more detail in section 3.13 below..

Figure 15. The conceptual model of a single CI asset in STELLA, a SD modelling software..



3.9 The Prototype Model of CI resilience

The prototype resilience model presented here was developed based on the literature and theory discussed earlier and from the feedback provided by consortium members during meetings and workshops over the course of the project. The model’s primary purpose is to show how the resilience framework can use the resilience capacities introduced in D4.1 and developed as indicators in D4.5 for calculating resilience of CI assets and/or networks for comparative analysis. The conceptual model so developed seeks to generate discussion among stakeholders in identifying critical functions of the CI asset, and then forming a baseline resilience score of those functions using the RAMTs and capacity scores described above.

After baseline resilience scores are determined, the model looks at identifying preventative measures in line with the adaptation strategies identified in D4.6. As stakeholders discuss the preventative measures, the model asks for inputs on what are the expected effects of these measures with regards to changes in the baseline resilience score determined in the first step. Once the preventative measures have been identified and their additions to the base line score are determined, a new resilience score is generated based on these improvements. The model then reruns the same disruption, conceptually showing how preventative measures can make system performance of the firm more resilient to disruptions. The remainder of this section looks at covering this process in more detail with examples shown for clarity.

It is suggested that the process of going through the conceptual model with stakeholders will be a useful exercise in itself, as a demonstration of the EU CIRCLE conceptualization of resilience as well as to generate discussions among participants that may inform the researcher of the thinking and logic behind decision making of senior management in crisis or disruption, especially with regards to resilience and preventative measures.

The prototype model can be quickly adapted for use to stakeholder requirements at the initial stage for conceptualization of CI resilience. To illustrate the conceptual framework, a graphical user interface (GUI) is introduced – see **Figure 16** below.

Figure 16. The Graphic User Interface (GUI) for the conceptual CI resilience model.

The GUI shown above is developed using the Stella Architect (V.1.3), a software that is designed specifically for developing system dynamics models as tools for participatory modelling and greater stakeholder engagement. The EU CIRLCE prototype resilience model is available online for use and testing at the following link: https://exchange.iseesystems.com/public/hisham-tariq/eu-circle

The version can be quickly modified to fit the needs of stakeholders and can be used to engage target audiences in helping researchers to conceptualize resilience through a discussion on resilience capacities and the impact of shocks on their organizations system performance. This GUI is based on the concept of developing desktop "business simulators" for decision making at senior management levels which have been used in public policy for disaster management as well, for example in the CIP/DSS models (Rene et al., 2007). The development of business simulators or interactive learning environments (ILE) like these for supporting decision making is a common approach in system dynamics and is used in conjunction with participatory modelling methods with stakeholders – called Group Model Building (GMB) sessions (Andersen et al., 2007).

It is proposed that using such an approach at the initial stage of resilience assessment may allow for a closer understanding of the system and the resilience of CI. The method also encourages the process of co-creation of knowledge regarding stakeholder's own perceptions of their resilience and the collection of data for RAMTs and may lead to a higher acceptance among stakeholders of what is being modelled (Hovmand, 2014). The benefits of using this approach is well documented in other public policy applications and is now finding use in developing an understanding of resilience at the community level in several public health, disaster risk reduction and developmental settings (Ramalingam, 2013, Hovmand, 2014, Inam et al., 2015).

The sections below go into greater details regarding the use of the GUI and the prototype model to use hypothetical RAMTs scores to generate a series of scenarios to demonstrate conceptually the resilience framework as developed here in this report.

Key functions

Although a full step by step process will be explained later in the section, this demonstration will provide a simple introduction to the GUI and the prototype model in general. As the first step, stakeholders are asked to define the base line resilience of their organization. To do this they are asked to identify critical functions of the organization from a list of pre-generated critical functions. This list can be developed through expert opinion, literature review or even at the start of the session if no list is available prior to the interaction with the stakeholder. If a function is identified that was not previously associated with this type of asset then this could be added to the list and the reason why the user/stakeholder considers this a critical function could be discussed.

After the identification of the critical functions, the model uses these functions to illustrate the relationship between resilience of sub-systems and overall organisational resilience. This demonstration will use the level of detail that looks into the elements of a CI asset where individual critical functions can be identified and a RAMTs assessment of each critical function may be feasible or desirable. If such granular detail is not required than the RAMTs will be derived for the asset using the resilience indicators developed in D4.5 only. Note in this case then only one line of the model needs to be used.

Generally, these critical functions might also be of general relevance to any enterprise or business organisational unit involved in production or service provision. For example, in this case example the following functions will be used to demonstrate the prototype:

- Production
- Distribution
- Management and Decision making
- Physical Infrastructure

Each was given equal weighting within the model, although this need not be the case as typically different functions will have different levels of contributions to the overall assets output or performance. For simplicity and clarity, in this conceptual model they were given the same weight.

Each of those components can in turn have critical subcomponents which are defined by stakeholders more familiar with each component and subcomponent – only those components of the asset are discussed that are considered critical for the problem being explored. For example, if power generation is considered then critical components could be production and distribution – a subcomponent would be a critical process within production such as fuel inputs, maintenance etc. - which may be considered if required. At the highest level the model incorporates high level functions and a lower level may focus on one particular aspect of the organization most vulnerable to a shock or disruption.

Feedback – key functions for CI interdependencies

Note that in this prototype model key feedback processes are not included – including the feedback from other CI assets (forming a network) and representing CI interdependencies. At this stage the prototype model uses the RAMTs score and the indicators within those measures may be designed to indirectly measure the assets resilience in case of critical path dependencies on other assets. These interdependencies can be modelled by linking together CI asset models together in a system dynamics model that incorporates the relationship between these assets and their networks.

For example in the case studies, the assets will be linked to each other through the RAMT scores – where critical path dependencies can identify dependence of one asset on another and hence result in a lower score if that asset is damaged – the SD simulation approach allows for feedback to be modelled between assets so the if one asset is impacted it may have a direct or indirect effect on the RAMT score of another asset. Note that because this is using SD modelling this impact will be modelled over time and be dynamic hence we can simulate changing RAMT scores of an asset over the duration of a hazard or stress event which more closely reflects the reality of disaster impact compared to using a static measure of resilience as in other approaches.

The components of resilience – AARCA approach

In this prototype model of the framework it is key to be able to explain the AARCA resilience capacities in detail and to consider how the RAMTs assessment can help stakeholders understand and quantify their resilience. The five resilience measures in the RAMTS should be considered by the stakeholders in relation to the CI operator's own operational strengths and weaknesses and examples should be drawn from the experience of stakeholders during the crisis situations in the past and how certain preventative measures could change the value of these five capacity measures depending on the type of preventative measure. The discussion is linked to the RAMTs discussed in section 2 above. For example, if additional protective measures like clearing of brush, trees and plant material around a power plant increased the absorbing capacity of power installation then that preventative measure would increase the absorbing capacity by a certain amount as represented in a higher RAMTs score for that capacity.

Each of the preventative measures considered in the study can similarly have an impact on resilience across the five resilience capacities (RC). A preventative measure can result in a change in more than one of the 5Rs and not necessarily on only one – these assessments will be made by stakeholders with the necessary expertise and will based on both qualitative and quantitative assessments in the final model. For instance in the above example of the power installation, this initiative could have been identified through activities planned under an increase in the anticipatory capacity and hence developing this capacity would increase the RAMTs score in both those categories at the same time. This could also be adjusted through the application of weights as will be discussed in 3.7 below.

3.10 Running the conceptual model

Baseline resilience assessment tool (RAMTs) scores in the model

A simple baseline score was allocated to each of the R1-R5 capacities for each of the key functions identified initially, as shown below (with low = 1, medium = 2, and high = 3). The low-medium-high scale was chosen for simplicity and clarity as well as its familiarity to stakeholders such as management staff at operators or service providers with qualitative risk maps using similar scales. The RAMTs indicators developed in D4.5 form the basis for using these numbers as for baseline resilience of the CI asset, asset network or network. For guidance, we summarize the RAMTs scores as follows; None is 0, Low is 1-3, Medium is 4-6 and 7-9 is high. In this example 10 is very high and represents the max value achievable.

Critical Function*	**R1 Anticipative**	**R2 Absorptive**	**R3 Restorative**	**R4 Coping**	**R5 Adaptive**
Production	Low	Low	Medium	Low	Low
Distribution	Low	Low	Medium	Medium	Low
Management and Decision making	High	High	High	High	High
Physical Infrastructure	Medium	Low	Low	Low	Medium
Other examples: Supply Chain	Low	Medium	Medium	Medium	Low
Local Infrastructure	High	Medium	High	High	Medium

Enabling Environment (Governance)	Low	Low	Low	Low	Low

***hypothetical list of critical functions either at asset, asset network or sector levels.**

Table 11. Hypothetical participant inputs to model to determine baseline resilience score.

A baseline resilience score for each function was calculated by multiplying the baseline scores for R1-R5; the total baseline resilience was calculated by summing those for each function. This baseline score is scaled to give a suitable value for use in the model (i.e. to produce a potential range of periods over which the disruption function is smoothed which produces a realistic pattern of response for CI assets in the sector). Note that in a multiple assets example there will be feedback between the assets that dynamically change these values if there are critical interdependencies.

For example, at the beginning of the simulation of a hazard event physical infrastructure of one asset may actually suffer a change in its AARCA values (as hazard impact or in relation to loss of system performance of another asset) and this may or may not return to its initial level as the hazard event recedes or ends indicating a longer term impact then the hazard event itself.

Use of RAMT resilience capacities scores in the model

The baseline resilience score is used in the model as follows:

An impact function is developed, with the period over which the disruption function (discussed in the section below) is smoothed and applied to baseline performance in proportion to the baseline resilience score: thus a score of 2 will result in a greater impact on SP than a score of 4 and vice versa. This represents the ability of the CI asset to withstand the shock.

A recovery function is also developed, with the period over which the disruption curve is smoothed and applied to baseline performance inversely proportional to the baseline resilience score: thus a score of 2 will result in a faster recovery time than a score of 4. The two functions are combined such that:

- when the trajectory of the disruption is downwards, the impact function is applied
- when the trajectory of the disruption is upwards, the recovery function is applied

This produces a modelled response to disruption with the following characteristics:

- It will take a shorter drop for the adverse impact of a disruption to be seen in terms of performance in a more resilient CI asset than in a less resilient one (and vice versa)
- It will take longer recovery from a disruption event to be seen in terms of performance in a less resilient CI asset than in a more resilient one (and vice versa).

Modelling a disruption

Within the prototype model, shocks are introduced via a graphical function which can be understood as representing the potential impact of a sudden hazard event or a prolonged long term stress on performance. Alternatively, it can be understood as representing the 'story' of an event in terms of severity and impact.

The two examples below in **Figure 17** and **Figure 18** show two possible types of disruption:

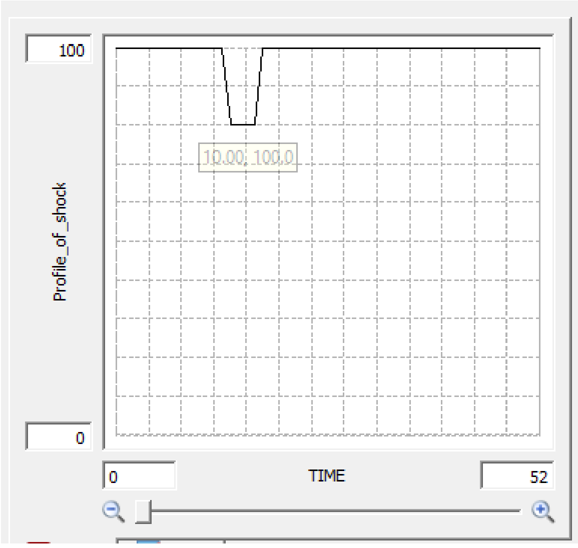


Figure 17. Graphical Input screen for Damage/Shock curve of event. Note numerical data could be entered instead of drawing a curve representing data generated by a climate model.

This example in **Figure 17** (used as the default in the prototype model) represents a disruption of relatively short duration, with the potential to cause a 20% reduction in performance at its worst.

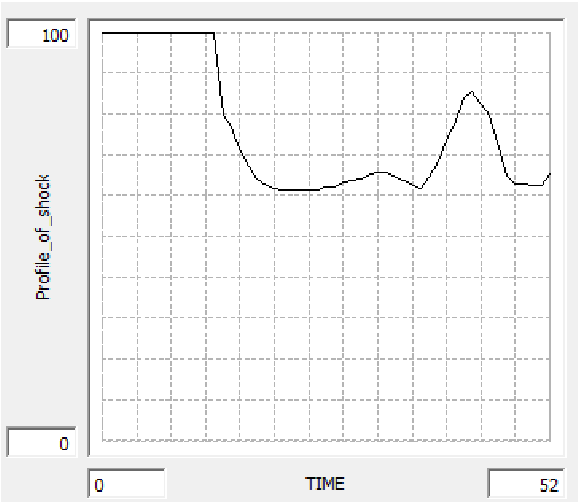


Figure 18. Hypothetical damage/shock curve drawn by user representing the impact of climate event (short term) or stress (long term).

By contrast, this example in **Figure 18** shows a disruption of greater magnitude and duration (with a period of partial recovery) which is not over by the end of the model run. Conceptually this indicates that the asset has not recovered to prior levels of service after the shock.

The GUI allows the user to define the shock magnitude as per their own experience or historical data. The data can be entered numerically through filing a table like in an Excel sheet thus allowing for inputting numerical data directly into the model (such as historical data) representing the loss of performance in the scenario. For example if the output of a power installation is being modelled as system performance in KW output – numerical data of the change in KW output could be directly entered representing the marginal loss of power at different time steps during the hazard event resulting in the damage function for that hazard event.

Modelling performance

Within the prototype model, default performance is set at a notional level of 100 units per week – this is arbitrary and can be any unit that the stakeholder feels appropriate to their needs. The time scale can also be changed to hours or months depending on the logic of the required analysis. This can be understood as representing any key performance indicator (revenue, output) where a hazard event or shock will have an impact with respect to the baseline resilience capacity score. However, as the model develops it would be possible to develop several performance indicators separately, to enable (for example) the effect of a disruption on both revenue and output to be modelled separately (and allowing for the effects of market price on revenue to be included, for example). In the power installation example give above – not only can the loss of output be modelled but the corresponding loss in revenue could also be modelled (as simple function of the total loss indicated by the resilience triangle).

Within the prototype model, an option allows projected growth to be applied to baseline performance. This could be used, for example, to project the impact of expected rises (or falls) in unit price and thereby to isolate the impact of unit price changes from that of a disruption on overall expected performance if this is a desired analysis by the operator.

Modelling improvements to resilience: Preventative measures and AARCA resilience capacities

The prototype model allows for the impact of projected changes to resilience to be simulated. If the option to change resilience capacities is selected, changes can be made to the resilience rating of any component of the resilience framework. This represents potential actions on the part of the organisation to increase resilience by improved readiness planning or actual physical infrastructure improvements. Examples of the changes that could be modelled include:

Table 12. Changes in resilience capacities due to measures taken

Change made **(Preventative Measures or Adaptation/Mitigation options)**	**Resilience Capacity and** **Which key functions will be affected?**	**Which components of resilience will be affected?**
Non Essential Staff Policy (soft)	• Absorptive (R1) • Flexibility; looks at the organizational capacity of the operator • It has a potential to impact all functions but not necessarily in the same way	• R1 (increased robustness as risk of injury or death is reduced due to less people coming into the workplace, i.e. reduced exposure) • May reduce other Rs in case administrative inefficiencies increase
Removal of forest around CI asset and Fencing (hard)	• Anticipatory (R2) • Could have an impact on other Rs that take place within physical location	• R2 Ability to anticipate and implement preventative measures at the ground level

	of the fence in the event of a wild fire	• R1 (increased robustness as risk of fire damage is reduced, i.e. reduced vulnerability and exposure)
Emergency Management Infrastructure – Rapid response Emergency Management Team	• Anticipatory (R2) and Adaptive (R5) • Corporate Culture and Flexibility • All management functions, Overall decision making	• R2 (increased redundancy if more alternatives are created) • R3 (increased resourcefulness if barriers to action are removed) • R4 (rapidity if resources are more readily available)
The identification of funds as a dedicated contingency fund for crisis response (soft and hard)	• Anticipatory (R2), Coping (R3), Restorative (R4) • Could be any, or all, depending on rules for deployment of the funds	• R2 (increased redundancy if more alternatives are created) • R3 (increased resourcefulness if barriers to action are removed) • R4 (rapidity if resources are more readily available)
Networking with other CI operators to share communications (soft and hard)	• Anticipatory (R2) and Coping (R3) • Corporate Culture, particularly Communication • Corporate responsibility	• R2 (increased redundancy as ideas are shared and more options are open to each individual firm) • R3 (increased resourcefulness as information is shared and delays to effective action are reduced)

Currently, the prototype introduces all changes on a single timescale from a chosen start date (week/hour 13 in the default run).

