Critical Infrastructures Resilience: A Guide for Building Indicator Systems

Based on a Multi-Criteria Framework with a Focus on Implementable Actions

Zhuyu Yang[1,2], Bruno Barroca[1], Ahmed Mebarki[3,4], Katia Laffréchine[1], Hélène Dolidon[5], Lionel Lilas[6]

[1]Lab'urba, Université Gustave Eiffel, Champs-sur-Marne, 77420, France

[2]LATTS, UMR CNRS 8134 Universit´e Gustave Eiffel/Ecole des Ponts ParisTech, Marne la Vallee, France

[3] University Gustave Eiffel, UPEC, CNRS, Laboratory Multi Scale and Simulation (MSME/UMR 8208), 77454 Marne-la-Vallée, France

[4]Nanjing Tech University (China), Permanent Guest Professor within "High-Level Foreign Talents Program" grant

[5]CEREMA, Nantes, France

[6]DIR Ouest (DIRO), Nantes, France

Correspondence to: Zhuyu Yang (zhuyu.yang@univ-eiffel.fr)

Abstract. Criteria and indicators are frequently used for assessing the resilience of Critical Infrastructures (CIs). Moreover, to generate precise information on conditions, the assessment designed for CIs resilience could rely on indicator systems. However, few practical tools exist for guiding CIs managers to build specific indicator systems in considering real cases. Therefore, the main objective of this study is to develop a step-by-step guide that contains guidance on operational steps and required resources for Criteria & Indicators setting, references definition, and data collection. This guide enables CIs managers to build systems of indicators tailored to different real cases. This guide could assist CIs managers in their decision-making process, as it is structured based on a multi-criteria framework that takes into account the cost-benefits and side effects of implementable actions. This guide could furthermore advance the application of indicator-based CIs resilience assessment in practical management. In addition, this study provides an example to demonstrate how to use this guide. This example is based on a given circumstance~~scenario~~ for the Nantes Ring Road (NRR) network: when the ring road is flooded and closed, the road network manager suggests alternative roads to the public. An indicator system, consisting of 4 criteria, 7 sub-criteria and 11 indicators, could be built for this circumstance~~scenario~~ through the developed guide. This example relates to criteria and indicators in technical, social, and environmental dimensions, and involves 62,676 data.

1 Introduction

The research for Critical Infrastructures (CIs) goes across disciplines, sectors, and scales, as the disruption or destruction of CIs would have a significant cross-border impact on human society. However, CIs might be vulnerable to natural and technological hazards worldwide. The concept of “Resilience”, presented as an inherent attribute of a system addressing external hazards, is developing rapidly in the field of CIs management. In addition, resilience assessments have become an important issue for CIs management. Thus, resilience assessments have~~s~~ to address the drop in~~of~~ capacities as well as the recovery, which depend not only on the availability of resources but also on their adequate management (Resilience Alliance). Moreover, the assessment of CIs resilience is frequently based on indicators (Hosseini et al., 2016; Mebarki, 2017; Cantelmi et al., 2021). Indicator-based resilience assessment could be simply considered as a process in which resilience values are derived from indicators. Furthermore, the indicator values could be obtained by reliable data.

To generate increasingly precise information on conditions, the assessment designed for a complex system could rely on indicator systems, because a single indicator can rarely provide useful information. An indicator system should contain numerous specific indicators that are associated with concrete conditions, requirements, or situations. These specific indicators could not be set without consideration of the realities of each particular studied case. Thus, it necessitates practical tools that enable CIs managers to set their specific indicator system tailored for their particular case study, without providing directly pre-defined indicators. As argued by Shavelson et al. (1991) “no indicator system could accommodate all of the potential indicators identified by a comprehensive process and remain manageable”. A desirable hazard-related indicators tool should be simple and flexible, adapting itself to different case studies and different kinds of users (Barroca et al. 2006). Even though existing CIs resilience assessments by indicators are diverse and multidisciplinary, few tools exist for guiding CIs managers to build specific indicator systems tailored to real cases. For example, Yang et al. (2023, a) review 68 scientific papers relating to indicators-based assessments for CIs resilience. Several papers reviewed by Yang et al. (2023, a) present assessments based on a large number of systemic indicators: Fisher et al. (2010), Martin and Ludek (2012), Petit et al. (2013), Bialas (2016), Upadhyaya et al. (2018), De Vivo et al. (2022). However, all these papers directly list the set of indicators but without describing the detailed steps to set them. Moreover, the review of Yang et al. (2023, a) shows that many studies about CIs resilience criteria setting have focused on the damages to CIs or CIs capabilities related to resilience, but have overlooked the fact: the benefits, costs or impacts of implementable actions for every CIs manager are critical. The lack of discussion and consensus about the effects of implementable actions causes the application difficulties of CIs resilience assessment in practical management. Therefore, as a contribution to fill the gap, the present study aims to provide a guide for CIs managers to enable them to build specific indicator systems tailored ~~for~~ to their specific case studies. This developed guide considers not only damages to CIs and CIs capabilities, but also different factors of implementable actions.

To achieve the objectives of this study, an immediate question is: which achievements should the developed guide assist the user in accomplishing? Another fundamental question necessitates deliberation: what should the developed guide contain to enable users to reach these achievements? For the first question, according to many studies focusing on indicator systems building (Lammerts Van Bueren and Blom, 1997; Vogel, 1997; Prabhu et al., 1999; Mendoza and Prabhu, 2000), the setting of Criteria & Indicators (C&I), and the collection of data are considered basic (Cutter, 2016; CORDIS-Smart Resilience Indicators for Smart Critical Infrastructures, 2018; Balaei et al., 2018). In particular, the criteria and indicators adapted to real cases are the key for CIs managers to apply indicator systems to practical management (Yang et al., 2023, b). For the second question, practical guides should include guidance on operational steps, required resources, as well as advice~~s~~ for finding required resources. Therefore, the developed guide should contain operational steps and resources finding advice~~s~~ that help CIs managers ~~to~~ set specific Criteria & Indicators and ~~to~~ collect data. Furthermore, for the indicator system to be applied in practical management, the developed guide in this study should consider the benefits, costs or impacts of implementable actions. This present study assumes that the developed guide can help CIs managers build indicator systems and attempts to illustrate its use and usage through an example.

