Critical Infrastructure Resilience in the PRECINCT Project

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ABSTRACT: The PRECINCT project brings together Critical Infrastructure owners and authorities from four "Living Lab" cities throughout Europe. These Living Labs then operate as a coordinated precinct responding to the various cyber-physical threats to which they are exposed. This paper describes the combined cascading effects / interdependency tool developed in the project to calculate the resilience of interconnected infrastructures. Serious Game play is simulated through stakeholder workshops which illustrate how the interdependency graph can be deployed for both training and as a tool to gather further information on threats and interconnections in the infrastructure.

1. INTRODUCTION

Enhanced connectivity and population growth has brought the issue of Critical Infrastructure protection to the forefront of research and governance in recent years. While Critical Infrastructure has always been at risk to Cyber Physical Hazards, compounding issues of aging infrastructure, climate change and deliberate attack has highlighted the need for a unified approach to quantifying the resilience of our infrastructure networks. Only by doing this can we effectively plan to put in place mitigation and adaptation measures to combat the myriad of threats to which infrastructure networks are exposed. The Horizon Europe funded PRECINCT project (www.precinct.info) commenced in 2021 in an effort to combat this issue. The project aims to connect private and public CI stakeholders in a geographical area to a common cyber-physical security management approach which will yield a protected territory for citizens and infrastructures, a 'PRECINCT' that can be replicated efficiently.

PRECINCT delivered a Resilience Methodological Framework (RMF) which allows calculation of the resilience index based upon the services provided by the infrastructure system. The framework was based on pre-standardisation on the topic, which quantifies resilience in terms of the service offered by the infrastructure system (CEN, 2021). The RMF is presented as a series of logical steps which describe the calculation of resilience based on indicators which can be enhanced through investment. Calculation of resilience of interdependent yet distinct systems is a complex issue. In PRECINCT, the RMF was programmed within a Cascading Effects Simulation (CES) which estimates the impact of various cyber-physical hazards on the infrastructure. It provides the probability of occurrence of states representing functionality or availability, indicating associated service losses, in turn lowering the resilience index.

This paper describes the CES tool and combined formulation of resilience. PRECINCT will later make these tools available within a serious game platform in order to provide training in the resilience concept to key stakeholders. This paper will also describe a demo application of the tool in a mock serious game application conducted through a stakeholder workshop.

2. COMBINED CASCADING EFFECTS SIMULATION AND RESILIENCE ANALYSIS

The CES uses a directed interdependency graph to describe the involved CIs (or relevant parts of it) and how they depend on one another in the sense that limitations in one CI may affect the other. Each node of the interdependency graph has a state that describes its functionality or availability, ranging from 1 (best) to 5 (worst). This state may change after an incident, natural hazard or intentional attack. Due to the high complexity in CI networks, these state changes are modelled through a stochastic transition matrix (König et al. 2019). In case of a state change, a notification is sent to all neighbours, and they may react on it as well. This mimics how the effects cascade through the entire network. Such simulations allow investigation of systems that cannot be tested in real life (Schauer et al. 2022).

In the early days of PRECINCT, it became clear that assessing the resilience of interdependent Critical Infrastructures (CIs) and simulation of cascading effects in a CI network are related tasks. This section gives the main idea of how the RFM and CES can benefit from one another. Further details can be found in (König et al. 2022). The interplay between RMF and CES is visualized in Figure 1.

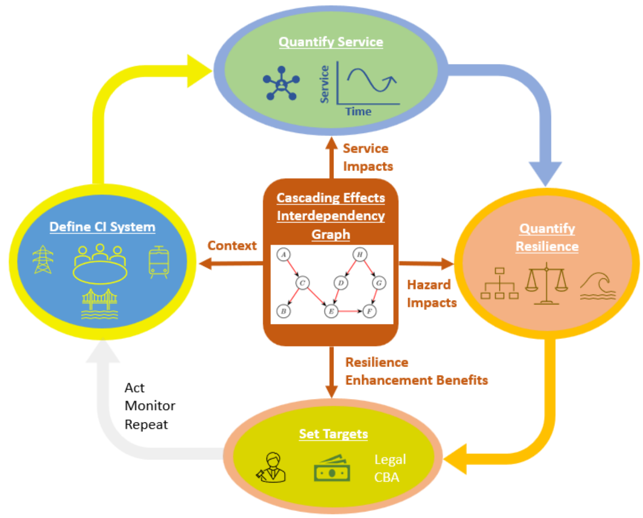

Figure 1: Interplay between RMF and CES (König et al. 2022)