The cost of changes made is defined within the prototype as an ongoing proportion of performance. However, in future model development it would be possible to improve modelling of costs to reflect a more realistic picture by:

- Including non-recurring as well as recurring costs of actions to increase resilience (for example the capital cost of constructing flood defences or rapid response units as well as the recurring costs of operating it)
- Relating costs to performance, so that for example the cost of increasing coping capacity provision might be related to the depth of the disruption at any given time (e.g. where during an epidemic infected people receive enhanced support to increase their likelihood of recovery and return to work)
- Including the potential benefits to performance of changes to resilience (for example ongoing cost savings resulting from 'crisis working' which drives out inefficiencies and which can be maintained after the disruption is over)
- Modelling underlying trends in expected future performance unrelated to a potential disruption, such as the market price of the extractive product, to enable the impact of this to be explored separately from the impact of the disruption for firms with differing levels of resilience

These aspects will be further analysed in D4.7 Cost effectiveness analysis.

The impact of performance on resilience – a feedback loop

Within the prototype model, there is an assumption that operating below baseline performance will have an impact on future resilience. This is to replicate the erosive effect of persistent 'crisis working' on morale and performance. This creates a (small) reinforcing loop within the model, that can as with all reinforcing loops can operate in two directions:

- A drop in performance may lead to a fall in resilience away from the baseline level, which will reduce the organisation's ability to respond to the disruption, which could (depending on the shape of the damage/disruption curve) lead to further drops in performance and/or slower recovery.
- A rise in performance may lead to a rise in resilience (or in this case a return to the baseline level), which will increase the organisation's ability to respond to the disruption, which could (depending on the shape of the disruption curve) lead to further improvements in performance and/or quicker recovery.

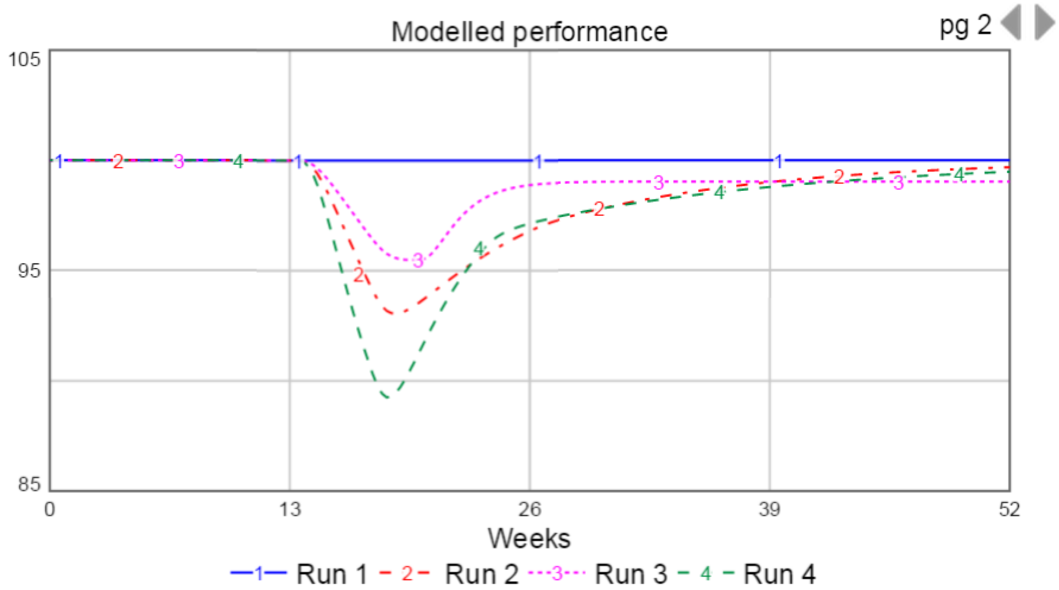
Outputs from the prototype model

It is important to note that the sections below consider simulations based on hypothetical data and not actual data and do not represent predictions – although the assumptions of some of the values used as data in the simulation might be based on qualitative indications from the interviews, focus groups or workshop. The figures below are not predictions or projections of future performance or output of a CI asset service provider, or any other firm, but of a hypothetical CI asset facing a shock.

Comparing baseline resilience

Using the modelling approach and baseline assumptions discussed above, the potential impact of disruption on organisational performance for three CI assets of the same type with different levels of resilience is shown in Figure 19. This could be the same asset at three different times or the same type of asset with three different RAMTs scores.

Figure 19. Projected organisational performance response to disruption with variation in resilience: weekly performance levels



Line 1 = baseline without disruption

Line 2 = projected performance with disruption and medium default resilience score

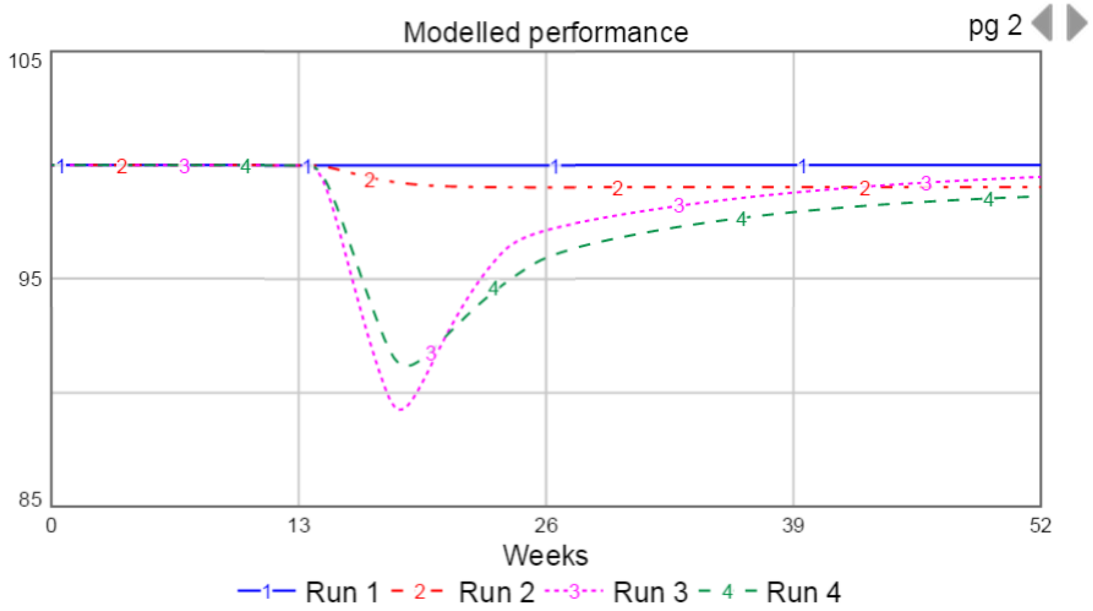
Line 3 = projected performance with disruption and high default resilience score

Line 4 = projected performance with disruption and low default resilience score

Modelling the impact of increasing resilience

Figure 20 shows outputs from the prototype model with the default resilience score when a resilience plan is implemented. The plan targets selected areas of the resilience framework (in this example, production: R1, R3 and R4 and management: R3). An ongoing cost is incurred, equivalent to a total of an amount, such for this example 0.3% of baseline production. This is intuitive if revenue is used as a system performance measure.

Figure 20. Projected organisational performance response to disruption with application of a resilience improvement plan: weekly performance



Line 1 = baseline without disruption

Line 2 = projected performance with no disruption and resilience plan from week 13 (precaution cost)

Line 3 = projected performance with disruption and no resilience plan

Line 4 = projected performance with disruption and resilience plan from week 13

The ongoing cost of the plan can be seen in the difference between lines 1 and 2, and thus if no disruption occurs the organisation's performance is poorer with the additional resilience developed under the plan. However, the difference between lines 3 and 4 show the impact of the plan on performance if a disruption occurs. The balance between plan costs and benefits will be dependent on:

- The profile of the disruption
- The areas of the framework that the plan affects, and the impact on their individual levels of resilience
- The timescale for implementation of the plan (NB this could vary for each element

Adding weights

The prototype model can also assign weights to the different RAMTs scores depending on their influence on the overall resilience of the CI asset. These weights can be assigned either directly through inputs on a table determining the weight of the resilience capacity or indirectly through the relative cost of increasing those capacities. Both these input tables are shown below in **Figure 21**.

Figure 21. Weights input page

Workshop Example

Figure 19 and **Figure 20** have demonstrated the conceptual model as it has been designed with the impact of changing resilience scores and the introduction of a cost function. The following example demonstrates how it was used in the workshop with participants to illustrate how an improvement in one of the resilience attributes translates into an improved resilience score and how that impacts on system performance.

Figure 22 and **Figure 22** show the general user interface (GUI) developed in Stella Architect for use by participants at a GMB or validation workshop. As explained above the GUI has several features that including the ability to define a disruption, allow the user to run a baseline scenario as well as implement a resilience plan. The user can also indicate the date at which the resilience plan is implemented as well as a general cost function as explained above.

Figure 22. The General User Interface developed by the researcher for use by participants at the validation workshop.

The GUI can be useful for involving the stakeholders in workshop or GMB session by allowing the participants to "game" their decisions regarding potential resilience plans as demonstrated below.

The resilience input table screen shows how the RAMTs are input into the model - showing the scores as inputted for the baseline resilience. Figure 23 to Figure 25 illustrate the process of getting participants to enter scores for a proposed resilience plan and the change in the resilience score, as perceived by them, using the low-medium-high scale discussed earlier.

Figure 23. Baseline Resilience score as determined by the participants

Figure 24 – Close up of the input table with baseline RAMTs score

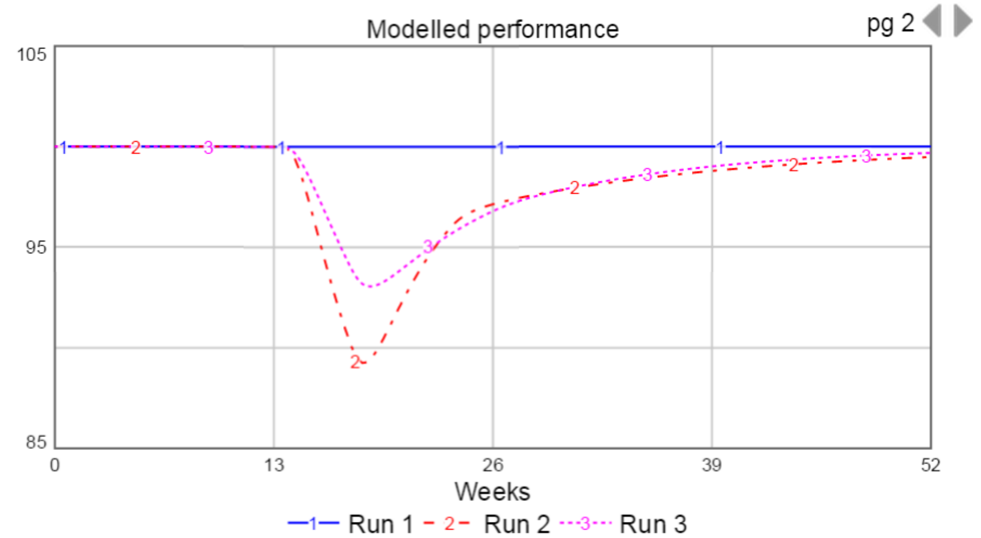
*1: RAMT Resilience Capacities input table					
	Absorptive	Anticipative	Restorative	Coping	Adaptive
Production	1	1	2	1	1
Distribution	1	1	2	2	1
Management and decn making	3	3	3	3	1
Physical infrastructure	1	1	1	1	1

Figure 25. A new resilience plan to be implemented investing in newer more resilient production facilities and hence a higher RAMTs score in Production.

*1: RAMT Resilience Capacities input table					
	Absorptive	Anticipative	Restorative	Coping	Adaptive
Production	3	3	3	3	3
Distribution	1	1	2	2	1
Management and decn making	3	3	3	3	1
Physical infrastructure	1	1	1	1	1

The model was then run at the baseline resilience without disruption, baseline resilience with disruption and then, finally, implemented resilience plan with disruption as shown below.

Figure 26. Projected organisational performance response to disruption with application of a resilience improvement plan: weekly performance



Line 1 = baseline without disruption

Line 2 = projected performance with disruption and default resilience score

Line 3 = projected performance with disruption and implemented resilience plan with cost

Figure 26 shows outputs from the prototype model with the default resilience score (as calculated by table a in **Figure 25**) and when a resilience plan is implemented (as calculated by the table in **Figure 25**). The plan targets selected areas of the resilience framework - in this example, participants chose to improve the resilience of production: R1, R3 and R4 as shown in **Figure 24**. This indicates that the participants chose to implement preventative measures targeted at the production process making it more resilient overall. Implementing a plan thus causes the disruption to have a smaller impact on the system performance despite the cost of the plan. This conceptually demonstrates the thinking behind the preventative measures, the resilience attributes and the respective functions it targets in the model.

This model can, if further developed with additional inputs from the stakeholders, provide a framework to rank and cost preventative measures and their perceived impact on system performance over time and hence be used for the adaptation module being developed in D4.6.

3.11 Resilience computation for single CI asset

This section looks at a step by step approach to developing a conceptual model for resilience capacities of a single CI asset. The guidelines for framework will look at how the improvement RAMTs score through investment in resilience capacities can demonstrably impact the shock on system performance and can be used for discussing the outcomes of alternative strategies. The simulation model consists of three parts; (i) the system dynamic simulation model of the CI asset; (ii) the spatial modelling aspect of the conceptual model linked to GIS mapping (not considered at this moment) and (iii) the link to the overall sector module (or network) for the larger CI sector/network model.

The conceptual model looks at the ability of the CI asset to handle or cope with the shock as a measure of the CI system performance (SP). The impact on SP is largely determined by the ability of the system to "bounce back" or recover from the shock and as shown in the preceding section this is directly related to the resilience capacities of the CI asset. Accordingly, in this model various adaptation options or measures can be taken and these can be assessed on the basis of the impact on system performance of the CI asset due to the differing strategies. These strategies, in turn, are determined by the variations in the combinations of various AARCA resilience capacity levels. The CI asset operator can select a number of different strategies and find out the corresponding change in performance by using the system performance value calculated from the performance loss and resilience capacity. Each such strategy will result in a system performance graph that represents the impact of the shock on the CI asset at the given resilience capacity levels.

The following steps can clarify how the conceptual model of a CI asset can be formulated:

1) Identify the number of critical functions within the CI asset
2) Identify the baseline AARCA resilience capacities of each of the Critical Functions identified in (1) for the CI asset under consideration – this could be from the quantitative/qualitative measures estimated by the resilience indicators (D4.5) or even based on a qualitative assessment by expert opinion. In most cases the scores will be generated from the RAMT assessment.
3) Identify the size and intensity of shock level on system performance due to the impact of the hazard event – this could be generated from another SD model of the hazard, pre-calculated case scenarios or even expert opinion.
4) Run the model at the baseline resilience capacities to generate a graph of the shock on the system performance of the CI asset representing the impact of the hazard event on the CI asset.
5) Generate several alternative strategies from stakeholder/expert input. These alternative strategies can be operationalized as the change in respective AARCA resilience capacity values hence showing a change in the RAMT scores.
6) For each strategy run the model and calculate loss to system performance.
7) Rank the strategies on the basis of total loss to performance or total time to recovery and select the best strategy according to stakeholder/expert objectives. These objectives could be to either to minimize total loss or minimize total time to recovery or some other approximation of the two like for example minimizing loss at a particular time regardless of the time to total recovery (where an acceptable level of degraded system performance over a period of time is a preferred option temporarily).