2 Research Method and Structure

Based on the presented research objectives and questions, this research could start with a presentation of the three basic key factors (criterion, indicator and data). Then, the main research work is designing the steps for C&I setting and data collection (Fig. 1). Moreover, for these steps to be better operational in practice, the steps designed in this guide should be clearly described and preferably with the support of schematic diagrams.

Fig. 1. Methodology and structure of the present study, created by authors.

In the second part, this study applies the designed steps to a French critical infrastructure to build an indicator system that can assess resilience during urban flooding (Fig. 21). The example focuses on the Nantes Ring Road (NRR) network, the investigation of which was assisted by a local management organisation, Direction interdépartementale des routes Ouest (DIRO) that is in charge of the road networks of Nantes City in France. This example involves 62,676 traffic flow data from DIRO, and over 15,000 road infrastructure data from French National Geographic Institute (IGN).

The present paper is divided into several sections. Section 3 will (Fig. 21) develop a step-by-step guide that enables CIs managers to build building indicator systems for their particular studied cases. Section 4 (Fig. 21) will illustrate how to use this developed guide to build an indicators system through an example focusing on Nantes Ring Road. Section 5 discusses the contributions, and limitations of this guide, and shows an assessment process (including resilience and indicator assessment phases in Fig.1) in applying the indicator system built in section 4.

3 Part 1: Guide's Steps Designing

3.1 Specific criteria setting

Suitable indicators should be set based on rational assessment criteria, which could be determined through studied goal phenomena, aspects and observed factors (Maggino, 2017). Criteria are characters or signs, which make it possible to distinguish a thing, or a concept, to make a judgment of appreciation. Each indicator is associated with a criterion, whereas a criterion is associated with one or more indicators. Criteria could be considered as the points, to which the information provided by indicators can be integrated, and where an interpretable assessment crystallises. To make judgments, different levels of each criterion are generally designed to show what is achieved, how much is accomplished, and to what extent. In the field of CIs, stakeholders or managers define frequently the function of studied infrastructures as a criterion. For instance, more than one indicator could assess the function level of a road infrastructure: number of passing vehicles, vehicle speed, or types of vehicles accepted (Fig. 2, Example).

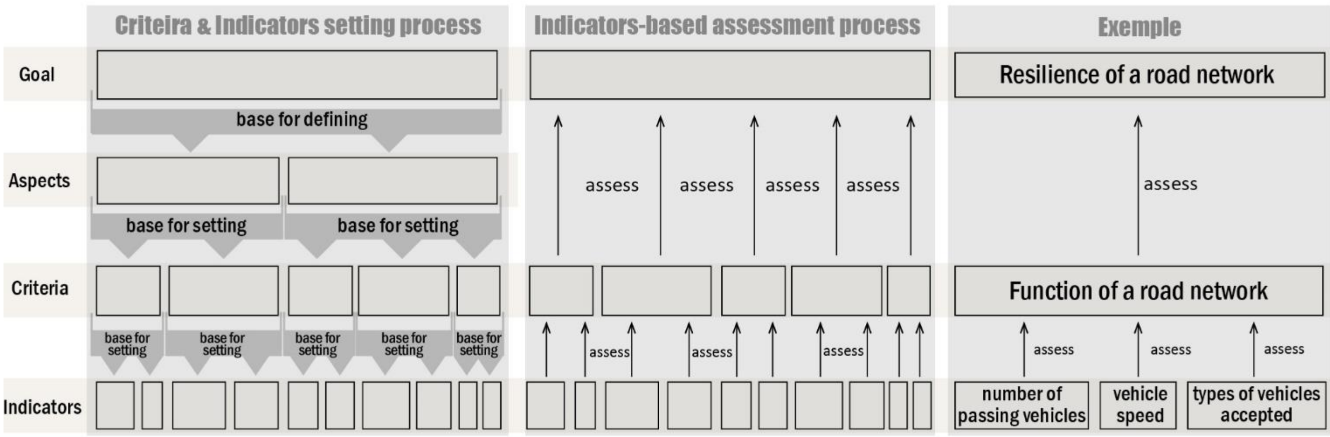


Fig. 2. A hierarchical structure in multi-criteria approaches for C&I-based assessment, adjusted from Yang et al. (2023, b).

Assessments consisting of Criteria & Indicators (C&I) could provide a commonly agreed framework for articulating and defining expectations. There is a hierarchical structure for C&I based assessments (Fig. ~~3~~2), firstly developed for forest sustainability assessment (Prabhu et al.,1996; Lammerts Van Bueren and Blom, 1997; Mendoza and Prabhu, 2000), today is also used in other disciplines (Montaño et al., 2006; Van Cauwenbergh et al., 2007; Koschke et al., 2012; Feiz and Ammenberg, 2017). This hierarchical structure is a common framework, in which a higher-level “goal” is divided into aspects or themes, which are in turn divided into criteria each with several indicators (Maggino, 2017). Criteria and indicators (Fig. 2, Criteria & Indicators setting process) are set from “goal” to “indicator”. ~~The assessment process (Fig3. Indicators-based assessment process) is from "indicators" to "goals", but criteria and indicators (Fig3. Criteria & Indicators setting process) are set in the opposite direction.~~ This means that the criteria and indicators are set based on certain important aspects of the assessed goal. Important aspects, in turn, are identified in terms of the definition and phenomenon of the assessed goal (Eurostat, 2014; Maggino, 2017). The aspects of the assessed goal may not be necessary for the assessment process, but they are important for criteria setting. In practical management, the criteria vary between different contexts. The designed criteria-setting steps in the present paper should enable managers to set specific criteria for adapting to different real cases. In contrast to the “Criteria & Indicators setting process”, the assessment process (Fig. 2, Indicators-based assessment process) based on an indicator system transforms indicators into criteria levels, and from criteria levels derive the resilience value.