1) **Integration of simulation results in the resilience framework**
   The CES provides an estimation of direct and indirect consequences of an incident, which is useful information that can be integrated in the RMF. The interdependency graph provides the context and supports quantification of services as well as the relative impact of each indicator. Finally, the simulation results support setting resilience targets by estimating the resulting state of relevant nodes.
2) **Refinement of the CES based on resilience**
   Knowledge about resilience of one or several nodes allows a more fine-grated simulation. The reaction of a node to a threat may now depend on the resilience indicator, i.e., the transition matrix is replaced by several transition matrices - one for each possible value of the resilience indicator. While this enables a more detailed simulation it of course has its price: the parametrization effort increases. Since resilience indicators usually only take a few values, parametrization is still feasible in most situations (König and Shaaban 2022).

The existing CES tool has been further developed to capture both points (AIT 2023). On the one hand, quantities such as service measures and service losses are integrated in the tool to compute the resilience of the network based on the simulation results. On the other hand, the state transition probabilities for a node may now depend on the value of a resilience indicator. Figure 2 shows the transitions for the node 'Tunnel' (as depicted in Figure 3) depending on the value of the resilience indicator of the tunnel.

This extended CES allows comparison of different resilience settings, i.e., how the impact of an incident changes for different values of the resilience indicators.

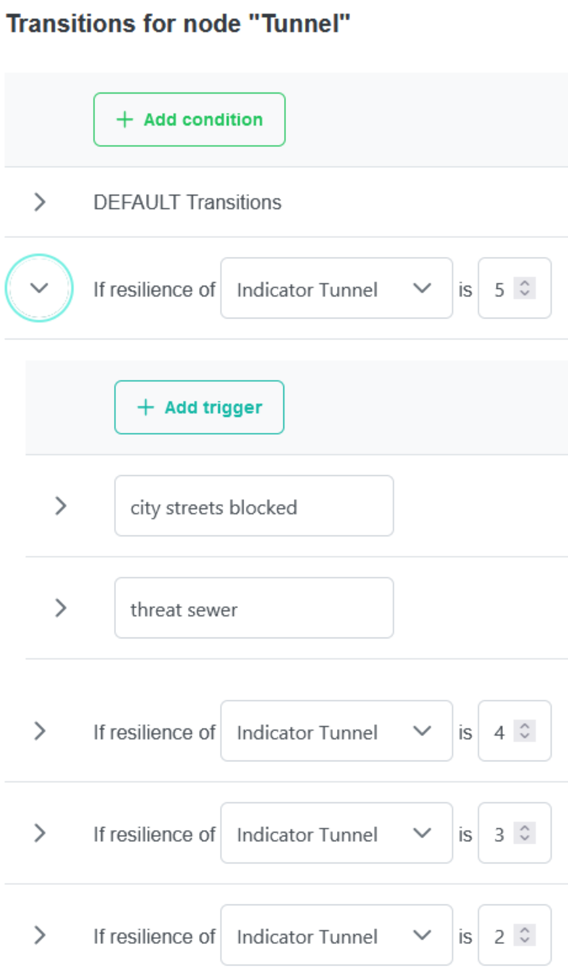

Figure 2: Transitions depend on value of indicator node

3. SAMPLE APPLICATION IN LIVING LAB

PRECINCT has applied the combined Cascading Effects Simulation and resilience framework to a concrete use case. The graph in Figure 3 illustrates the interdependencies in a notional CI system within a city PRECINCT that is exposed to a flooding hazard. The flood event can impact the PRECINCT's citizens (e.g., people), energy infrastructure (e.g., power generation node), transport infrastructure (e.g., city centre streets) and the water infrastructure (e.g., raw water node), with indirect impacts on various other CIs including tunnels and roads in / out of the city, telecommunications, sewer systems and power networks which impact nursing, childcare and hospitals. There are also various emergency services which impact the response to the flood event.