The 7 steps above provide a basic guide to using the conceptual framework to determine CI resilience at the asset level and use that for comparing the relative cost effectiveness of different resilience capacity improvements. These steps will be documented into a workshop format so that training course could be developed where researchers can become familiar with the tool and the process of using the GUI for running simulations with stakeholders. It is anticipated that this can then form the basis of conducting group model building sessions with those stakeholders.

3.12 Resilience computation for CI assets in a Network

The five major CI sectors as identified in D1.5 that are being considered in the EU CIRCLE CI Resilience framework are energy, water, ICT, transport and government services as outlined in D1.5. These sectors require the development of a modular system dynamics simulation model to fully model the CI network of systems as may exist according to local conditions at the hazard event.

1.1 Energy sector
1.2 Water sector
1.3 ICT sector
1.4 Transport sector
1.5 Chemical/Industrial sector
1.6 Government services sector

The conceptual modelling of a single CI asset is important not only to understand the impacts of different hazards but also for the consideration of different resilience capacity strategies and is useful for deeper engagement with stakeholders. Although the single asset conceptual model can be adequate in some cases, there is a need to for the framework to be extendable to larger units of analysis, namely the CI asset Network.

Again, the conceptual model can be similarly divided into three parts; (i) the system dynamic simulation model of the CI Network; (ii) the spatial aspect of the conceptual model linked to GIS network map (not considered at this moment) and (iii) links to the other CI sectors/networks and the overall CI resilience model.

The conceptual model remains the same as above but in the case of networks the steps are adapted to accommodate the larger unit of analysis of the network of assets. In this case the conceptual model simulates the system performance of the whole CI asset network or sector. Accordingly, the RAMTs assessment for input into the capacities table in the prototype model now includes the RAMTs scores of all the component assets within the network. For example, if a power generation network between two locations is being simulated then all CI assets within the network consisting of the power sector in the problem area will be considered and not just one CI asset as was considered above. Each of those assets would have generated a separate RAMTs score based on an individual resilience assessment as carried out in the section above for one CI asset. The steps are as below:

1) Identify the number of CI assets within the CI asset Network by sector – if within sector analysis is required. Note only include those CI assets that have been historically impacted or are expected to be impacted. This is so researchers focus on modelling the problem rather than the system alone.
2) Identify the baseline AARCA resilience capacities generated by the RAMT of each of the CI assets identified in (1) for the CI Network under consideration – this could be from the quantitative/qualitative estimated by the RAMT resilience indicators (D4.5) or even based on a qualitative assessment by expert opinion.

3) Identify the size and intensity of shock level on system performance of the Network due to the impact of the hazard event – this could be generated by another SD model of the hazard as shown in section 2.3, another SD model of CI asset Network or Sector (if looking at cascading effects), pre-calculated case scenarios or even expert opinion.
4) Run the model to generate a graph of the shock on the system performance the CI Network at the baseline resilience capacities representing the impact of the hazard event on the CI Network.
5) Generate a number of alternative strategies from stakeholder/expert opinion. These alternative strategies are denoted in the conceptual model by the changes in AARCA resilience capacity values.
6) For each strategy run the model and calculate loss to system performance.
7) Rank the strategies on the basis of total loss to performance or total time to recovery and select the best strategy according to stakeholder/expert opinion objectives.
8) If Sector level analysis required, then Repeat Step 1-7 for each sector – note only include those CI assets that have been historically impacted or are expected to be impacted. Each CI sector will have a separate SD model which will link to each other.

The objectives in (7) could be to either to minimize total loss or minimize total time to recovery or some other approximation of the two like for example minimizing loss at a particular time regardless of the time to total recovery (where an acceptable level of degraded system performance over a period of time is a preferred option temporarily). The conceptual model can be used run different scenarios and to simulate behaviour of the system while testing decision rules generated through stakeholder participation – see below for more discussion on decision criteria.

The multi-sectoral CI Network simulation model will be a large SD model that will logically connect each relevant CI sector with the other making sure the behaviour of the overall system reflects reality. For example, power sector is related to the functioning of the ICT sector and an impact on one might or might not feedback onto each other or additional sectors. The strength of SD methods is that it can simulate behaviour like feedbacks and delays across multiple sectors. These interconnections will be determined by processes identified in deliverables like D3.1 and D4.2 as well as in part based on stakeholder participation, expert opinion and historical precedent as indicated in the literature and operator documents.

It is important to emphasize that conceptually the network's system performance can be understood in this way but if the feedback between the hazard and the individual components of the network is dynamic (changing over the course of the hazard event or shock) and of analytical interest then additional steps are required. If for example, greater detail is required in understanding cascading hazard impacts across networks then a more detailed model is required for each separate CI asset. This is so that the shock can be modelled separately on each asset and then linked to each other through feedback loops between the assets. This is demonstrated below in an example using generic models.

The CI asset models form part of a library of generic system dynamics simulation models; 7 in total – one for each of the CI sectors and one for the overall composite model. The CI SD composite (CISDM-7) model can be unpacked as the following models:

a) CISDM-E: Energy Sector Simulation Model
b) CISDM-C: Chemical Sector Simulation Model
c) CISDM-W: Water Sector Simulation Model

d) CISDM-T : Transport Sector Simulation Model

e) CISDM-ICT : Information Technology Sector Simulation Model

f) CISDM-P : Public Sector Simulation Model

g) CISDM-6 : CI Simulation Model

It is import to note that there is very little difference between the structure of each of the generic models at this conceptual stage. The crucial difference between them arises when the different elements, components and variables in each of the sectors is mapped out and developed through deliverables like D3.1 and others and either current literature and document analysis or by collecting data directly from stakeholders. This is where Layer 2 (Resilience of what) can contribute.

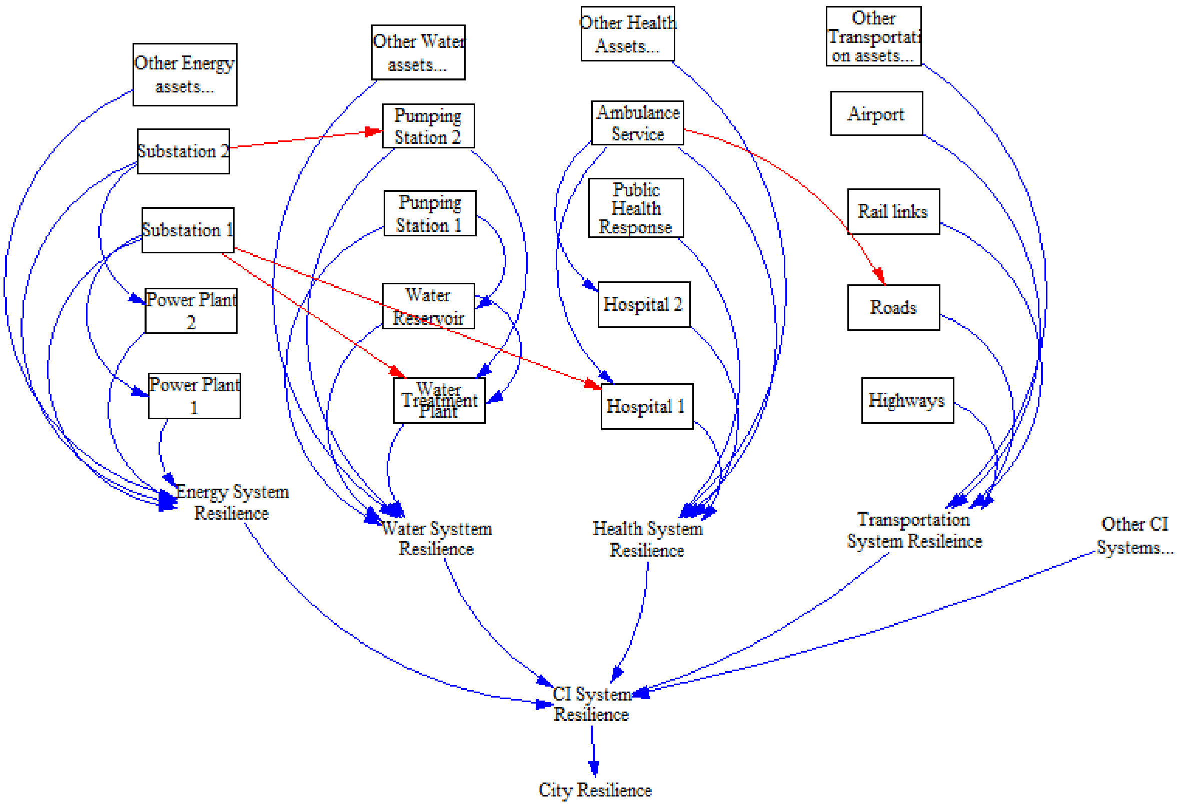


Figure 27. Example of generic sector level models.

3.13 Interpreting the SP Curves/Shocks

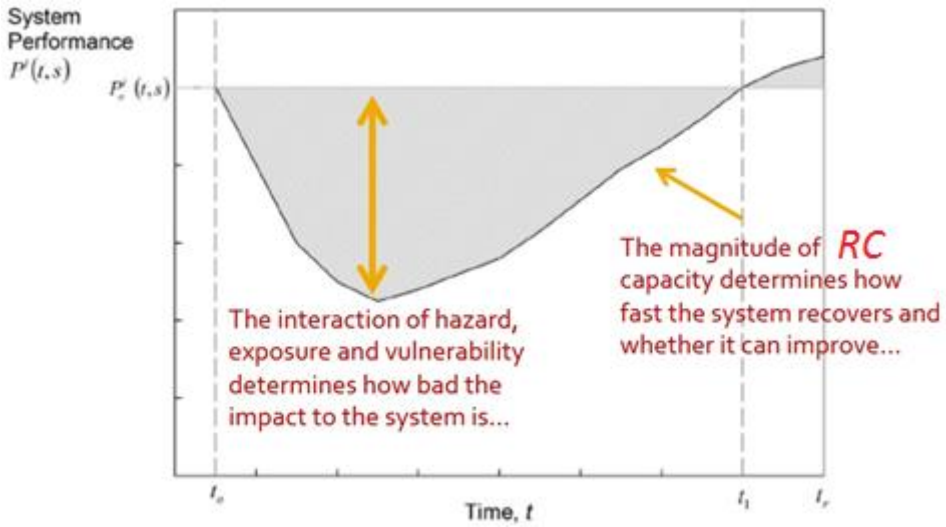


Figure 28. Understanding the impact of damage curve/profile on system performance adapted from Gotangco et al. (2016).

As mentioned in section 2.5-8, the EU CIRCLE resilience framework includes risk analysis as one of the many components of the AARCA resilience capacities. In our conceptual model, risk analysis can be determined by the threats, vulnerabilities and consequences of the shocks to the system that indicate a loss in system performance or critical functionality in the system (Linkov et al., 2014). As mentioned in section 2.1 and conceptualized in section 3.3, the EU CIRCLE definition of resilience places risk in the broader context of the CI asset or network's ability to withstand, anticipate, recover from and adapt to shocks over time. In the system performance profile, risk in CI asset system can be interpreted as the total reduction in system performance and the resilience of the system is related to the slope of the absorption curve and the shape of the recovery curve. **Figure 29** illustrates the link between risk and loss of system performance where a change in any one factor such as vulnerability, threats or consequences can lead to a change in total risk. The greater the risk level the greater the expected impact on the system performance and vice versa.

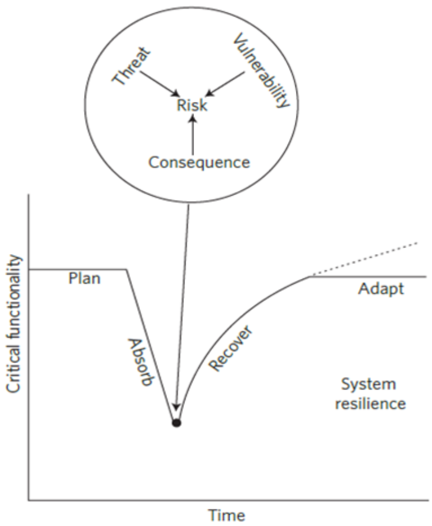


Figure 29. The link between risk and system performance (denoted here as critical functionality) adapted from Linkov et al. (2014).

The diagrams in **Figure 30** below show the interplay of risk and resilience on the changes in system performance over time in a CI asset during a shock or hazard event. The size of the initial shock reflects the total risk to the system while the shape of the recovery curve is controlled by the system's AARCA resilience capacities. As indicated above, the area under the curve indicates the total system performance or functionality of the CI asset or network. As expected the conceptual model demonstrates that those CI asset systems that face high risks with high resilience perform better than those facing similar risks but with low resilience. The conceptual model also demonstrates that with high risk and low resilience the SP of the CI system is most affected (Linkov et al., 2014).

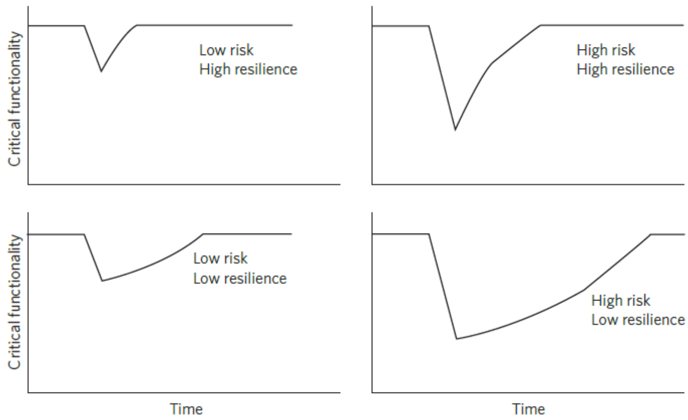


Figure 30. Impact of differing levels of risk-resilience on system performance (denoted here as critical functionality of the system) adapted from Linkov et al. (2014).

Assessing the impact of changes in resilience capacity levels by selecting preventative measures that have an impact on system performance.

Finally, **Figure 23** to **Figure 26** demonstrates how preventative measures and mitigation options are represented in the conceptual model through inputting new AARCA resilience capacity values. Each set of choices would potentially have a different impact on the total Resilience Loss suffered by the system. Conceptualizing disruption at the asset level as the impact on system performance allows researchers to use this as a framework for understanding impacts on a firm as well as providing a reliable and valid basis for understanding how preventative measures can potentially impact system performance and hence overall resilience of the enterprise.

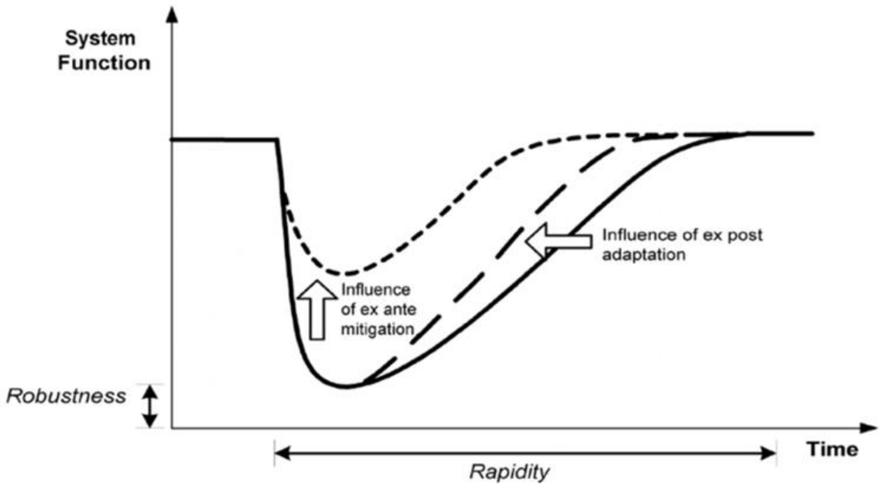


Figure 31. Impact of preventative measures on system performance (Peck and Simonovic, 2013)

Peck and Simonovic (2013) have illustrated what impact the implementation any preventative measures or mitigation options can reduce the total Resilience Loss. This is represented within the framework by the shift in the damage curves as shown above in **Figure 31**. Conceptually it can be seen that any such measure would reduce either the impact of the hazard or affect the duration or both. In other words, either the sensitivity or the exposure of the system to the disruption is affected. This results in either a smaller impact on the system performance or a faster recovery both as a result of changes in the AARCA resilience capacity scores as generated by the RAMT. As indicated previously, this corresponds to how we have defined resilience of a system in section 3.3 and fits the purpose of the conceptual framework and the output of the prototype model described in section 3.9.