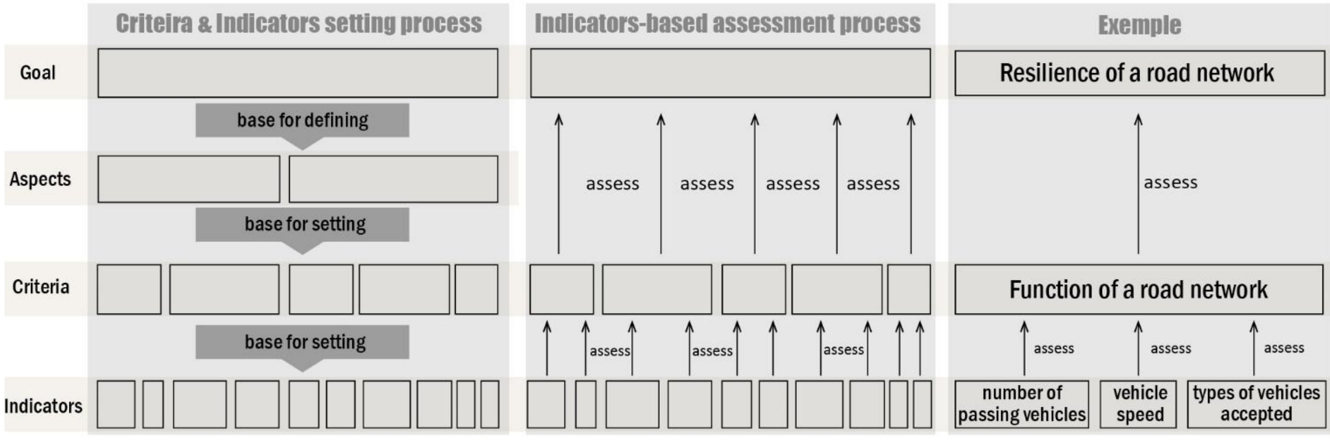


Fig. 3. A hierarchical structure in multi-criteria approaches for C&I-based assessment, adjusted from Yang et al. (2023, b).

The integration of implementable action into assessment criteria is one of the keys to resilience assessment application in practical management (Yang et al., 2023, b). One of the objectives of CIs resilience studies is to help CIs managers find more sustainable and efficient measures or actions to practically deal with increased hazards. A resilient critical infrastructure (CI) should involve diverse implementable actions to improve its different capabilities (Barroca and Serre, 2013). Implementable actions refer to all possible operations that could be taken for optimising CIs resilience, like programs, strategies, projects, measures, or practices for both temporary (short-term) and permanent preventive (long-term) management. Meanwhile, implementable actions aiming at one CI potentially bring unexpected negative effects to itself or externally to its environment, like side effects or over-budget expenses. Therefore, an effective assessment should provide CIs managers with information on the both positive and negative effects of implementable actions. Thinking about the spatial and temporal impacts of implementable actions, across urban systems, helps enhance beneficial strategies and suppress dangerous ones.

To meet the requirements (specific criteria and consideration of implementable actions) mentioned above, the Multi-Criteria Framework (MCF) developed by Yang et al. (2023, b) is deployed for criteria setting. This MCF aims at criteria setting for CIs resilience. Through an analysis of the definition, phenomena, of the concept of CIs resilience, this MCF defined two aspects and four associated general criteria:

- Consequence aspect: “damage to internal components”
- Actions aspect: “effectiveness of action”, “efforts for action” and “damage of actions” (also associated with consequence aspect).

These criteria consider direct damage to CIs -and both the cost-benefit and side effects of implementable actions. -In addition, this MCF contains a guide to set specific sub-criteria inferior to the four general criteria, for different real cases. The consideration of Yang et al. (2023, b) of implementable actions and specific criteria correspond to the objective of the present study.

According to this MCF, the setting of specific criteria requires an investigation for every component of the CI under study. Consideration should also be given to the functions of studied CI and its components, as well as the efforts required for implementable actions. The specific criteria setting is particular, tailored to real cases, and meets the commands, requirements or conditions of relevant stakeholders. The importance of criteria may vary between different contexts. Thus, this MCF requires first defining a studied scenario in which a target CI is affected by a hazard. Four factors in the studied scenario should be defined (Fig. 43):

- The “affected system” is a target CI. The resilience of a CI relates to its expected function or services derived by the system of this CI.
- The “hazard” is one hazard causing negative effects on the target CI, in particular to its function and service;
- The “consequence” refers to the negative effects (damage) on the target CI due to the hazard;
- The “action” is one or more implementable actions for improving the resilience of the target CI.

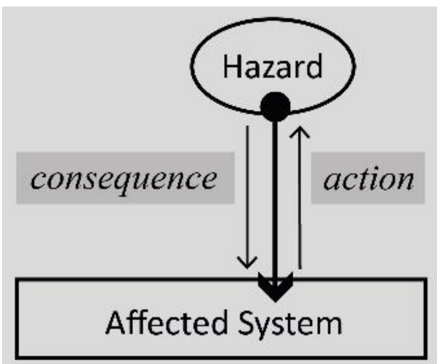


Fig. 43. Conceptual scenario of resilience, source: Yang et al. (2021).

After the definition of the four factors in the analysed scenario, the criteria setting process involves two focuses: direct and indirect damages; and costs-benefits of actions.

3.1.1 Direct and indirect damages

The determination of significant damages is related to two criteria: “damage to internal components” and “damage of actions”. Significant damages could be determined based on Form 1 introduced by Yang et al. (2023, b) (Fig. 54). This Form 1 can be considered as a process of setting specific sub-criteria under these two damage damage-related criteria. According to Form 1, once the target CI (Fig. 54,. Affected system) has been defined, its functions and three categories of components should be identified: collective human components, individual human components, and physical non-human components. After that, the damage of the elements considered important should be set as a sub-criterion of resilience assessment.