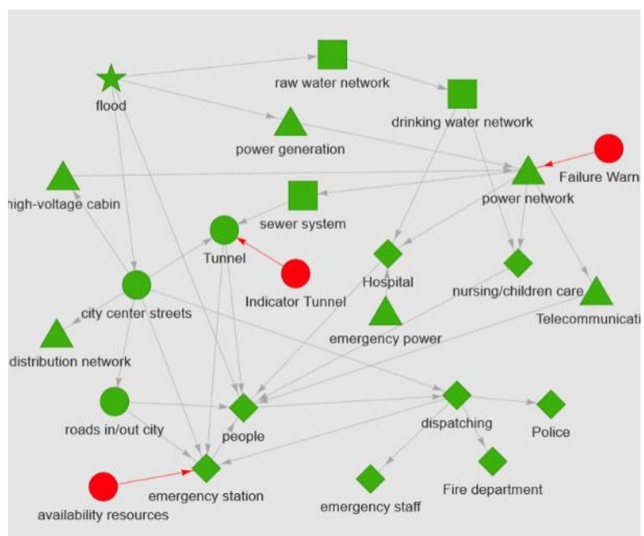

Figure 3: Interdependency graph with 3 resilience indicators nodes

The nodes 'Indicator Tunnel', 'availability resources' and 'Failure Warning' are indicator nodes that influence the reaction of the nodes 'Tunnel', 'emergency station' and 'power network', correspondingly. Indicator nodes are coloured in red to represent the current situation. The resilience of these nodes can be improved by investment and the colour of the node is then adapted according to the level of improvement. The following section describes how this resilience calculation can be considered within the CES as part of a serious game to make decisions in relation to resilience enhancements.

4. IMPLEMENTATION AS SERIOUS GAME

Within the Serious Game, learning manuals are provided that describe how the cascading effects and resilience are calculated. It is important for the game players to be able to understand the basic concepts of resilience and cascading effects to help them interpret and understand gameplay results, but also decide on the best gameplay strategies.

The services by which resilience is measured are defined using expert opinion (resilience experts and LL participants). While various measures are possible (e.g., transport delays, power availability or water availability), the only service measure considered in this example are the safety of people. This service measure is modelled by the "people" node, which is impacted by the states of the tunnel node, roads in/out of city, nursing / childcare, hospitals, and emergency services. Worsening the state of these nodes will change the state of the "people" node, which in turn results in loss to life or limb. The total service considered to be provided by the CI is therefore the value of safe use of the entire system by all users within one day, which is quantified as €39 million for this flooding example. The expected losses in terms of death or injury then reduces this service. The Resilience Index (RI) is calculated based on the original Service Value (SV) and the Service Losses due to the hazards (SL) by:

$$RI = \frac{SV - SL}{SV} \tag{1}$$

Indicators are modelled in Figure 3, illustrated by the red nodes. These include (road) tunnel flood protection measures, electricity failure warning systems and availability of resources for emergency response. These resilience indicator nodes can take various states which change the probabilities of subsequent nodes reaching more severe states. For example, the indicator for tunnel flood protection may take any of 1-5 states, with 5 being the worst state and constituting no flood protection measures, and 1 being the best state constituting full tunnel resistance to the considered flood. There is a certain cost associated with enhancing the state of each indicator value, and this has a certain impact on the outcome probabilities of the "People" node.

An application of this example in the context of gameplay was provided at the second PRECINCT stakeholder workshop. Initially, each indicator was assumed to be in its worst state. For this example, losses are calculated for the people node, associated with loss of life and limb for the people node changing state following a flood event. It should be noted that various methods are available for valuing services such as loss of life. The estimation of monetary values should as far as possible be related to published values, which may be often found in codes, or collected using one or more valuation techniques, such as hedonic pricing (Kask and Maani, 1992). The cascading effects and interdependency graph calculates the probability of each of these states given the triggering flood event (e.g. different severity of floods have different return periods and intensity). From this, the expected value of the losses is calculated as shown in Table 1. The number of injuries or fatalities associated with each potential state within the "people" node are estimated (5 being the worst possible state). The average value of an injury or fatality is used to calculate the service value losses associated with each state. These are then multiplied by the outcome probabilities for each state, and summed to calculate the expected value.