4 The Risk Resilience Framework

As indicated in section 1, the EU CIRCLE project aims to provide a platform with multiple tools for CI operators to assess their individual infrastructure's resilience and identify options to improve it in the context of climate hazards and climate change stresses.

For this purpose, D4.3: Final Resilience framework has developed a framework that will be consistent with D3.5: Holistic CI Climate Hazard Risk Assessment Framework as described in section 2.5 were the steps of the risk management process were detailed in relation to the multi-layered approach. Figure 32 below presents the combined risk resilience framework which seeks to demonstrate the intricate link between the two frameworks.

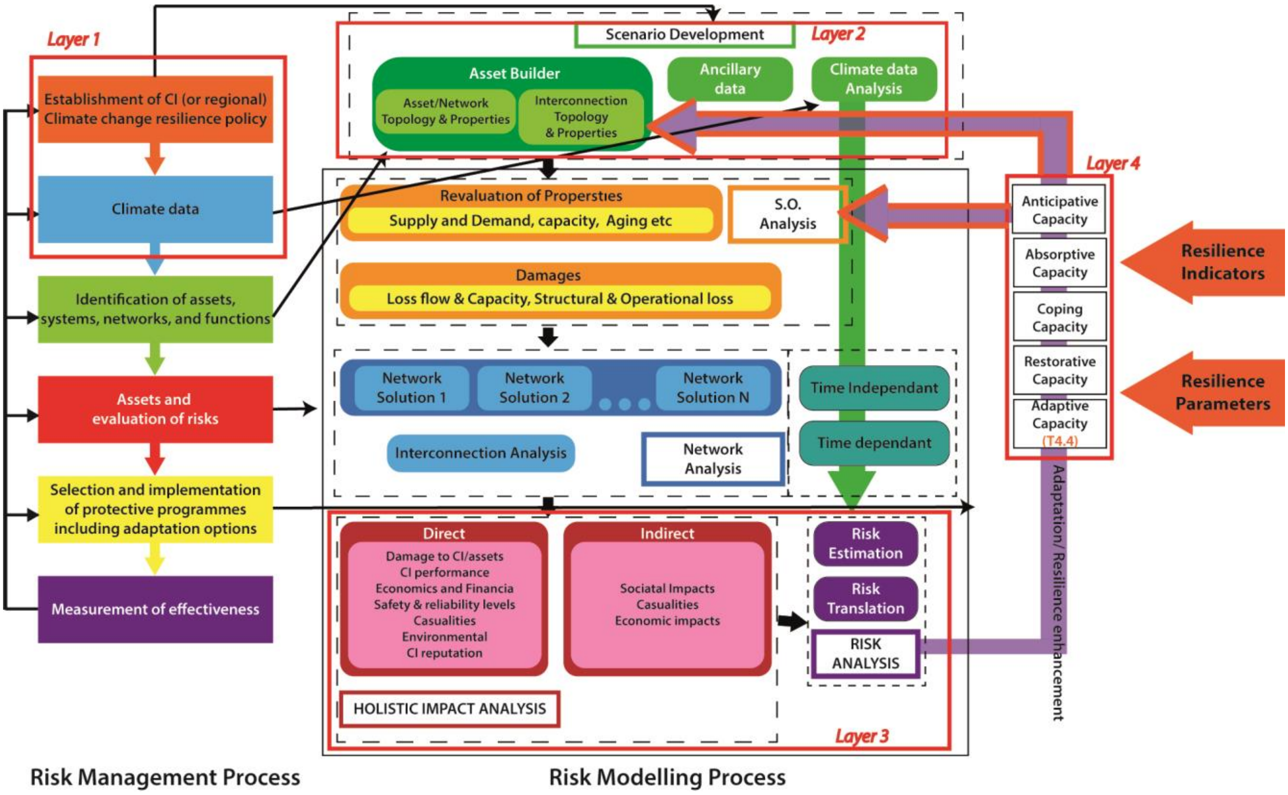


Figure 32. Combined risk resilience framework

As demonstrated above and mentioned in several sections throughout this report, the layers incorporate the integral parts of the risk management and risk modelling process into the resilience framework. More precisely, the resilience framework uses the following four sections of the EU CIRCLE Risk framework (the red boxes titled as layers 1 to 4 above):

1) Layer 1 where climate hazard and climate change stress modelling can be done with input from the orange and blue boxes:
    a) Establishment of CI Climate Change resilience policy
    b) Climate data
2) Layer 2 where the context of CI, their networks and dependencies are detailed in the green boxes where scenario development is done based on input from Layer 1:
    a) Asset Builder
    b) Ancillary data
    c) Climate data analysis
3) Layer 3 where the risk and impact assessment is integrated by the red and purple boxes:

    a) Risk Analysis
    b) Holistic Impact Analysis: Direct and Indirect Impacts
4) Layer 4 where the resilience capacities of CI are measured represented by the white boxes and then used as feedback into the analysis through the purple and orange arrows:
    a) AARCA capacities
    b) Feedback 1: Asset Builder
    c) Feedback 2: Structural and Operational (S.O.) Analysis

Figure 32, the combined risk resilience framework illustrates the integration of the two approaches and how this integration lies at the heart of the multi-layered approach and the simulation modelling method. The project has thus far (till M24) developed the above holistic framework in Figure 32 to identify the risks of multi-climate hazards to heterogeneous interconnected and interdependent critical infrastructures, as the first step to improving resilience of vulnerable social and economic support systems to climate change impacts while climate proofing existing critical infrastructure (in terms of identifying indicators and reference states, anticipated adaptive / transformation activities, and investment costing). This report D4.3 contributes to the EU CIRCLE holistic framework which consists of the following key points:

- The EU-CIRCE process of climate risk management, adapting the NIPP framework (DHS, 2013) for different temporal and spatial scales.
- A multi-hazard risk modelling approach, where an asset based approach is used to identify damages to CI from climate stressor's leading to the identification of the impacts on CI operations using network simulation for the modelling of critical services within interconnected CI.
- The determination of multi-hazard risk compatible with major national, EU and International initiatives (National Risk Assessments, EPCIP, Sendai Framework for Disaster Risk Reduction) and standards (ISO 31000), accounting for impacts directly affecting the CI and consequences to the society, the environment and other sectors of the economy.
- The identification of resilient capabilities (anticipation, absorption, coping, restoration, adaptation) that feed into components of the risk modelling framework
- The determination of modular indicators for quantifying risk and resilience that are compatible with the above and that could be used, alongside reports and maps, for conveying information to the end-users and relevant stakeholders.
- The integration of the suitable modelling components into CIRP and SimICI
- The determination of the output, though suitable visualization and reporting

5 Future Work

As future work, an application of D4.3 resilience framework in the case studies is going to be considered. Discussion on how to implement the framework in 3 of the 5 case studies has already begun with partners and the conceptual model has been converted into an online simulator to enhance discussions with stakeholders on resilience capacities. Development of the online simulator has also sparked interest among partners for possible implementation as a module in CIRP – this is being considered at the moment and will be an additional functionality not considered before.

A more detailed extension of the resilience framework that integrates the business continuity model, adaptation module and cost-effectiveness analysis is also expected as soon as those deliverables are completed.

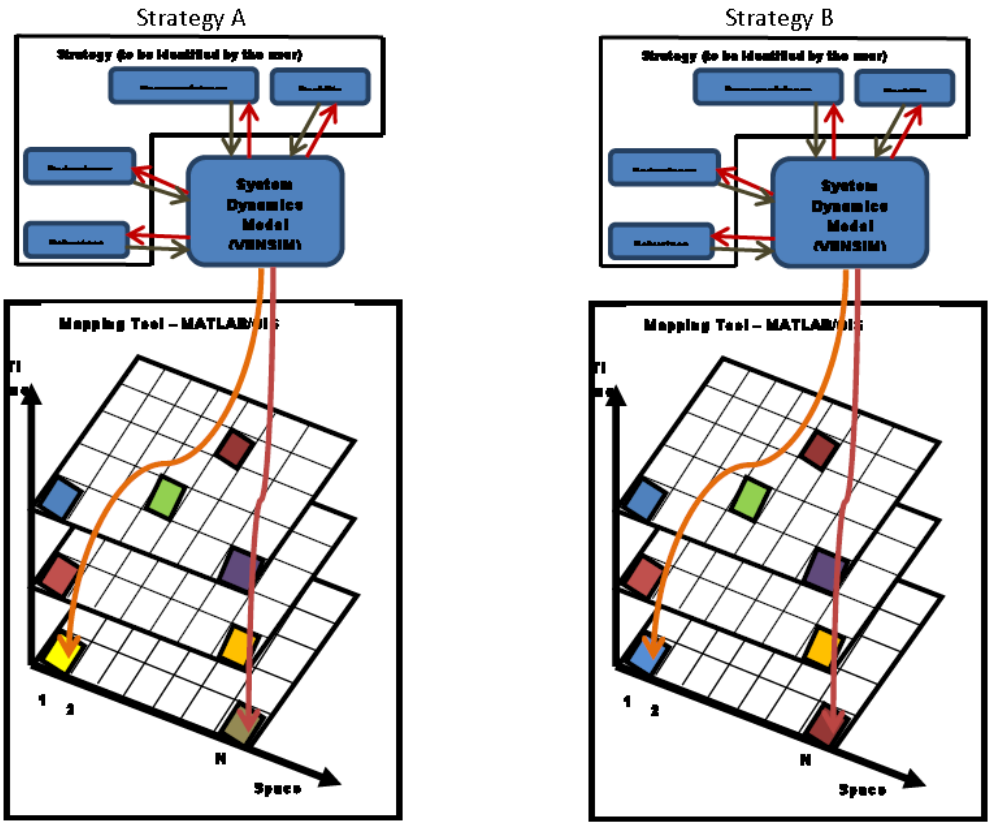


Figure 33. Integrating spatial analysis into the conceptual model (Srivastav and Simonovic, 2014b).

Finally, one of the aspects being considered in the future as an extension to the resilience framework in this report is to integrate spatial analysis directly into the model. This will allow users to look at the impacts of different preventive measures and options spatially across a map – **Figure 33** above looks at how this can be done using a mapping tool in Matlab to overlay geographical information.

6 Conclusions

D4.3 proposes a SD simulation approach to achieve the following objectives: (i) present a systems framework for quantifying resilience and introduce a CI resilience measure; (ii) present the theory behind the resilience capacities and indicators; (III) introduce the conceptual SD simulation model at the CI asset level and develop an example; and (iv) present a high level CI asset network model structure.

The analytical framework developed here can be used by CI asset stakeholders, operators, service providers; (i) for the comparison of different resilience strategies for system performance improvement; (ii) support decision making.

By using this framework, in combination with D4.5 Resilience indicators, CI asset stakeholders, operators, service providers can: (i) to quantitatively compare different hazard response strategies for the same CI asset; (ii) to compare the system performance of different CI assets to similar hazard events; and/or (iii) extend this analysis to compare the system performance of CI network of assets.

The analytical resilience framework presented in this report addresses the following key questions:

4) How short term (or long term) choices in resilience capacities makes an asset or network more resilient;
5) How these choices can minimize system performance loss when shocks occur;
6) How operational (short term) and strategic (long term) choices can minimize the time taken for an asset (or network) to recover and minimize the total loss of system performance

The conceptual model developed in this report can be used by researchers to implement the novel layered approach with resilience capacities introduced in D4.1. The resilience capacities can be calculated using the indicators developed in D4.5 and can be used as inputs into the conceptual model. The model also can use the change in resilience capacities to demonstrate the impact of different preventative measures and adaptation options on a CI asset, network or NoN. Using the conceptual model with stakeholders will ensure that the right information and data are collected from the stakeholders.

7 Appendix A: Context of the report

7.1 Infrastructure as Complex systems

Infrastructure systems, such as the energy production & distribution systems, the chemical industry, water system, transportation, ICT Networks and public sectors, are one of the defining features of modern societies. We rely heavily upon them and their smooth operation to carry out our day to day activities. Infrastructures thus facilitate economic growth, protect human health and the environment and promote welfare and prosperity.

When infrastructure systems are damaged or fail, the smooth functioning of society is disrupted, with negative impacts on our ability to continue in our daily activities; well-being; and security. Damage or failure may result in severe economic losses and interruption of many services that we rely on (NIST vol 1).

To further complicate matters, modern infrastructures operate as a 'system of systems' with many interactions and interdependencies among these systems. Thus damage in one infrastructure system can cascade and result in failures and cascading effects onto all related and dependent infrastructures. For example, loss of an electricity substation may stop a water treatment plant from functioning; which may stop a hospital from functioning. This is a failure cascade chain that spans energy, water and healthcare systems. (UNISDR)

Such failures are made worse because of the nature of our modern societies which are characterised by high density urban centres, high levels of material wealth, and rapid, immediate and interconnected lifestyles (Rogers et al).

The societal disruption caused by infrastructure failures can frequently be disproportionately higher in relation to the actual physical damage (Chang, 2009). It is for these reasons that the ability of systems to cope and bounce back from shocks, their resilience, is so important (Rogers et al).

Various disasters over the past few decades, including man-made and natural disasters, have highlighted that avoidance of all threats at all times for all infrastructures is practically impossible (Sandia report, 2014). This realisation, combined with the disruptive societal impacts of infrastructure damage or failure, has led to the wide recognition in recent years for the need for resilience – for example, ICE's state of the nation report: 'Defending critical infrastructure' (ICE, 2009); the European Commission's policy on the prevention of natural and man-made disasters (EC, 2009), the national response framework (NRF) (DHS, 2008), prepared by the USA's Federal Emergency Management Agency (FEMA) and globally by the Hyogo Framework for Action 2005- 2015: Building the Resilience of Nations and Communities to Disasters and its successor the Sendai Framework for Disaster Risk Reduction 2015 - 2030.

CI as Complex Adaptive Systems

Due to the inherent nature of shocks and disruptions from hazard events, CI systems can be considered as complex adaptive systems (CAS) that require specific approaches that can deal with this level of complexity. A number of scientists such as Dooley (1997) and McManus (2006) have looked at complex adaptive systems and have indicated the following essential components:

- CAS are composed of agents each acting semi-autonomously and which evolve over time.
- Agents scan their environments and develop mental models, or schema, of that environment.
- Agents can increase their fitness by acting to change the schema to fit the observation, or act to change the observation to fit the schema.

- The schema define how agents interact with other agents in the environment around them.

CI systems are inherently complex and require the application of tools developed to cope with these elements.

A number of approaches exist in the literature to cope with this complexity such as agent based modelling, social network analysis and system dynamics to name a few.

complexity science approaches.

CI systems as Complex Adaptive Systems

7.2 The Sendai Framework for Disaster Risk Reduction 2015-2030

The Sendai Framework for Disaster Risk Reduction 2015-2030 (Sendai Framework) is a voluntary and non-binding agreement, which coordinates work on disaster risk management and maps the global course in this field over the next 15 years. It was adopted by UN Member States on 18 March 2015 at the Third UN World Conference on Disaster Risk Reduction in Sendai City, Miyagi Prefecture, Japan.