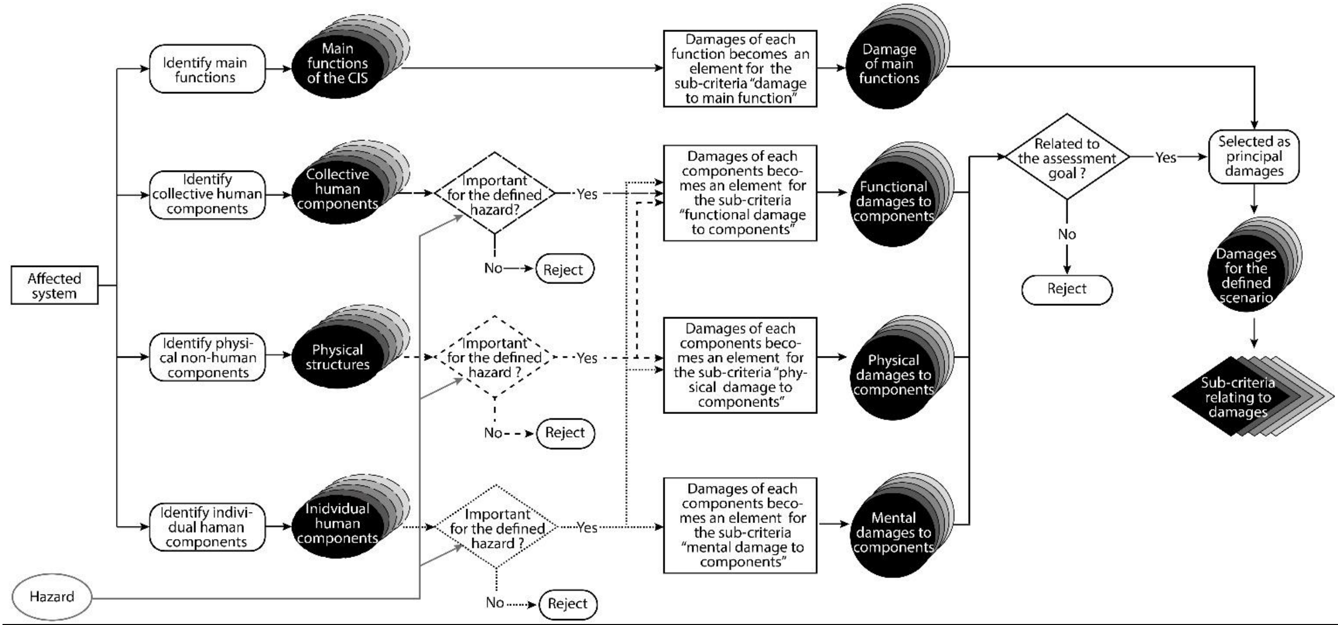


Fig. ~~5~~4. Form 1 for setting sub-criteria of "Damage to internal components" and "Damage of action" criteria, source: Yang et al. (2023, b).

It is worth noting that the "Damage of action" criterion requires defining new scenarios, in which the defined implementable action causes side effects. Side effects can be damage to the target CI, or damage to the environment of the target CI. Thus, the process of Form 1 could be repeated, when the side effects of implementable actions act on one infrastructure (the target infrastructure or another one). In the new scenarios, "Hazard" refers to the defined implementable action that causes side effects. The "Affected System" in 'Form 1' refers to the target CI or its environment that suffered side effects.

3.1.2 Effectiveness and efforts of actions

The second focus is on the sub-criteria related to the "action" aspect. Before setting relevant sub-criteria, an implementable action needs to be defined. The identification of implementable actions in the present study is based on the "Behind the Barriers" model (BB model), developed by Barroca and Serre (2013), which allows effective and comprehensive development of infrastructural system resilience by considering the interdependencies in various urban scales. The applications of the "Behind the Barriers" model to action identification have been presented in several studies (Gonzva, 2017; Gonzva et Barroca, 2017; Yang et al., 2022; Barroca et al., 2023). BB model argues that the actions for improving capabilities could be described in four dimensions:

1) A cognitive dimension refers to knowledge, awareness, and the identification of resilience by the persons concerned;

2) A functional dimension specific to material objects and technical urban systems forming the territory;

3) A correlative dimension that recognizes that service and utilisation form a whole whose different sections are interconnected together;

4) An organisational dimension that raises the question of the persons involved (public and private players, populations, etc.) and the territorial strategies that contribute to improving resilience

Next, the defined implementable actions allow~~s~~ for describing the desired outcome, which is then treated as a sub-criterion of the 'effectiveness of action' criterion. By investigating the components (function, collective human components, individual human components and physical non-human components) related to the defined actions, it is possible to determine the costs of the defined actions in terms of four dimensions: functional, environmental, economic and human or material resources. The costs of the defined actions are considered as sub-criteria of the 'Effectiveness of actions' criterion. The process of sub-criteria setting is presented in Form 2 (Fig. ~~6~~5) and the details ~~could~~ can be found in the paper of Yang et al. (2023, b)

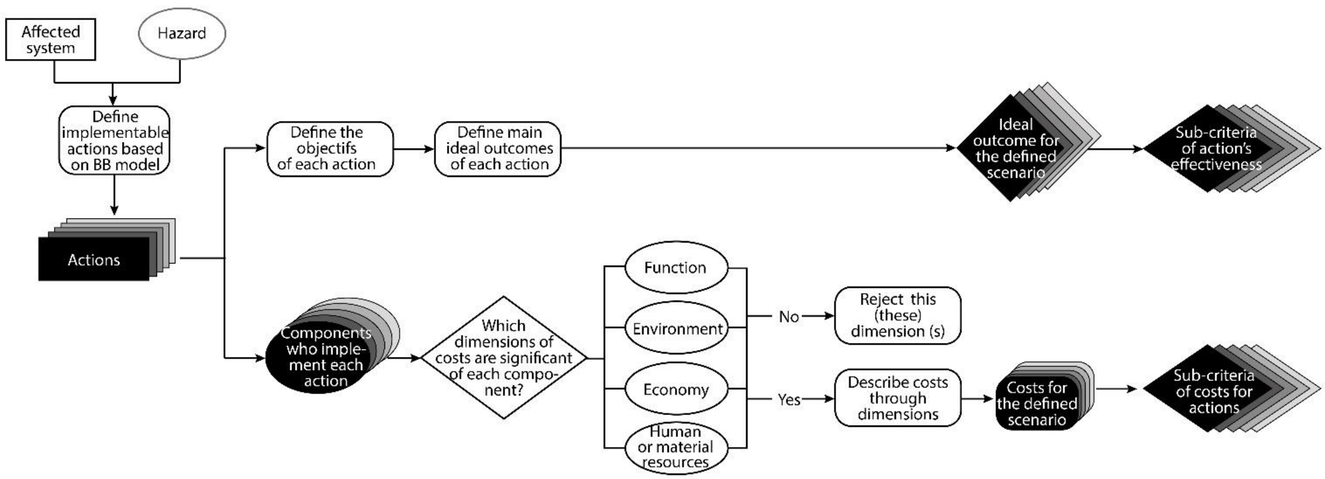


Fig. ~~6~~5. Form 2 for setting sub-criteria of "Effectiveness of action" and "Effort for action" criteria, source: Yang et al. (2023, b).