Table 1: Expected Value of Losses in "People" node

State	No. Injuries / fatalities	Service Value (millions)	Prob	Value (millions)
1	0	€0	0.2	€0.0
2	10	€1	0.7	€0.7
3	1000	€100	0.1	€10
4	10000	€1,000	$1x10^{-4}$	€0.1
5	20000	€2,000	$1x10^{-5}$	€0.02

Expected value	**€10.82**

The considered losses of €10.8 million correspond to a Resilience Index of 0.72 for the "do nothing" or baseline scenario example as per Equation 1, Resilience Index = (39m-10.8m)/39m = 0.72. A Resilience Index of 1.0 would mean no losses resulting from a flooding event in this example.

The indicators have several possible states. Each indicator is initially assumed to be in its worst (highest) state. Table 2 illustrates what each indicator state might mean for the "Availability of emergency resources" node. Since each node is initially in its worst state, we can see that this means there are only 20 voluntary emergency staff available. Investment in emergency resources would then allow us to hire more staff and move toward the best state (State 1), with 100 trained emergency staff.

Table 2: Indicator state description

Indicator Value	Meaning
4	20 voluntary emergency staff
3	10 trained emergency staff & 20 voluntary emergency staff
2	40 trained emergency staff
1	100 trained emergency staff

The cost of enhancing each indicator is illustrated in the righthand most column in Table 3 ('Cost to achieve indicator state from the worst state). Assigning a budget for enhancements of €2 million, a list of 21 affordable maintenance strategies was enumerated. For each of these strategies, the resilience index was calculated.

Table 3: Indicator costs for theoretical example

Indicator	Possible values	Cost to achieve indicator state from max state
Condition of Tunnel flood protection measures	5	N/A
	4	€100,000
	3	€500,000
	2	€1,500,000
	1	€3,000,000
	3	N/A
Presence of Electricity failure Warning Systems	2	€100,000
	1	€1,000,000
Availability of emergency resources (Number of emergency staff)	4	N/A
	3	€500,000
	2	€1,800,000
	1	€4,050,000

In order to make decisions on optimum enhancement strategies, information is needed relating to not only how resilient the new CI is, but also, whether the strategy used will be the optimum from an investment perspective. For this reason, the Return on Investment (ROI) was also introduced for the proposed workshop and shown in Eq. 2. The ROI is defined by comparing the service value before investment (referred to as Stage 0) to the service value after the investment (referred to as Stage 1) as follows:

$$\mathrm{ROI} = \frac{(V_S^1 - V_S^0) + (V_{RS}^1 - V_{RS}^0)}{V_{CIP}^1 + V_{CInv}^1} \qquad (2)$$

where,

V_s = Value of service
V_{RS} = Value of Resilient service (services after losses due to hazard)
V_{CIP} = investment in infrastructure (no change in service).
V_{CInv} = investment in infrastructure (with change in service).

Consideration of the ROI allows stakeholders to consider not only resilience, but also value, as presented in Figure 6. The ROI was calculated for each potential maintenance scenario. During the stakeholder workshop, gameplay was simulated using interactive stakeholder surveys and engagement. Stakeholders were presented with the relative impact of each indicator, as well as an overview of the dependency model. They were then asked to engage with the process by selecting which indicators were important, as well as which strategies they would select. The selected strategies are presented in Figure 4.

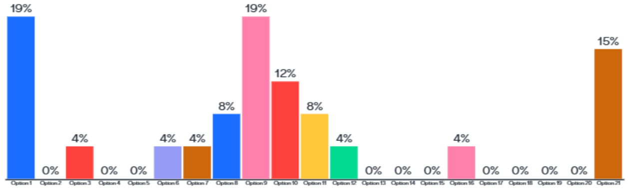

Figure 4: Resilience Enhancement Strategies selected by stakeholders during mock game play

Workshop stakeholders were presented with "good" strategies in terms of both resilience index enhancement and ROI, as well as an overview of the associated interdependency graph impacts in order to clarify why these strategies made sense. Strategies which appeared to produce bad results were also demonstrated. An example of a strategy (refer to Table 4) which produced a high ROI was Option 3, which is presented on the interdependency graph in Figure 5. In Option 3 strategy, only the "Failure Warning" indicator was enhanced by one level (to Level 2). This has a low cost of €100,000, and an increase in the resilience index to 0.84 from a baseline of 0.72. While the resulting ROI was extremely high (44.8), the increase in resilience index is not significant. The exercise of optimising resilience and ROI would ultimately depend on stakeholder priorities, availability of resources, etc.