The Sendai Framework is the successor to the Hyogo Framework for Action 2005- 2015: *Building the Resilience of Nations and Communities to Disasters* and previous global efforts in the field of disaster management[1]. It is notable for representing a shift in emphasis from disaster management to *disaster risk management* and its goal is to prevent new disaster risks, reduce existing disaster risks and ultimately increase resilience globally. It advocates actions on tackling underlying risk drivers as a tool for achieving its goal, and recognises that climate change is one such risk driver. The Sendai Framework thus strongly promotes taking into account of climate change and climate change adaptation in disaster risk management activities and policies across the globe.

The Framework is underpinned by seven global targets, which relate to the reduction of: 1) global disaster mortality; 2) the number of people affected by disasters; 3) direct disaster economic loss; 4) disaster damage to critical infrastructure and disruption of basic services; whilst increasing: 5) the number of countries with disaster risk strategies; 6) international cooperation to developing countries; and 7) the availability of and access to multi-hazard early warning systems (see Annex 1 for the targets in detail).

Of particular relevance to EU-CIRCLE is target four of the framework: *Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030*. This target (and the other six) are underpinned by four priority areas for action:

Priority 1: Understanding disaster risk.

Priority 2: Strengthening disaster risk governance to manage disaster risk.

Priority 3: Investing in disaster risk reduction for resilience.

Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction

Through these priority areas the Framework proposes the following actions in relation to critical infrastructure:

- integration of disaster risk reduction in laws and regulations that apply to publically owned, managed or regulated services and infrastructures;

[1] Including the International Framework for Action for the International Decade for Natural Disaster Reduction of 1989, and the Yokohama Strategy for a Safer World: Guidelines for Natural Disaster Prevention, Preparedness and Mitigation and its Plan of Action, adopted in 1994 and the International Strategy for Disaster Reduction of 1999.

- investment in structural, non-structural and functional disaster risk prevention and reduction measures in critical infrastructures;
- **promotion of resilience of new and existing critical infrastructure**, including water, transportation and telecommunications and health infrastructure, to ensure that they remain safe, effective and operational during and after disasters in order to provide live-saving and critical services.

Resilience of critical infrastructure is thus recognised in the Sendai Framework as of vital importance; as their continuing operation and provision of critical services is crucial, both during and after a disaster.

7.3 Systems approach to CI Resilience

The systems approach to understanding CI impacts uses a holistic point of view where the relationships between elements in a system are more important than the elements themselves. Johnson (2009) describes that as the number of elements in the system rises and the resulting behavior of the system becomes non-linear, then the system becomes complex, or in other words, there is an increase in the domain complexity (Johnson, 2009, Simonovic, 2011).

The systems approach requires researchers to carefully list the elements in the organizational system, first those elements that are external and then those elements within the firm, to understand how behavior might be influenced (McManus, 2008, Gharajedaghi, 2012, Srivastav and Simonovic, 2014b). This approach is consistent with the complexity of CI assets and their interdependencies and requires researchers to explore both the external environment (i.e. suppliers, competitors, markets) and the internal environment (i.e. organizational processes, supportive technologies and employee relationships) (Gharajedaghi, 2012). This is especially true when looking at disruptions in the CI system and the vulnerability of the system to disruptions and shocks.

D4.1 provides an extensive review of resilience frameworks that conceptualize and define resilience in various ways. The report provides an overview of frameworks that are mostly qualitative with a few notable exceptions.

As mentioned earlier, the response of systems to real world phenomenon is often complex, especially when considering public policy matters related to disaster impacts and when considering preventative measures for mitigation and preparedness (Ramalingam et al., 2008). Systems analysis provides researchers with an integrated approach to developing mitigation and prevention strategies. This holistic approach highlights interconnections between elements, drawing attention to root causes and providing insights into new opportunities for “bouncing back” better (Simonovic, 2011).

As noted in the review, traditional engineering or psychological definitions of resilience often include concepts like flexibility, bending and the ability to bounce back after a shock (Donoghue 2007) but when human systems are involved then capacities to cope with these adverse impacts is emphasised upon (Burton, 2012). The CI resilience definition stated above seeks to incorporate a holistic approach to understanding resilience and this requires a set of tools that can incorporate the complex nature of interdependencies as in CI systems. Norris et al. (2008, 2009) have proposed a view that classifies resilience as set of capacities that can be measured and increased through preventative and adaptive measures, which in turn enhance a community, or this case an assets or networks, ability to recover from disasters.

System Dynamics is an academic discipline introduced in the 1960s by researchers at the Massachusetts Institute of Technology. System Dynamics was originally rooted in the management and engineering sciences but has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological and ecological systems.

Table 13. Stakeholder perspectives to resilience (Hughes and Healy, 2014).

Stakeholder	Perspective
User: The direct or indirect customer/user of the infrastructure, which may be for business or personal purposes. For example: • direct – freight companies, or commuters using the road network • indirect – those who receive goods and key supplies, such as supermarkets.	Users expect the level of service they are accustomed to, to be restored following an event. They may accept a lower level of service for a period of time that is proportional to the severity of an event; however, they may be less accepting of a lower level of service for extended periods. The owner and operator of the infrastructure need to understand the length of time the user will tolerate decreased levels of service.
Operator and maintainer: Government agency, local government, utility company or private contracted organisation.	Operators need to deliver resilience which does not adversely raise the cost of maintenance and operational expenditure. They have a key interest in interdependencies and potential cascade failure.
Government/owner: Both central and local government, related agencies and utilities.	Government and related agencies deliver resilience for the community, and therefore need to consider broader social as well as economic objectives, with a key interest in interdependencies. Infrastructure reliability has political significance through the way infrastructure disruptions are perceived by constituents. Robust business cases are required for investment in resilience.
Funding organisation: Private financier of capital and/or operations and maintenance.	Funding organisations need to deliver resilience to protect the investment in existing assets, with a focus on value for money and a robust business case.
Insurer:	The insurer has a vested interest in reducing the risk profile as a result of resilience improvements.

Understanding the perspectives of the different stakeholders is an important component of resilience and tends to be overlooked in other approaches to modelling resilience. Using a systems approach that is based on participatory modelling allows the researchers to incorporate perspectives into analysis. Table 13 discusses these perspectives in detail and indicates that differing motives can play a crucial role in the development and implementation of CI policies.

7.4 Multiple modelling approaches

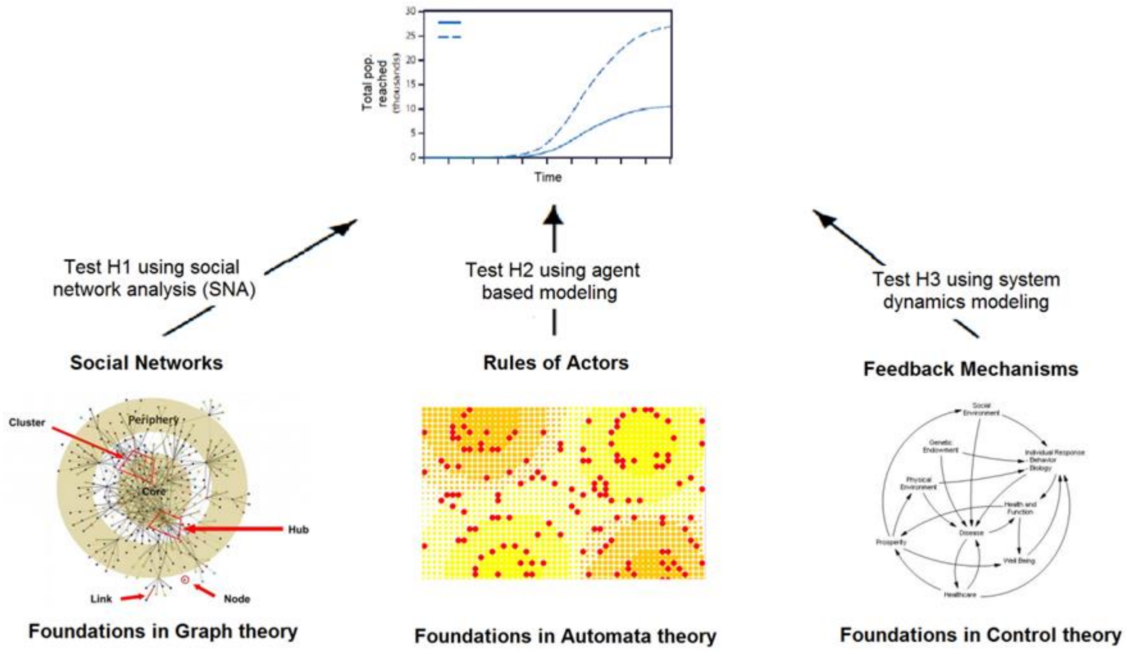


Figure 34 . Methods of Complexity

Three of the most popular complexity tools used in disaster management research that may prove useful for our research context are social network analysis (SNA), agent-based modeling (ABM) and systems analysis (SA) (Simonovic, 2011). Even though there may be some overlaps between these three methods, they employ three very different approaches to understanding complex phenomena as can be seen in **Figure 34** above. For example, if the study was looking at individual actors and their behaviors in a system then either SNA and ABM would be better suited to understand and analyze this particular phenomenon. For SNA, this is due to the focus on the social networks in which those actors are embedded. On the other hand, if the researchers are interested in what impact individual rules actors follow in the system then ABM would perhaps be the preferred tool (Lich et al., 2013). Alternatively, if feedback mechanisms between the components of the system are to be the focus of the research question, then SD would be better suited (Sterman, 2000a).

7.5 The SD simulation approach

System Dynamics simulation approach relies on understanding complex inter-relationships existing between different elements within a system. This is achieved by developing a model that can simulate and quantify the behaviour of the system. Simulation of the model over time is considered essential to understand the dynamics of the system. Understanding of the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model and simulating the model for understanding its behaviour are some of the major steps that are carried out in the development of a system dynamics simulation model. It is interesting to note that the central building blocks of the principles of system dynamics approach are well suited for modelling any physical system. The power of simulation is the ease of constructing “what if” scenarios and tackling big, messy, real-world problems. In addition, general principles upon which the system dynamics simulation tools are developed apply equally to social, natural, and physical systems. Using these tools in disaster management allows enhancement of models by adding social, economic, and ecological sectors into the model structure.

SD approaches are designed to capture the dynamic behaviour of a system as it changes over time and are particularly helpful in understanding phenomenon where a bidirectional relationship exists between components of a system or even across systems. These relationships are known as feedback mechanisms and can be shown diagrammatically in causal loop diagrams (Sterman, 2000a). These methods are also designed to understand non-linear relationships where disproportionate responses or feedback may exist in a system, for example where threshold limits or tipping points exist before large changes within a system. Another aspect of social phenomenon that these methods can help in understanding are time-delayed effects in the feedback process where delays in the response may cause significantly different effects than expected if the feedback was simultaneous (Mabry et al., 2008, Mabry et al., 2010).

By using a SD simulation approach to the framework, in combination with the capacities developed in D4.5 Resilience indicators, CI asset stakeholders can: (i) compare different hazard response strategies for the same CI asset; (ii) compare the system performance of different CI assets to similar hazard events; and/or (iii) extend this analysis to compare the system performance of CI network of assets.

According to EU CIRCLE objectives the proposed approach should address the following questions as well:

4) How measures (short and long term related to operational or strategic issues, respectively) make a network more resilient.
5) How investing in these measures can reduce service loss when disruptive events occur.
6) How these measures can minimize the time taken for a network to recover and, thus, minimize the total cumulative loss of services.

A number of critical infrastructure decision support systems use system dynamics as one of the primary simulation methods in their analysis. In the next section, this report briefly introduces the most successful or popular examples from the literature that have been either implemented and still in use or have been validated through multiple case studies and are coming into implementation.

As explained in section 2, a system is broken down into simple objects or processes which interact to produce complex behaviours. To produce a system dynamics model, feedback loops, stocks, and flows are used to represent the system under study based on the knowledge of a subject matter expert. Feedback loops indicate connection and direction of effects between objects. Stocks represent quantities or states of the system, the levels of which are controlled over time by flow rates between stocks.

In order to create a quantitative system dynamics model, formulas are developed to calculate a value for each variable. The model is tested to verify that it reproduces the behaviour of interest in the system and it then provides a framework to quantify the effects of hypothetical events, and to compare proposed interventions. It may also serve to identify inconsistencies between processes which occur in reality and the mental models used by decision makers.
This type of model has been applied in academic research (see for example the publication *System Dynamics Review*) as well as business, supply-chain, and operations management. In economic applications, models developed using the system dynamics approach have been used to answer such questions as what the impacts of regulation, investment choices, and pricing might be on profitability as well as optimization of manufacturing and retail stocking.

This type of model has been applied in academic research (see for example the publication *System Dynamics Review*) as well as business, supply-chain, and operations management. In economic applications, models developed using the system dynamics approach have been used to answer such questions as what the impacts of regulation, investment choices, and pricing might be on profitability as well as optimization of manufacturing and retail stocking.

7.5.1 CIP/DSS, US

The Critical Infrastructure Protection Decision Support System (CIP-DSS) is a modelling application developed as a collaborative effort between the Los Alamos, Sandia, and Argonne National Laboratories, sponsored by the Science and Technology Directorate of the U.S. Department of Homeland Security (DHS). It is one of the many modelling capabilities of the DHS's National Infrastructure Simulation and Analysis Centre (NISAC), one of US's premier research institutions regarding critical infrastructure research. NISAC has a number of simulation modelling tools that it uses and the CIP-DSS is one of the tools using system dynamics for analysis of cascading effects of CI due to natural and/or manmade disasters – for a comprehensive review of the tools and methods used by NISAC see Brown (2006), Pederson et al., (2006) and Hyeung-Sik et al. (2008).

CIPDSS provides an aggregate-level model of all critical infrastructure sectors and their major interdependencies. CIPDSS allows government (federal, state, and local) and industry decision makers to determine what consequences might be expected from disruptions to infrastructure, explore the mechanisms behind these consequences, and evaluate mitigations for a particular risk. It is designed for analysis of high-level behaviour of metropolitan or regional infrastructure.

CIPDSS enables analysis which takes into account the way disruptions in one infrastructure sector may propagate to other infrastructure systems. It is a system dynamics simulation model of all critical infrastructure sectors as defined by Homeland Security Presidential Directive 7 (e.g., water, public health, emergency services, telecom, energy, transportation) and their major interdependencies at an aggregate level.

According to Brown (2006), CIP/DSS assists decision makers in making informed choices by (i) functionally representing fourteen critical infrastructures with their interdependencies, (ii) computing human health and safety, economic, public confidence, national security, and environmental impacts, and (iii) synthesizing a methodology that is technically sound, defensible, and extendable. Examples of questions that this decision support system is designed to address includes:

1) What are the consequences of attacks on infrastructure in terms of national security, economic impact, public health, and conduct of government—including the consequences that propagate to other infrastructures?

2) Are there choke points in our Nation's infrastructures (i.e., areas where one or two attacks could have the largest impact)? What and where are the choke points?

3) Incorporating consequence, vulnerability, and threat information into an overall risk assessment, what are the highest risk areas?

4) What investment strategies can the U.S. make that will have the most impact in reducing overall risk?

Method

The SD approach used by the CIPDSS model is a methodology for studying complex systems involving feedbacks or interdependencies – see above for more explanation on the SD method. CIPDSS has been programmed in Vensim, a commercial system dynamics modelling software package. In 2007, when the tool was first released, CIP-DSS modeled 14 critical infrastructure systems. The process required teams of one to three analysts for each infrastructure system who developed the models with contributions from relevant CI experts, and with the teams collaborating to model system interdependencies – an example of the output between the teams might be the influence diagram in figure x on the following page which shows how an epidemic might impact CI in an urban location. Overall the model utilizes the 2007 version of the tool uses 4,482 variables – **Table 14** below shows a summary of number of variables per CI sector. Infrastructure systems are subdivided into more than 100 subsectors; for example, bus, road, and subway subsectors are created within the transportation system. This results in over 5,000 potential interactions between infrastructure subsectors; as this number of potential interactions is too large to evaluate, expert judgment was used to identify and represent only the most significant interactions between subsectors and those are represented in the final model.