3.2 Indicators setting and references definition

According to Cambridge Dictionary, an indicator is a sign or a signal that shows something exists or is true, or that makes something clear. Indicators are objective information. A single indicator can rarely provide useful information. Generally, it is a collection of indicators that help to present the most important and relevant features of a given issue or topic (Eurostat, 2014). Indicators setting consists of setting the expected evolution of indicators by references. The reference of an indicator can be used as a ruler for measuring a criterion by this indicator, with a scale marked on it. We take the example indicator just mentioned for road infrastructures, "number of passing vehicles" and "types of vehicles accepted". For the former, for instance, high function could refer to more than 10,~~-~~000 passing vehicles by day, while low function refers to less than 500 passing vehicles. For the second indicator, a high function means that all types of vehicles could enter the road network, whereas a low function means the network is available only for motorbikes only. It can be seen that the setting of the indicator reference also includes the choice of object, unit, and types of attributes (quantitative and qualitative). As argued by Acosta-Alba and van der Werf ~~et al.~~ (2011), “the determination of reference values, norms, or veto thresholds constitutes a key stage in the procedure for developing an indicator”. Appropriate indicator reference values are required to assist in the interpretation of assessment results (Acosta-Alba and van der Werf~~et al.~~, 2011). Indicator references are an indispensable element of comparative assessment (Franchini and Bergamaschi, 1994). Indicator references for CIs resilience assessment could furthermore indicate the desirable state of CIs resilience.

It is not simple to define indicator references that indicate desirable state for resilient CIs. References for the same indicator may vary according to local conditions and they are highly relevant to the real context of studied CIs. An indicator reference could be suitable only for one territory, one scenario, or one particular CI. During indicator setting, the existing indicators, which have rational references and are suitable to defined sub-criteria, could be deployed directly or after adjustments. However, if no suitable or relevant indicators can be found through available resources, new indicators should be created. The indicators could be created by describing sub-criteria (damage, outcome and costs) in four dimensions (Scerri and James, 2010; Serre and Heinzlef, 2018):

- The temporal dimension focuses on the duration of sub-criteria.
- The spatial dimension emphasises the spatial or geographical extent of sub-criteria, which can often be represented as a planar or elevation image
- The quantitative dimension relates to the quantifiable data associated with sub-criteria.
- The qualitative dimension relates to non-quantifiable, qualitative data about sub-criteria and might be based on people’s observation and analysis, like the nature (including type, property, characteristic, etc.), importance level, and the degree that needs to be surveyed by experts or operators, such as the indicator “types of vehicles accepted” mentioned.

The indicators created based on these four dimensions could be called pre-set indicators (Fig. ~~7~~6,~~,~~ part A) because they are not usable without reference definitions. Therefore, once possible indicators have been pre-set, reference definitions for these indicators should be established (Fig. ~~7~~6,~~,~~ part B). Since indicators references are extremely pertinent to the object in particular studies, they should rely on the documents, laws, regulations, policies, guidelines, plans, and other information sources provided by relevant institutions or stakeholders. Finding references sometimes requires considering the sources not publicly available. The indicators with reference definitions could be called determined indicators (Fig~~.~~, 6.~~7,~~ part B). However, they are only possibly used for CIs resilience assessment, as their data resources have not been verified. The setting of possible indicators is shown in Fig.6~~7~~. To ensure ~~make sure~~ the use of determined indicators, the verification of their available data is required.