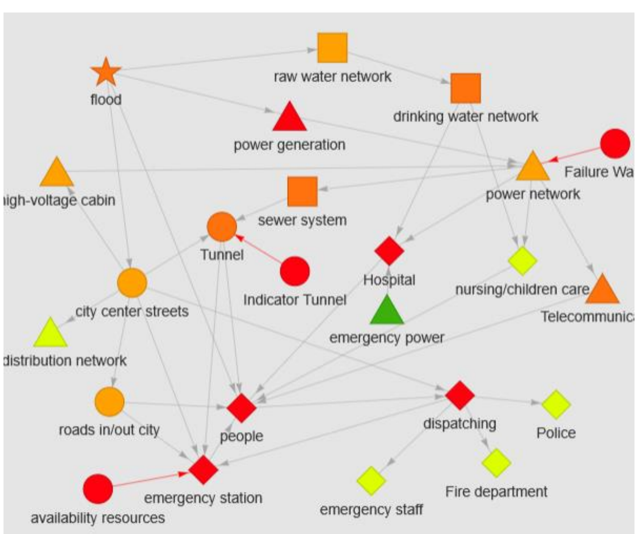

Figure 5: Interdependency graph with resilience indicators for Option 3 strategy that produced the best ROI

It is also important for decision makers and investors to be able to understand and interpret the relationship between return on investment and resilience (Bruneau et al., 2003). This relationship is broadly presented in Figure 6. Game players might expect that resilience enhancing interventions always make good economic sense (i.e. good return on investment), but this is not always the case. Figure 6 shows the resilience index and return on investment plotted for various strategies. Game players would clearly wish to avoid strategies in the red zone i.e. low improvement in resilience for low return on investment. Additionally, strategies in the two yellow zones are also not advisable e.g. low resilience improvement and medium-large return on investment. Based on the overall scheme of the possible strategies, there are strategies in the green zone which can be quickly identified as important i.e., high resilience and high return on investment.

Figure 6: Resilience and ROI correlation and strategy comparisons

Table 4: Affordable strategies for indicator enhancement

No.	Indicator 1: Tunnel Flood protection	Indicator 2: Electricity Failure Warning	Indicator 3: Emergency resources	Cost of Scenario (millions)
1	5	3	3	€0.5
2	5	3	2	€1.8
3	5	2	4	€0.1

No.	Indicator 1: Tunnel Flood protection	Indicator 2: Electricity Failure Warning	Indicator 3: Emergency resources	Cost of Scenario (millions)
4	5	2	3	€0.6
5	5	2	2	€1.9
6	5	1	4	€1.0
7	5	1	3	€1.5
8	4	3	4	€0.1
9	4	3	3	€0.6
10	4	3	2	€1.9
11	4	2	4	€2.0
12	4	2	3	€0.7
13	4	1	4	€1.1
14	4	1	3	€1.6
15	3	3	4	€0.5
16	3	3	3	€1.0
17	3	2	4	€0.6
18	3	2	3	€1.1
19	3	1	4	€1.5
20	2	3	4	€1.5
21	2	2	4	€1.6

5. CONCLUSIONS

This paper demonstrates the Resilience Methodological Framework (RMF) developed in the PRECINCT project which is formulated with a Cascading Effects Simulation (CES). The framework and simulation provide functionality to users to investigate the impacts of resilience enhancements in order to make decisions for cyber-physical threat mitigation.

The methodology was demonstrated in a serious game setting within a stakeholder workshop where stakeholders were educated on potential investment strategies, previously unforeseen interdependencies resulting in service losses, and metrics to concurrently evaluate resilience and value (Return on Investment). The RMF and CES will be further developed before project completion, demonstrating the methodology for a further three Living Labs and implementing the calculation within a serious game tool supported by bespoke Digital Twins

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