Sector	*Count*
Agriculture	10
Banking and Finance	251
Chemical Industry and Hazardous Materials	42
Emergency Services	521
Energy	802
Food	373
General Urban	444
Global Data	29
Government	54
Information and Telecommunications	237
Key Assets	72
Postal and Shipping	43
Public Health	325
Scenario	925
Transportation	208
Water	156
Total	***4482***

Table 14. Number of variables in each CI sector in the CP/DSS model (Min et al., 2007)

CIPDSS models systems within each subsector at an aggregate level. For example, within the metropolitan scale model discussed here, all roads within a city are treated as an aggregate entity with properties similar to a single road – the aggregate represents the system function of the road. This contrasts with the approach used, for example, in an urban transportation demand model where individual roads are represented.

Using an aggregate approach makes it possible to directly parameterize the dependency of traffic flow on other subsectors, for example, on another CI like the availability of electricity through power lines, and also reduces the need for finely resolved site-specific data and analysis unless required in the analysis. For instance, when modelling a shock on CI in a specific geographic location then the model requires aggregate data describing local infrastructure (e.g., population, number of hospital beds, electricity production) which must be obtained locally which may sometimes be challenging because of the complexity of the systems and interactions, identification and parameterization of dependencies.

In addition, the prioritization of dependencies and also the types of interactions between the CI sectors differ depending on the type of shock to the system and the application for which model results are intended. Even at the level of complexity present within the CIPDSS model, the model architecture and processes which it can represent inevitably reflects the priorities and assumptions of its programmers, and processes important to a particular scenario may be left out. Such an observation can be made with regard to the implementation of the CIPDSS model. For example, changes in population caused by evacuation or immigration propagate through only some infrastructures but this may not be something considered by an agency or service provider as essential for their analysis but may have an effect nonetheless. **Figure 35** on the next page illustrates the complexity of a multi-sectoral CI model that forms the core of the CIPDSS model.

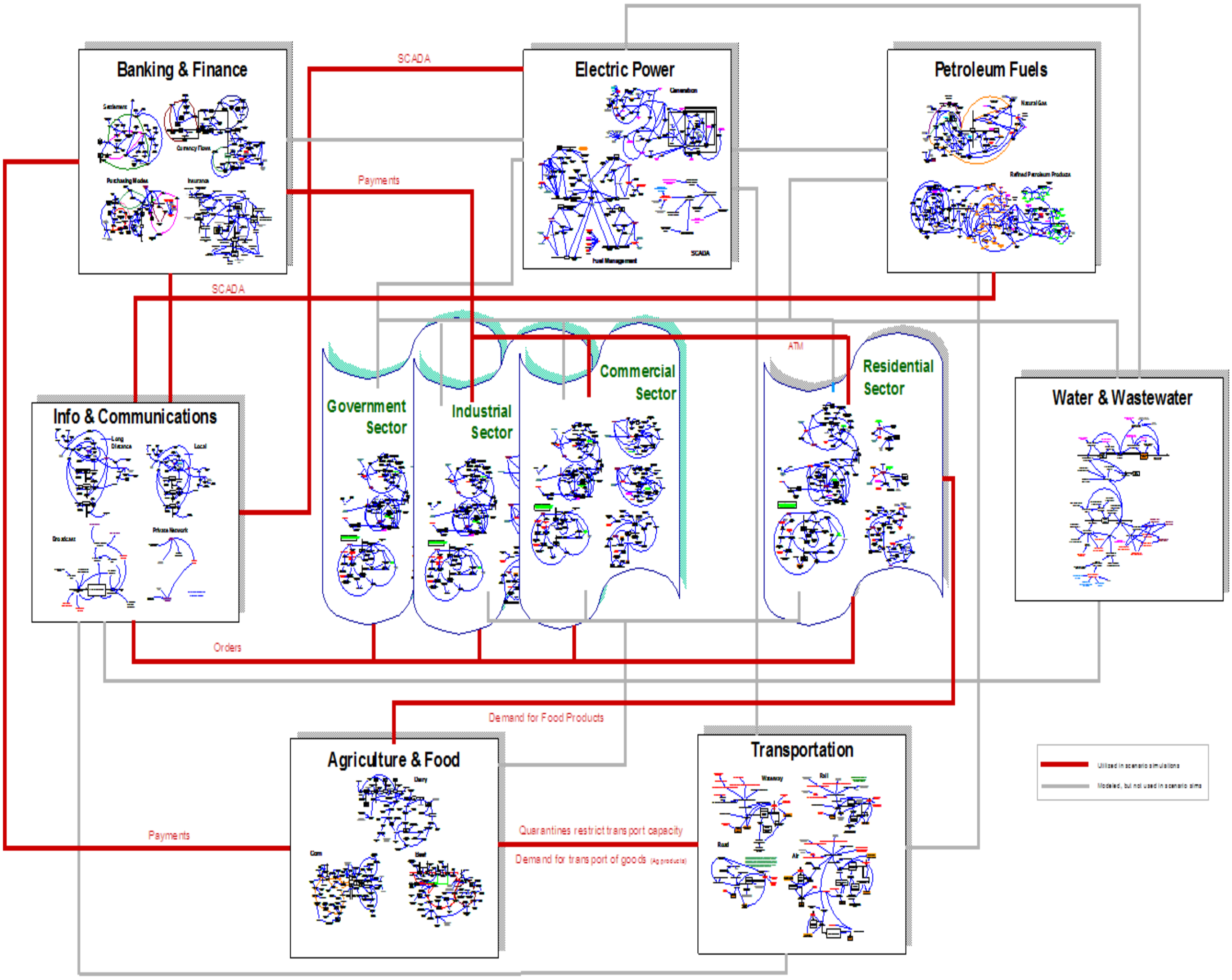


Figure 35. SD simulation model of CI interdependencies (Min et al., 2007).

7.5.2 CIR/DSS for highways using HAZUS MH, US

HAZUS is a risk assessment methodology for analyzing potential losses from floods, hurricane and earthquakes and distributed by FEMA. HAZUS couples scientific and engineering knowledge with geographic information systems (GIS) technology to estimate physical, economic, and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake, hurricane and floods. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific hazard being modeled, a crucial function in the pre-disaster planning process.

Hazus, like other DSSs used in disaster management, uses geographical information system technology to visualize the interaction between the spatial extent of the hazard and physical, social, economic components of an urban system. Hazus is used to estimate potential losses of buildings and infrastructure, and impacts to populations as a consequence of the natural disaster (earthquake, flood, hurricane). The Disaster Decision Support Tool is another example of a web-based disaster management DSS that is designed for application in Puerto Rico. It provides access to geo-referenced demographic and economic data for all municipalities across the country as well as physical (infrastructure and natural features) data in a geographic information system (GIS) environment. The tool aims to provide accurate, freely accessible data to its users in order to visualize the social vulnerabilities of a municipality to hazardous impacts.

Like the other methods shown in this appendix, the CIRDSS framework also uses a SD approach. System dynamics is used to represent the sequence of events, the relationship among decision makers (e.g. FEMA, local providers and CI stakeholders) that play major roles, the types of policies that enabled certain actions (e.g. FEMA's Mitigation Grant), and the critical infrastructure system (e.g. transportation – roads) throughout different conditions and performances resulting from the stress imposed on the infrastructure by the hazard. System dynamics is a way to recognize that the critical infrastructure system and the disaster together are a complex problem (Dhawan 2005).

This approach captures the behaviour of the system including the perspectives of different stakeholders, inherently strengthening the system in a flexible and adaptable way based on feedback, allows the system to be reduced to subsystems that require specific types of information for each component, and supports information flow and feedback mechanisms.

The feedback mechanism used is based on the SD methodology that consists of a systematic process that views complex feedback structures (a control mechanism) to verify data and analysis results allowing for adjustments to and inclusion of more data, and the adjustment of parameters in a computerized simulation model (Dhawan 2005). This feedback mechanism helps to develop a more robust hypothesis generation, hypothesis verification, and final adjustment for mitigation strategies (Mirmehdi, Palmer, Kittler, and Dabis 1996). The complex feedback includes parameter optimization through the processing chain, and high level inputs of decision-makers for the resulting improved critical infrastructure system resilience through mitigation strategies.

The feedback from mitigation strategy hypothesis generation provides the first insight developed. The vulnerability analysis confirms or rejects a strategy on the basis of the impact and damage assessment. The feedback for mitigation strategy hypothesis verification, which includes the asset management and financial systems considerations, is used to accept, reject, or include solution alternatives from the hypothesis generation. This includes looking at the different mitigation project approaches chosen, damage value per segment, causal agent, calculation, and assumptions made for the overall mitigation project of the infrastructure network.

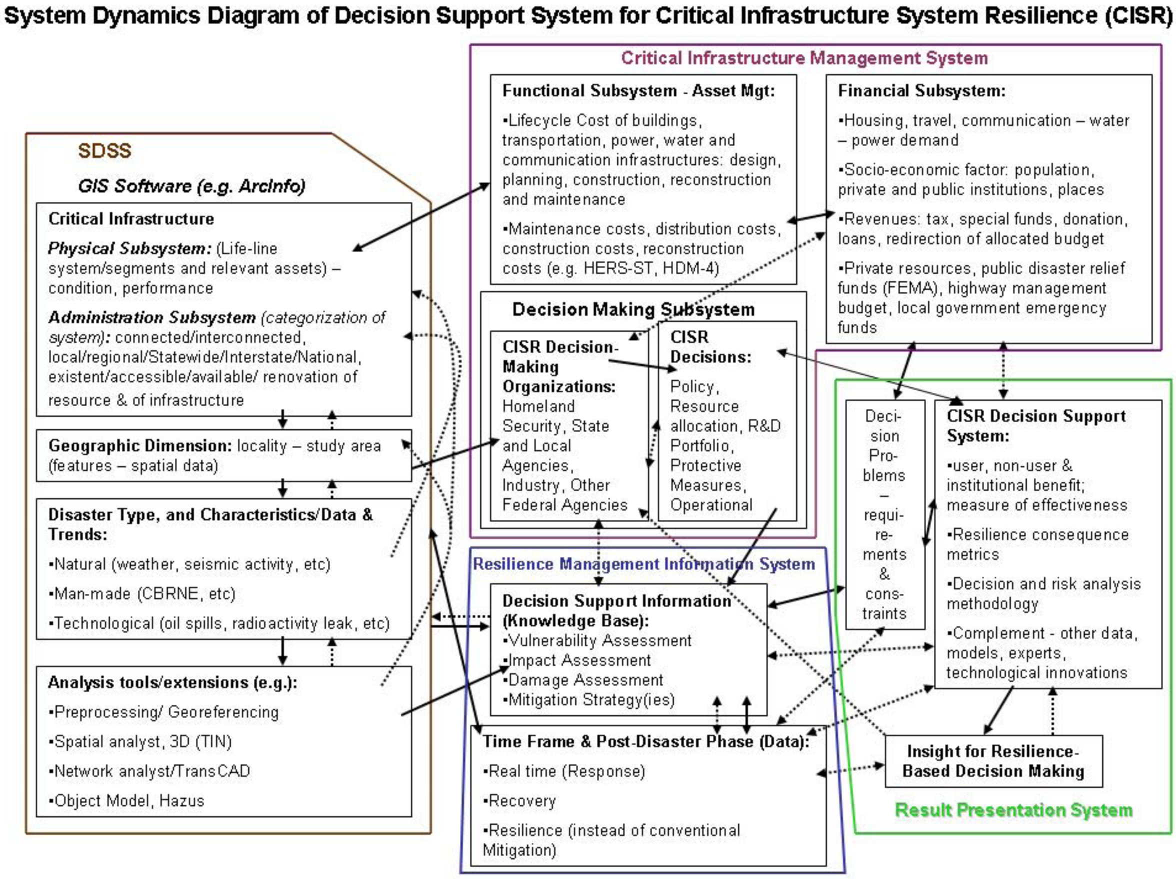


Figure 36. Systems dynamics diagram for Critical Infrastructure Resilience Decision Support System used in HAZUS-MH. Source: Croope (2013)

The SD diagram used to represent the CIR-DSS framework shown in Figure 36 above, is based on mental models, which were then used to develop the computer-based software tool in STELLA, and later simulated using the most likely values of variables (Dhawan 2005). The framework is modelled to test whether the recognized framework for improving critical infrastructure system resiliency changes with the hypothesized system dynamics and developed mitigation strategies. This process helps viewing the interconnected system rather than just viewing isolated parts.

The model development in STELLA uses SD techniques to see how the structure of the system governs its behaviour through the analysis of feedback loops and computer simulations (Dhawan 2005). It helps improve the mental models of decision makers by looking at how policy determines behaviour. The model views the financial implications of decisions by including variables that represent:

- FEMA mitigation grants,
- project financial shares among stakeholders,
- final level of protection by infrastructure mitigation projects
- infrastructure mitigation projects future impacts and benefits considering future other disasters, and
- the calculations of benefits.

The improvement in system resilience viewed using system dynamics is the metric for the critical infrastructure system. This metric shows both the strength (value of resilience of the infrastructure system before and post-disaster system improvement), and the capacity for flexibility and adaptability after a disaster (Tierney and Bruneau 2007).

The CIRDSS model is a good template of how EU CIRCLE case studies can use the SD method to capture the both the impact of the disaster and the impact of policies. In the next section we look at examples of SD approach being used in the EU context.

7.5.3 CRISADMIN, EU

The Critical Infrastructure Simulation of Advanced Models for Interconnected Network Resilience (CRISADMIN) is focused on developing a tool for evaluating the impacts of critical events on critical infrastructures. The tool is intended to serve as a decision support system that is able to test and analyze critical infrastructure interdependencies, determine the modalities through which they are affected by predictable and unpredictable events (e.g., terrorist attacks and natural disasters), and investigate the impacts of possible countermeasures and prevention policies.

The CRISADMIN Project studies the effects produced by critical events in an environment in which the interdependencies among several critical infrastructure sectors are modelled using a system dynamics approach and simulated in a synthetic environment. The approach has been used in contexts where standard analysis is made difficult by the wide range of available data and/or relationships in place. In this project the main areas covered were transportation, energy and telecommunications infrastructures which modelled using this system dynamics approach.

The project emphasises that the SD approach is specifically helpful in considering infrastructure systems, which are highly influenced by “soft” variables – variables that are connected to human behaviour. This systemic approach, which closely follows the Systems Thinking & System Dynamics (SD) Methodology prescriptions, has allowed for a simple yet very effective representation of such context, with an identification of those parameters that, in a “domino effect”, influence the behaviour of the whole interconnected system.

The final document in the project details the methodology used for the System Dynamic modelling of critical infrastructures and their behaviours (Armenia et al., 2014). The SD approach provides decision makers with a useful tool in the form of the Interactive Learning Environment (ILE), to understand and evaluate some of the expectable risks triggering Critical Events. The ILE was actually designed to be used by analysts of specific agencies, like Utility or service providers, to simulate crisis events. The resulting model will have to be adapted to the specific context, so that the relevant variables and parameters will have to be calibrated to real events and to simulation exercises.

The approach uses a three-step methodology to set up and implement a case in order to model a complex system and it’s behaviours in critical events. First of all, a theoretical model has been defined to establish the boundaries of the investigation to be performed and to define the data domains, which would lead the subsequent modelling activity. Secondly, a system dynamics model has been designed to investigate mutual interdependencies among the systems of interest, which can have either reinforcing or dampening effects in case of a critical event occurrence.

Finally, based on the above two steps, an Interactive Learning Environment has been created to provide decision makers with a means of testing different investments opportunities at stake, as well as to understand which could be the most effective strategy to pursue in the long run to enhance critical infrastructures' security and resilience.