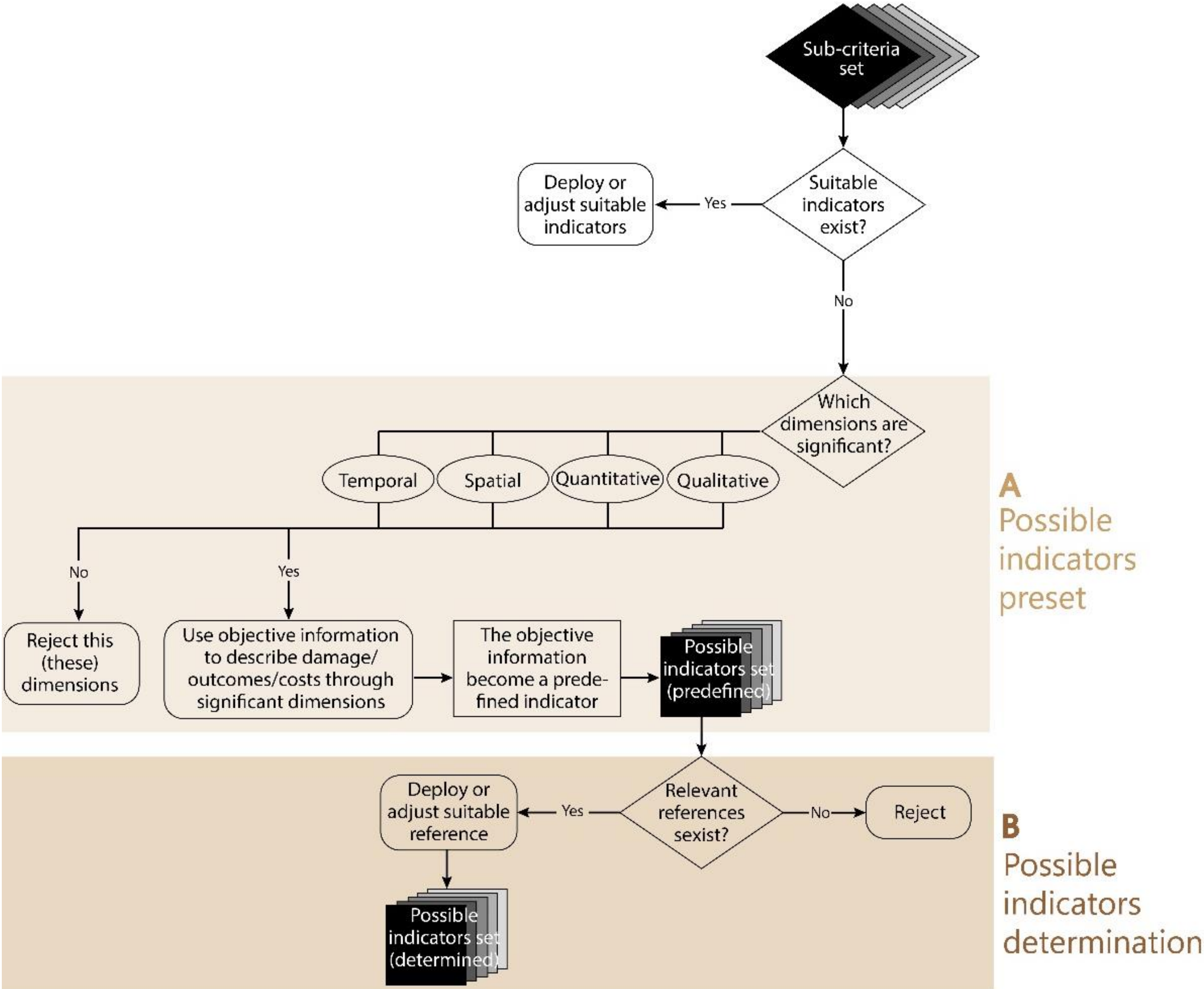


Fig. 76. Form 3: Possible Indicators predefinition and determination associated with indicator references definition, following Form 1 and Form 2, created by authors.

3.3 Verification of available data

As presented in the introduction, Indicator assessment indicator values are obtained by needs reliable data. (Vogel, 1997; Cutter, 2016; CORDIS-Smart Resilience Indicators for Smart Critical Infrastructures, 2018). Data is a discrete fact, a raw element, or the result of an observation, an acquisition, or a measurement, carried out by a natural or artificial instrument. Data collection is one of the most important parts of constructing indicators. Even though data are objective and do not have to function to evaluate or assess an object, the difficulties of data collection, lack of unity on definitions, and deficiency of data impact indicator values (Balaei et al., 2018). Prabhu et al. (1999) believe even that the difficulty and cost-effectiveness of data should be taken into account in the evaluation of the indicator's confidence.

In general, CIs stakeholders would not create immediately a new database or a new type of information for one assessment. It is therefore particularly important to collect data for indicators from available resources. If the indicator setting is based on available data resources, then relevant data resources are better collected. For example, submersion levels are frequently used in France for flood risk assessment. These submersion levels are oriented by the Ministry of Ecological Transition of France, for providing a concrete, visual, and precise element on the threat of major flooding on a large number of rivers. Many institutions engaged in data create or optimise the data about submersion height. In considering data availability, height submersion could be set as an indicator for assessing the physical damage to CIs during flooding.

Indicators could be assessed by historical data or modelling data. Each country has national databases for different areas and various documents for diverse infrastructures and hazards, which are potential resources for indicators assessments. Traditional data types are numerical, text, graph, Web, and image (Han et al., 2022). The current tendency is big data, which could be categorised by collection technique: Satellite imagery, Aerial imagery and videos, Wireless sensor web network, Light Detection and Ranging (LiDAR), Simulation data, Spatial data, Crowdsourcing, Social Media, Mobile GPS and calls record (Sarker et al., 2020). The indicators without available data should be rejected (Fig. ~~8~~7). For the indicators with available data, three points are emphasised for available data analysis (Fig. 7) ~~8)~~ :

- Relevance. The data must be relevant to set indicators and criteria. For example, in studying flood hazards, flood-related institutions, websites or documents should be the focus of data collection.
- Adaptability. The studied scenarios are related to specific hazards and types of CI, and the information obtained should be adapted to them.
- Usability. Managers should confirm their authority over obtained data before using them. The duration of data availability should be also verified to ensure continuous assessment.

Although modern data is diverse, databases and information technology have systematically evolved from primitive file processing to complex and powerful database systems since the 1960s. Therefore, if the research involves databases with huge numbers of data, the data mining techniques proposed by Han et al. (2022) are suggested to collect valuable data.

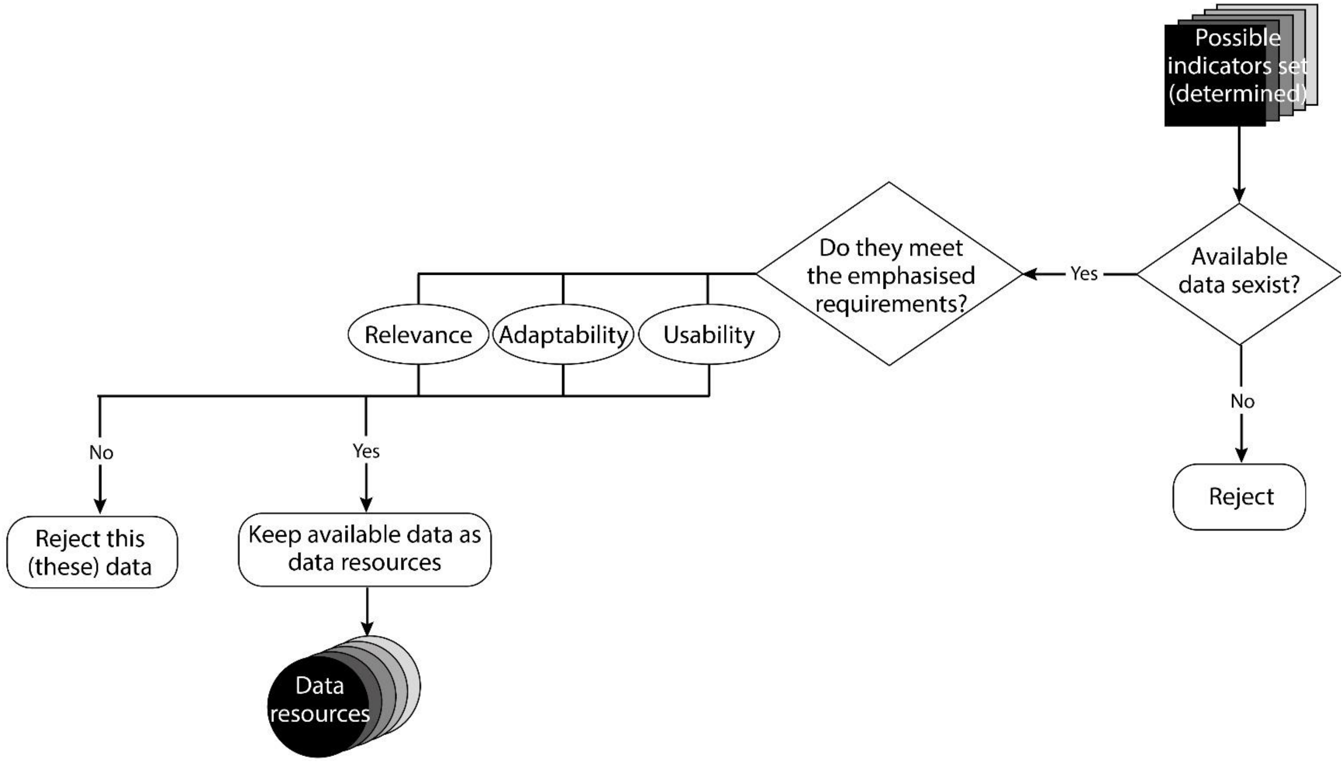
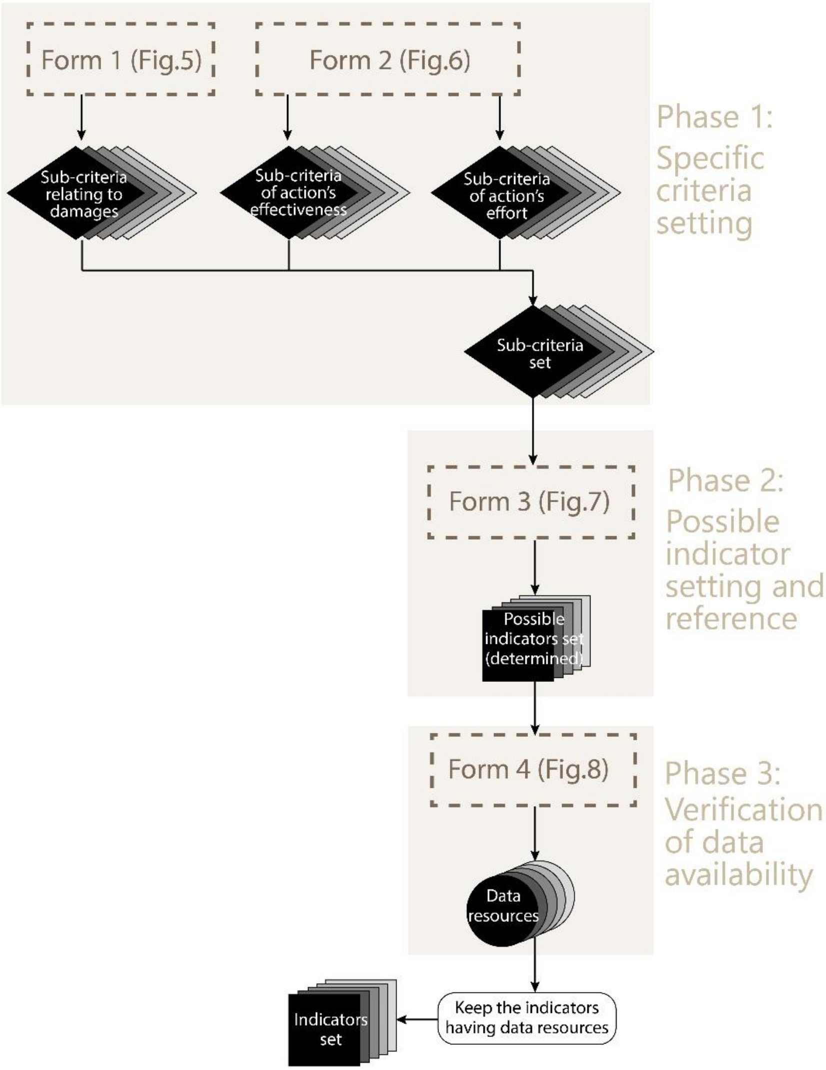


Fig. 87. Form 4: Verification of available data, following Form 1, Form 2 and Form 3, created by authors.

3.4 Result of part 1: Step-by-step guide

A step-by-step guide for building an indicator system for CIs resilience assessment is developed in this section. This guide has three phases: 1) specific criteria setting; 2) possible indicators setting and references definition; 3) Verification of available data. This guide combines Forms 1, 2, 3 et 4 (Fig. 45, Fig. 56, Fig. 6, 7 and Fig. 78) and is summarised in Fig. 98. The process of indicators setting ,incorporating reference definitions (Fig. 8, phase 2), is based on set sub-criteria setting (Fig. .98,. phase 21). The fFinal indicators set is determined after the verification of available data (Fig. 98., phase 3), as indicator assessment needs reliable data. All steps require the mutual collaboration of relevant stakeholders or decision-makers since collaborative approaches ensure the shared diagnosis and the efficiency of implementing measures (Hollnagel et al., 2011). C&I setting relies on managers' knowledge of the target CI and necessitates investigation of references and data appropriate. It can be argued that the construction of an indicators system depends on the local human (managers) and material resources (documents, data, terms, etc.) of the studied infrastructure. Indicator systems could be understood as a framework for transforming local resources into practical assessments, which contribute to CIs management. The next section will illustrate how to use this developed guide to build an indicator system for an example case.