The theoretical framework defined in the project considers the main boundaries and points of reference of the study, focusing on the main dependencies impacting on the evolution of the event. It defines the context through the following considerations: 1) features of the territory and of the socio-economic environment, where the critical event occurs, 2) timing of the event (including when it occurs and its duration), 3) preparedness of actors (both as population with experience in similar events and as strained first respondents). To this purpose, data domains have been used to group the outstanding parameters to be included in the model. In particular, for critical events to be investigated in the CRISADMIN project, the following four data domains have been considered, namely Territory, Events, Environment and Apparatus as shown in the **Figure 37** below (Armenia, et al., 2014).

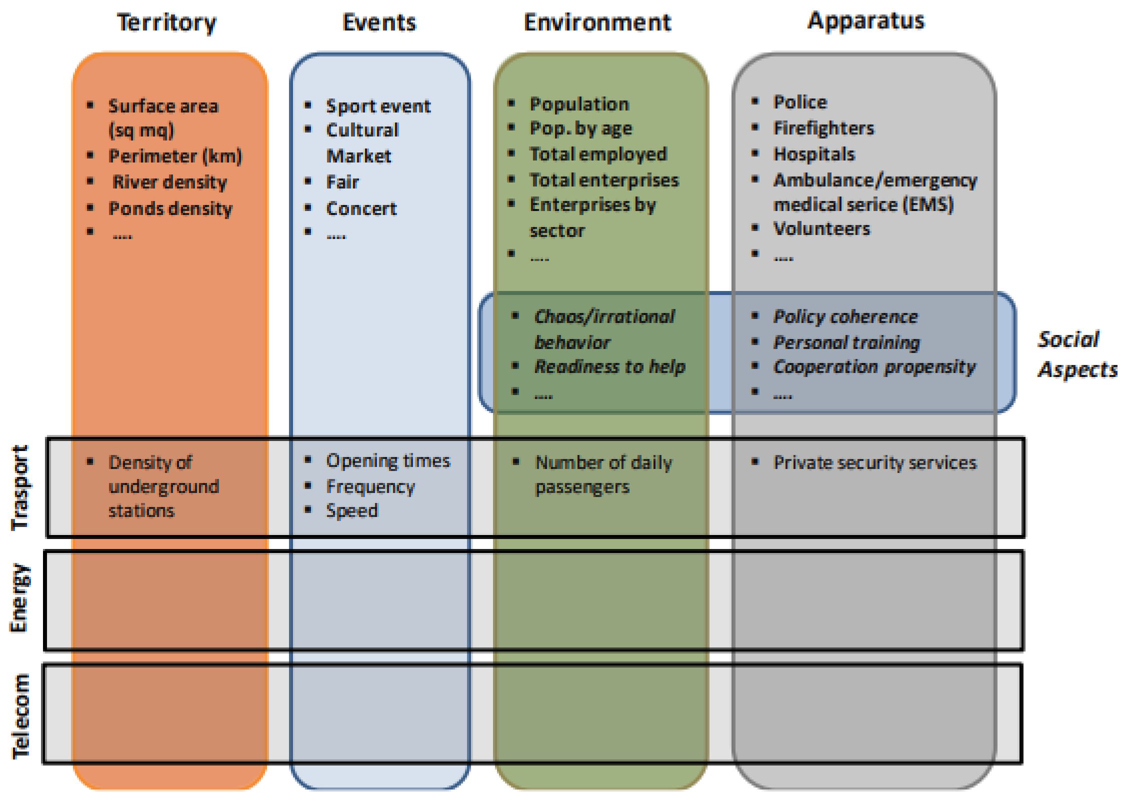


Figure 37. CRISADMIN theoretical framework (Armenia et al., 2014)

The main objective of the data domains in the project was to represent with specific parameters, the stage where the critical event happens and where counter-measures should be taken as well as damages assessed. For this reason, social aspects, involved both in the preparedness and the reaction to critical situations, were included in the Environment and Apparatus Data Domains as shown in **Figure 37** above. In particular, special attention was paid on:

• The actors that participate in the activities being modelled;
• The ordinary events that represent the context's normal life;
• The CIs, in terms of provided services that are focused in the models.

For the purposes of the CRISADMIN project, the focus was on only three main infrastructures, namely Transport, Energy Supply and Telecommunications. This selection was based on the key role played by these infrastructures within critical events and critical events' management and also on legislative provisions. The project sites the European Programme for Critical Infrastructure Protection (EPCIP), the Council Directive on the identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection in December 2008 specifies that "[…as such, this Directive concentrates on the energy and transport sectors and should be reviewed with a view to assessing its impact and the need to include other sectors within its scope, interalia, the Information and Communication Technology (ICT) sector" (DIRECTIVE, 2008/114/EC 8 December 2008). For example **Figure 38** below looks how CRISADMIN models the High Voltage energy sector and how simulation modelling of a sector might look like, in general.

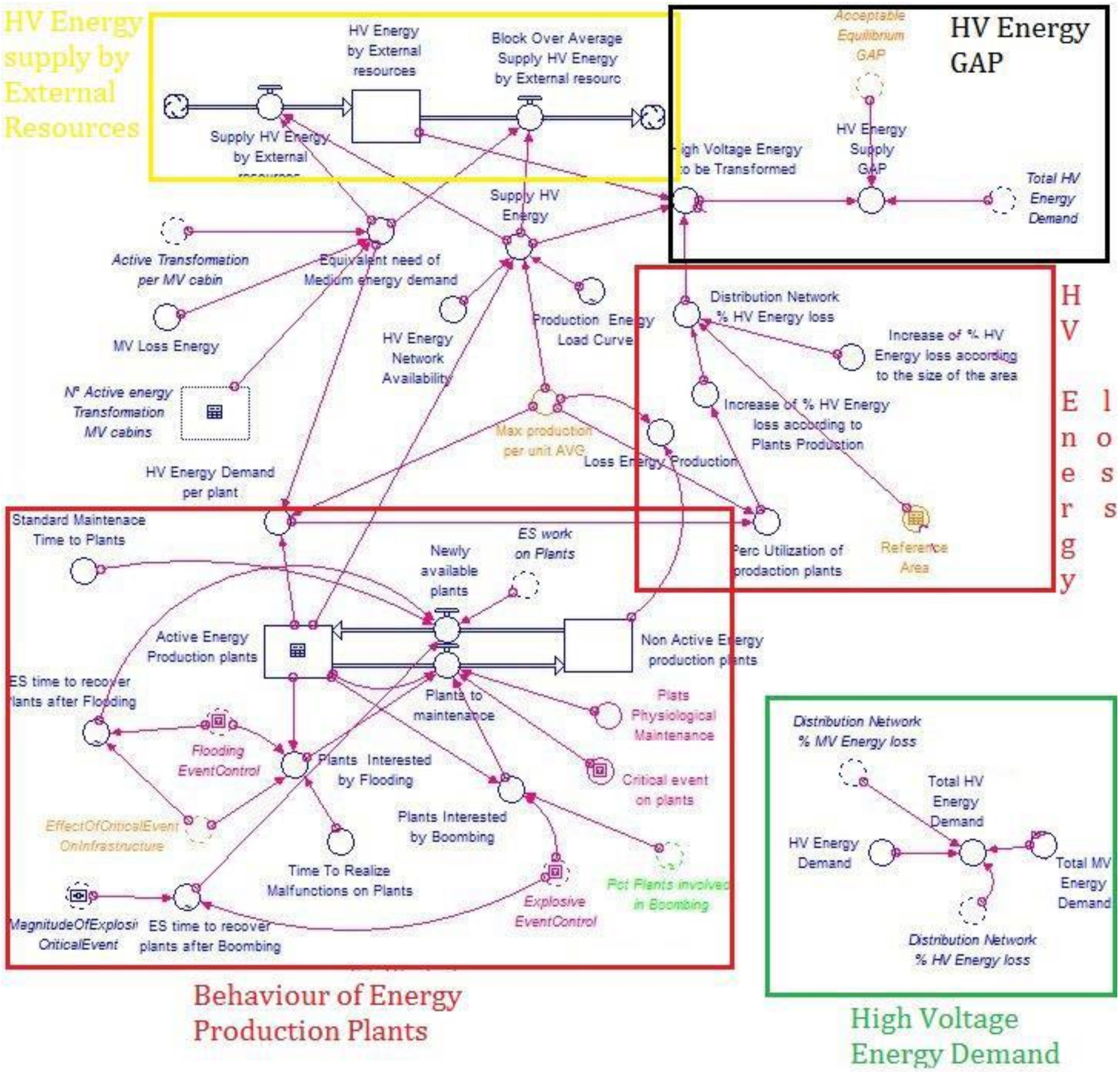


Figure 38. CRISADMIN HV Energy production simulation model (CRISADMIN, 2014).

Another point of interest for EU CIRCLE consortium members is the ILE prototype developed, which allows for the execution of simulation runs and comparison of the effects on the territory. This will enable operators, both territory analysts and first responders, to test and analyse the impacts of different policies in reaction to various scenarios, in terms of nature and size of the event, timing and extent of direct damages, as well as to comparatively assess different possible evolution in presence of alternative mitigation policies and/or different resources deployment.

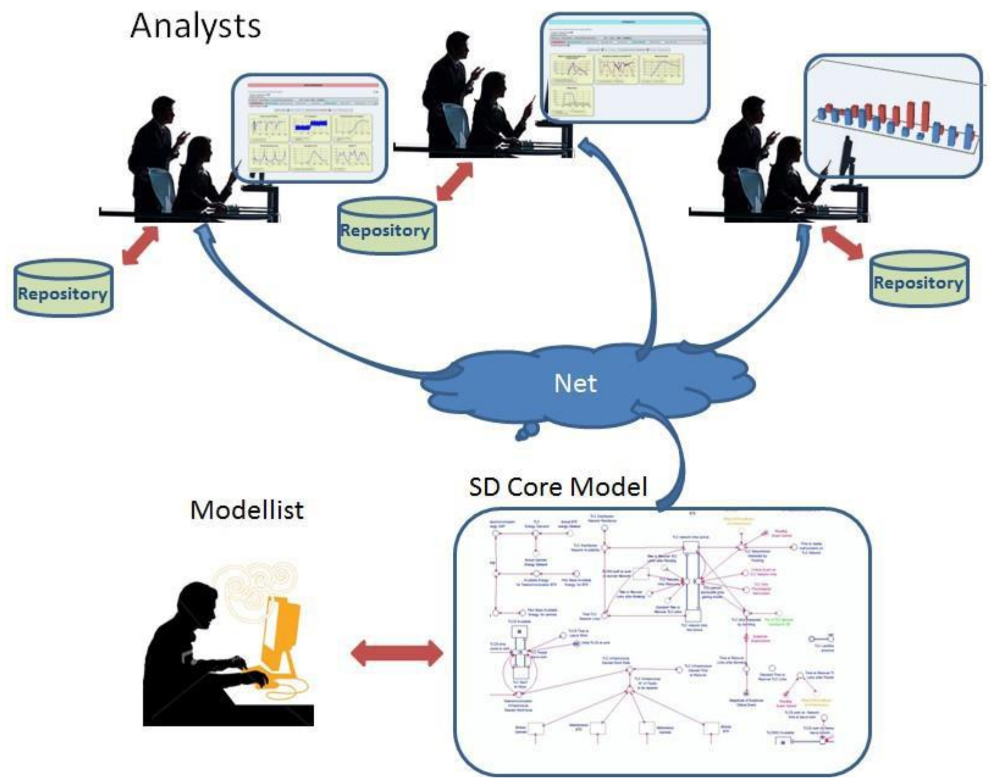


Figure 39. CRISADMIN ILE architecture (CRISADMIN, 2014)

As previously mentioned, one of the key deliverables of the CRISADMIN project was demonstrating of the value of using ILEs, via the prototype, which in the EU CIRCLE perspective might be used and easily tailored and transformed into a Decision Support System (DSS) module for CIRP. Similar ILEs designed for CIRP could be effectively usable in specific environments, both by disaster preparedness analysts and by personnel acting in disaster management control rooms as demonstrated in CRISADMIN in **Figure 39** above.

The CRISADMIN project sought to address the need of decision makers to understand the consequences of policy and investment options before enacting solutions. The project did this by identifying the main interdependencies among systems' parameters, the main interconnections among critical infrastructures and the main variables influencing the evolution of critical events using SD simulation modelling. It used the ILE to generate scenarios where decision makers could interact with the interface and respond by making decisions regarding preventative and mitigation measures in different time frames.

For EU CIRCLE consortium, the CRISADMIN project provides an EU based example of how SD can be used to model critical interdependencies within CI networks and sectors. It also can help consortium members to observe some of the strengths of the SD approach particularly when standard analysis is made difficult by the wide range of available data and/or relationships in place as in the CI context.

7.5.4 Smart Mature Resilience (SMR)

The SMR project is another EU Horizon 2020 research and innovation program that uses SD method in its analysis. The main objective of the project is to develop a Resilience Management Guideline to aid in the implementation of a resilience building process for a city. The guidelines consist of five tools designed to improve the resilience of European regions against natural and man-made hazards.

In the SMR project, resilience is understood to include the ability to resist, absorb and accommodate and recover from the negative effects in a timely and effective manner as well as to preserve and restore vital basic structures and functions.

The five tools developed in the project are as follows:
1. Resilience Maturity Model
2. Risk Systemicity questionnaire
3. Portfolio of Resilience building policies
4. System Dynamics model
5. Resilience engagement and communication tool

The SMR project focuses on five different dimensions:

1. Leadership and Governance
2. Preparedness
3. Infrastructure and Resources
4. Cooperation
5. Learning

There are relevant lessons that the EU CIRCLE can learn from the experience of the SMR consortium particularly with regards to modelling the impacts of hazards on urban processes such as critical infrastructure.

7.5.5 RESILSim, Canada

ResilSIM is a DSS tool that uses SD simulation modelling at its core and has an interface like the ILE described above. It is specifically developed to simulate disaster impacts on urban systems in two cities, Toronto and London in Ontario, Canada. It is web based tool that operates a simulation model of a hydro-meteorological hazard in the urban system using flood inundation maps and subsequently calculates an initial value of resilience in response to the disturbance. The tool offers a sample list of measures for adaptive capacity that can be applied to improve system resilience. The user can select adaptation options to be implemented virtually and observe how the resilience is impacted. After the adaptation option(s) has/have been integrated into the urban system, resilience is rapidly re-calculated and compared to its initial value, serving as a basis for comparison for potential combinations of community upgrades. Overall, ResilSIM enables users to quickly make decisions that can reduce the physical, socioeconomic consequences of a disturbance. These include damages to the built and natural environments as well as the danger posed to human welfare

The innovative and novel contribution of ResilSIM is that it is a DSS that directly uses resilience as a disaster management measure; it is the first validated DSS tool to do so as it is based on the CCAR project that tested a dynamic resilience measure across 4 large cities around the world (CCAR, 2014). It uses a resilience-based decision making tool to prioritize infrastructure upgrades and develop plans for emergency response to adapt to changing external forces. It also can be used during an emergency to provide for informed decision making regarding the allocation of material, equipment, human and financial resources to recover from the impacts of hazardous events as quickly as possible. The ResilSim tool is a web-based decision support tool (with mobile access) used to estimate the resilience of an urban system to flooding events that is based on a metric developed by Simonovic and Peck (2013).

The tool uses spatial programming techniques and publicly available data to calculate the value of the resilience metric. The users are then able to virtually employ different measures of adaptive capacity to assess how they improve or degrade the resilience of an urban system. The outcomes assist decision makers in selecting and prioritizing community upgrades to protect against the impacts of a hydro-meteorological hazard and transform the system to accommodate basic functions during the disruption. The initial, pilot ResilSIM tool is developed for application in London and Toronto, Ontario, Canada as both cities are susceptible to climate change caused flooding events.

ResilSIM estimates resilience with respect to physical and socioeconomic indicators of urban system performance in the event of a hydro-meteorological hazard. A key feature of the tool is its use of freely available datasets to calculate the resilience metric. To represent the physical component of the urban system, shape-files containing engineering infrastructure, critical facilities (hospitals, schools, ambulance, fire and police stations) and other buildings (commercial, industrial, and residential economic sectors) are used. This type of data is often provided by the local, municipal government. Socioeconomic data include the vulnerable population based on age, marital status, residency, language, education and income as well as certain physical datasets.

In Canada (and many other countries), demographic information is available through a census program. It is ideal for datasets to be complete and consistently generated/collected across a large area (such as a country) so that the tool can be more easily transferrable between urban systems.

Currently, however, this is not feasible and due to the inconsistencies of engineering and socioeconomic data provided at a local level of government, the tool must be programmed to reflect each system it is applied to. The methodological framework together with the ResilSIM DSS architecture will remain the same for all applications.

The procedure for estimating disaster resilience can be described in two broad steps: (i) simulation of the hazardous (hydro-meteorological) event; and (ii) the computation of the resilience metric. Once the extent of flood inundation is simulated, measures of physical and socioeconomic system performance with respect to impacts of the hazard are determined.

The ResilSIM tool consists of the following major components; i) the user interface; ii) spatial database; and (iii) mathematical module.

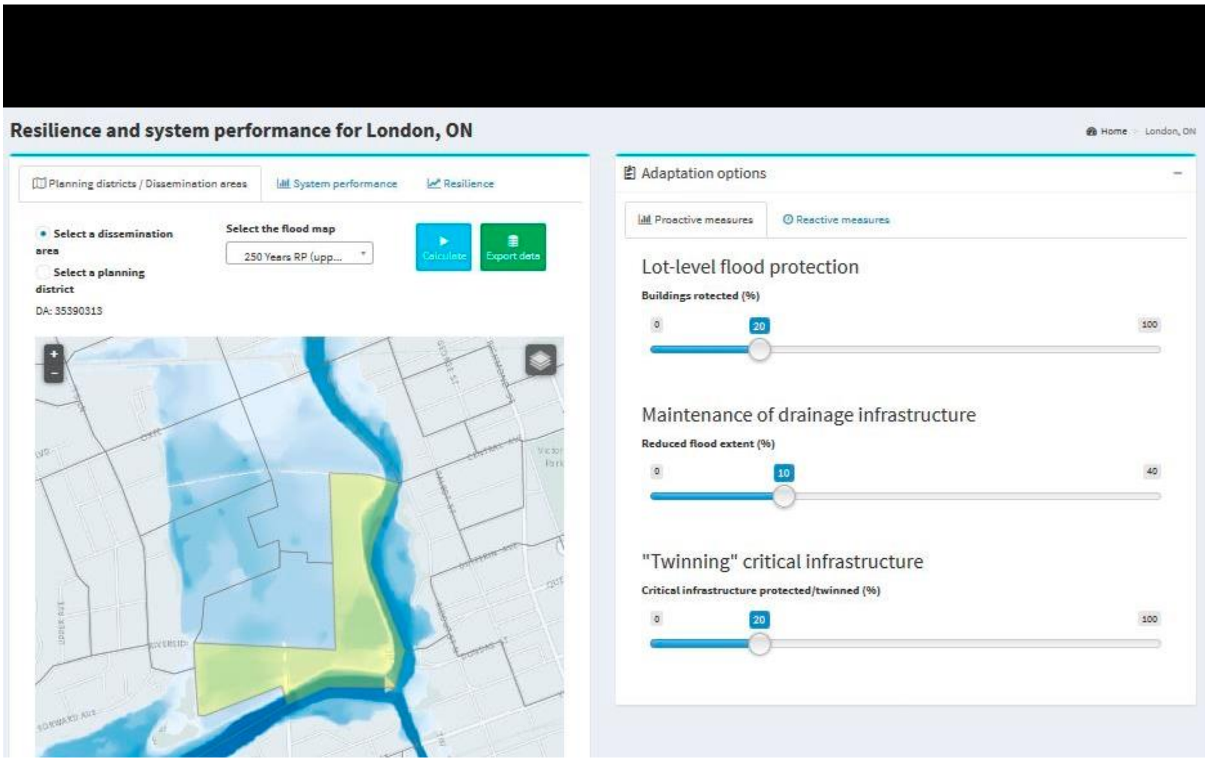


Figure 40. User Interface (Irwin et al., 2016)

Figure 40 above shows the user interface of ResilSIM as it is available to users online. The ResilSIM SD model provides a good example of how SD simulation modelling can be used to quantify resilience as a dynamic variable and allows for the computation of resilience of an urban location throughout the duration of a hazard event.

The above examples provide a brief overview of SD simulation modelling is being used in different research projects across the world and how it might be used in the EU CIRCLE project as well.

8 References:

ANDERSEN, D. F., VENNIX, J. A., RICHARDSON, G. P. & ROUWETTE, E. A. 2007. Group model building: problem structing, policy simulation and decision support. *Journal of the Operational Research Society***,** 691-694.

ARMENIA, S., ASSOGNA, P., CAVALLINI, S., D'ALESSANDRO, C., VOLPE, M., CARLINI, C. & BREIN, E. 2014. *A System Dynamics Approach for Modeling Network Resilience*.

AS/NZS 2009. AS/NZS ISO 31000 Risk Management. Standards New Zealand.

BAHADUR, PETERS, K., WILKINSON, E., PICHON, F., GRAY, K. & TANNER, T. 2015. The 3As: Tracking Resilience Across Braced,. *In:* PAPER, W. (ed.) *BRACED Knowledge Manager.* [Online] Available from: http://www.braced.org/ Accessed April 2015.

BECCARI, B. 2016. A Comparative Analysis of Disaster Risk, Vulnerability and Resilience Composite Indicators. *PLOS Currents Disasters,* 1.

BÉNÉ, GODFREY, NEWSHAM, A. & DAVIES, M. 2012. Resilience: new utopia or new tyranny? Potentials and limits of the concept of resilience in relation to vulnerability reduction programmes. Brighton: : Institute of Development Studies. .

BHAMRA, R. 2015. *Organisational Resilience: Concepts, Integration, and Practice*, CRC Press.

BIRINGER, VUGRIN, E. & WARREN, D. 2013. *Critical infrastructure system security and resiliency*, CRC press.

BOUCHON, S. 2006. The Vulnerability of interdependent Critical Infrastructures Systems: Epistemological and Conceptual State-of-the-Art. *EC Joint Research Centre Papers.* Luxemburg: Institute for the Protection and Security of the Citizen.

BRUNEAU, M., CHANG, S. E., EGUCHI, R. T., LEE, G. C., O'ROURKE, T. D., REINHORN, A. M., SHINOZUKA, M., TIERNEY, K., WALLACE, W. A. & WINTERFELDT, D. V. 2003. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra,* 19**,** 733-752.

BRUNEAU, M. & REINHORN, A. 2007. Exploring the Concept of Seismic Resilience for Acute Care Facilities. *Earthquake Spectra,* 23**,** 41-62.

CIMELLARO, G. P., REINHORN, A. M. & BRUNEAU, M. 2010. Framework for analytical quantification of disaster resilience. *Engineering Structures,* 32**,** 3639-3649.

COPPOLA, D. P. 2015. *Introduction to International Disaster Management,* Saint Louis, Saint Louis : Elsevier Science.

COUNCIL DIRECTIVE 2008. On the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. . *In:* EUROPEAN COUNCIL (ed.). Brussels: Official Journal of the European Union.

CRISADMIN 2014. Final Report. EU.

CROOPE, S. V. 2013. *Managing critical civil infrastructure systems: Improving resilience to disasters.* PhD, University of Delaware.

CUTTER, S. L., BURTON, C. G. & EMRICH, C. T. 2010. Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management,* 7.

DFID 2011. Defining Disaster Resilience: A DFID Approach. Online: Department for International Development

DHS 2013. National Infrastructure Protection Plan. United States Department of Homeland Security.

FOLKE, CARPENTER, S. R., WALKER, B., SCHEFFER, M., CHAPIN, T. & ROCKSTRÖM, J. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society,* 15.

FRANCIS, R. & BEKERA, B. 2014. A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety,* 121**,** 90-103.

GHARAJEDAGHI, J. 2012. *Systems Thinking: Managing Chaos and Complexity: A Platform for Designing Business Architecture*, Morgan Kaufmann Publishers Inc.

GILES, B. 2016. *Lasting Forests* [Online]. Available: http://ruralsystemguide.com/LastingForests/Concept1.html [Accessed 20/6/2017 2017].

GOLDSTEIN & BOBROW, D. G. 1980. A layered approach to software design Palo Alto Research Center: Xerox Corporation.

GOTANGCO, C. K., SEE, J., DALUPANG, J. P., ORTIZ, M., PORIO, E., NARISMA, G., YULO-LOYZAGA, A. & DATOR-BERCILLA, J. 2016. Quantifying resilience to flooding among households and local

government units using system dynamics: a case study in Metro Manila. *Journal of Flood Risk Management,* 9**,** 196-207.
HANANIA & G., C. 2017. Policy Brief: SMART MATURE RESILIENCE FOR MORE RESILIENT CITIES IN EUROPE. ICLEI Europe.
HOSSEINI, S., BARKER, K. & RAMIREZ-MARQUEZ, J. E. 2016. A review of definitions and measures of system resilience. *Reliability Engineering & System Safety,* 145**,** 47-61.
HOVMAND, P. 2014. *Community Based System Dynamics*, Springer Link.
HUGHES & HEALY 2014. Measuring the resilience of transport infrastructure. *Research Report 546.* NZ Transport Agency.
INAM, A., ADAMOWSKI, J., HALBE, J. & PRASHER, S. 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the Rechna Doab watershed, Pakistan. *Journal of Environmental Management,* 152**,** 251.
IRWIN, S., SCHARDONG, A., SIMONOVIC, S. & NIRUPAMA, N. 2016. ResilSIM—A Decision Support Tool for Estimating Resilience of Urban Systems. *Water,* 8**,** 377.
JOHNSON, N. F. 2009. *Simply Complexity: a clear guide to complexity theory,* Oxford, Oneworld.
KELLETT & PETERS 2014. Dare to Prepare: Taking Risk Seriously. *Working Papers.* London: ODI.
LICH, K. H., GINEXI, E. M., OSGOOD, N. D. & MABRY, P. L. 2013. A call to address complexity in prevention science research. *Prevention science,* 14**,** 279-289.
LINKOV, I., BRIDGES, T., CREUTZIG, F., DECKER, J., FOX-LENT, C., KROGER, W., LAMBERT, J. H., LEVERMANN, A., MONTREUIL, B., NATHWANI, J., NYER, R., RENN, O., SCHARTE, B., SCHEFFLER, A., SCHREURS, M. & THIEL-CLEMEN, T. 2014. Changing the resilience paradigm. *Nature Clim. Change,* 4**,** 407-409.
MAANI, K. & CAVANA, R. Y. 2007. *Systems thinking, system dynamics: Managing change and complexity*, Prentice Hall.
MABRY, P. L., MARCUS, S. E., CLARK, P. I., LEISCHOW, S. J. & MÉNDEZ, D. 2010. Systems Science: A Revolution in Public Health Policy Research. *American Journal of Public Health,* 100**,** 1161-1163.
MABRY, P. L., OLSTER, D. H., MORGAN, G. D. & ABRAMS, D. B. 2008. Interdisciplinarity and Systems Science to Improve Population Health: A View from the NIH Office of Behavioral and Social Sciences Research. *American Journal of Preventive Medicine,* 35**,** S211-S224.
MANYENA, B. 2009. *Disaster resilience in development and humanitarian interventions.* Doctoral Thesis, Northumbria University.
MCMANUS, S. T. 2008. *Organisational resilience in New Zealand.* Doctor of Philosophy, University of Canterbury.
MIN, H.-S. J., BEYELER, W., BROWN, T., SON, Y. J. & JONES, A. T. 2007. Toward modeling and simulation of critical national infrastructure interdependencies. *IIE Transactions,* 39**,** 57-71.
MURRAY, MATISZIW, T. C. & GRUBESIC, T. H. 2007. Critical network infrastructure analysis: interdiction and system flow. *Journal of Geographical Systems,* 9**,** 103-117.
OECD 2012. Disaster Risk Assessment and Risk Financing A G20 / OECD Methodological Framework Organisation for Economic Co-operation and Development.
OUYANG, M. 2014. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety,* 121**,** 43-60.
PECK, A. & SIMONOVIC, S. P. 2013. Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator. *Water Resources Research.* London, Ontario, Canada: Facility for Intelligent Decision Support.
PHILLIPS & TOMPKINS, A. 2014. Resilience Metrics for Energy Transmission and Distribution Infrastructure *Quadrennial Energy Review Technical Workshop.*: Infrastructure Assurance Center.
PRIOR, T. 2014. Measuring Critical Infrastructure Resilience: Possible Indicators, Risk and Resilience. ETH Zürich: Center for Security Studies.
RAMALINGAM, B. 2013. *Aid on the edge of chaos: rethinking international cooperation in a complex world*, Oxford University Press.
RENE, DONATELLA PASQUALINI, ALISA B, MARY EWERS, JEANNE M. FAIR & HIRSCH, G. B. 2007. A Prototype Desktop Simulator for Infrastructure Protection: An Application to Decision Support Systems. *International Conference of the System Dynamics Society.* Boston.

RINALDI, PEERENBOOM, J. P. & KELLY, T. K. 2001. Critical Infrastructure Interdependencies. *IEEE Control System Magazine*.

ROGERS, BOUCH, C. J., WILLIAMS, S., BARBER, A. R., BAKER, C. J., BRYSON, J. R., CHAPMAN, D. N., CHAPMAN, L., COAFFEE, J., JEFFERSON, I. A. & QUINN, A. D. 2012. Resistance and resilience paradigms for critical local infrastructure. *Proceedings of the Institution of Civil Engineers-Municipal Engineer* Vol. 165**,** 73-83

SHEFFI, Y. & RICE JR., J. 2005. Building the Resilient Enterprise. *MIT Sloan Review,* 47.

SIMONOVIC, S. P. 2011. *Systems Approach to Management of Disasters: Methods and Applications,* New Jersey, John Wiley & Sons, Inc.

SIMONOVIC, S. P. 2016. From Risk Management to Quantitative Disaster Resilience – A Paradigm Shift. *International Journal of Safety and Security Engineering,* 6**,** 85-95.

SRIVASTAV, R. K. & SIMONOVIC, S. P. 2014a. Generic Framework for Computation of Spatial Dynamic Resilience. *Water Resources Research Report.* London, Ontario: The University of Western Ontario.

SRIVASTAV, R. K. & SIMONOVIC, S. P. 2014b. Simulation of Dynamic Resilience: A Railway Case Study. *Water Resources Research Report.* London, Ontario: The University of Western Ontario.

STERMAN, J. 2000a. *Business dynamics: systems thinking and modeling for a complex world,* Boston, Irwin/McGraw-Hill.

STERMAN, J. 2000b. *Business dynamics: systems thinking and modeling for a complex world,* Boston, Irwin/McGraw-Hill.

STERMAN, J. D. 2006. Learning from evidence in a complex world. *American journal of public health,* 96**,** 505-514.

TURNQUIST & VUGRIN, E. 2013. Design for resilience in infrastructure distribution networks. *Environment Systems & Decisions,* 33**,** 104-120.

TWIGG, J. 2009. Characteristics of a disaster-resilient community: a guidance note. *Disaster Risk Reduction Interagency Coordination Group.* DFID.

TYLER, S., NUGRAHA, E., NGUYEN, H. K., NGUYEN, N. V., SARI, A. D., THINPANGA, P., TRAN, T. T., VERMA, S. S., SWANSON, D. & BIZIKOVA, L. 2014. Developing indicators of urban climate resilience. *Climate Resilience Working Paper No. 2.* Boulder, CO: Institute for Social and Environmental Transition-International.

UNISDR. 2009. *Terminology [Online]* [Online]. UNISDR. Available: http://www.unisdr.org/we/inform/terminology [Accessed 8 August 2017].

WISNER, B., BLAIKIE, P., CANNON, T. & & DAVIS, I. 2004. *At Risk: Natural Hazards, People's Vulnerability and Disasters.*, Routledge.

ZIO & AND KROGER, W. 2009. Vulnerability assessment of critical infrastructures. *IEEE Reliability Society.,* Annual Technology Report**,** 186.