Form 1 (Fig.5)
Form 2 (Fig.6)
Phase 1:
Specific criteria setting
Sub-criteria relating to damages
Sub-criteria of action's effectiveness
Sub-criteria of action's effort
Sub-criteria set
Form 3 (Fig.7)
Phase 2:
Possible indicator setting and reference
Possible indicators set (determined)
Form 4 (Fig.8)
Phase 3:
Verification of data availability
Data resources
Indicators set
Keep the indicators having data resources

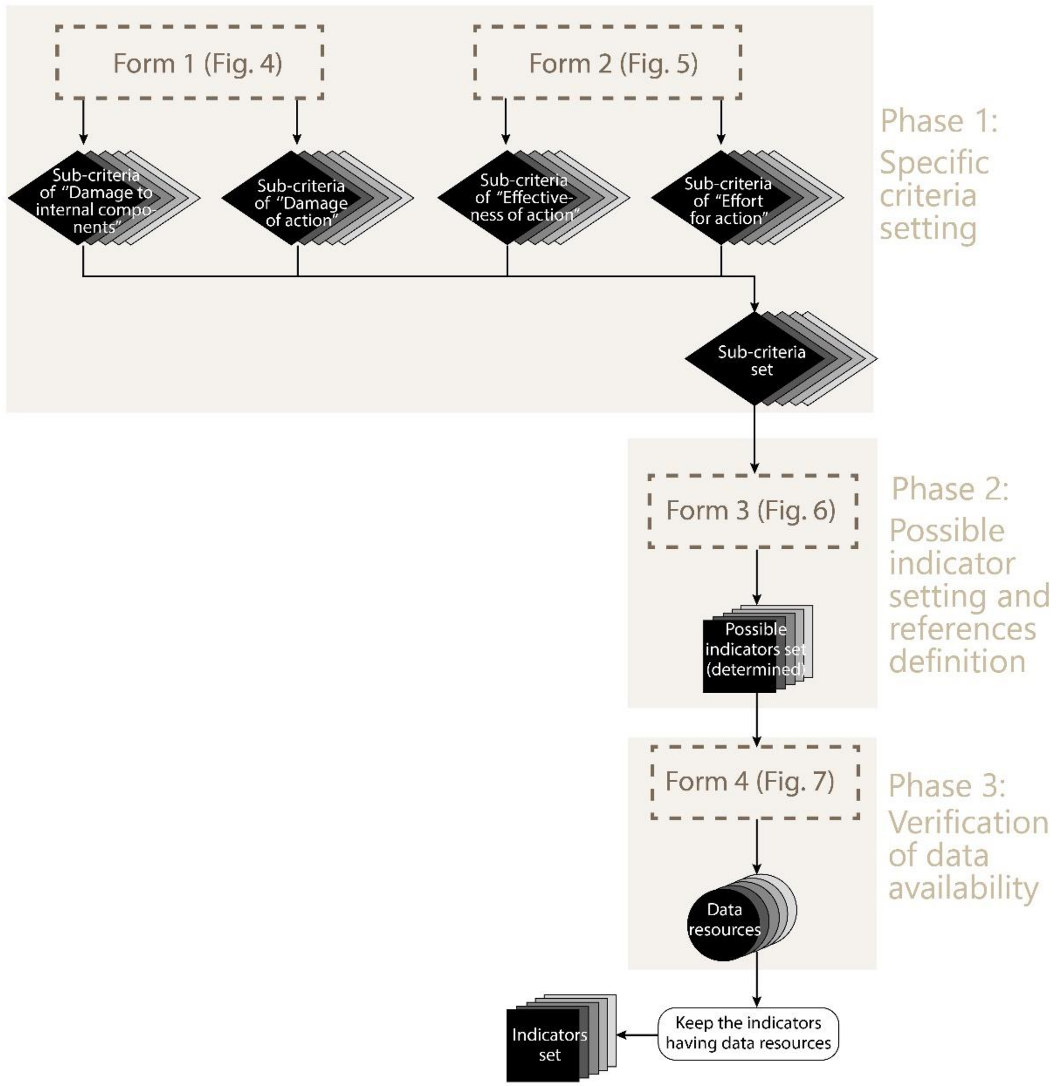


Fig. 98. Guide for building an indicators system for critical infrastructures resilience assessment (in combining Form 1, Form 2, Form 3 and Form 4), created by authors.

4 Part 2: Example of Guide Usage

For demonstrating how to build an indicator system through the developed guide, this study targets a specific circumstance, in which Nantes Ring Road (NRR) is affected by urban flooding. With a length of 42 kilometers, the NRR has services extending beyond the local level and is attractive in the region and even in the nation. However, the section (Fig. 109, lines in red) between the "Porte de la Chapelle" (Fig. 109, point B) and the "Porte de la Beaujoire" (Fig. 910, point C) is frequently closed due to the flooding of the Gesvres River. This study takes the flood event in February 2020 as an example, during which this section was closed on both sides for 56h (Cerema, 2023). During the closure of this section, local road management DIRO suggested~~s~~ alternative roads (Fig. 9~~10~~, lines in green). These alternative roads contain a part of another highway, Cofiroute network (Fig. ~~10~~9, lines in bleu). The data from 6 stations, Bonjoire, Bastignolles, Carquefou, Anjou, Bel and Vignoble (Fig. 9~~10~~), provide important information on the traffic of the sections that connect the frequently flooded section (Fig. ~~10~~9, lines in orange) of the Nantes ring road. These stations monitor the traffic flows per six minutes on the NRR. Furthermore, in the decision-making process for risk management~~in decision-making process for risks management~~, the consideration of experts' opinions is undeniable because of their professional knowledge (Merad, 2010). Therefore, during the whole study process, the research team, including university scientists, researchers in Cerema (Centre for Studies and expertise on risks, the environment, mobility, and development), and the practicing managers DIRO, make collective decisions based on the content of their meeting discussions.

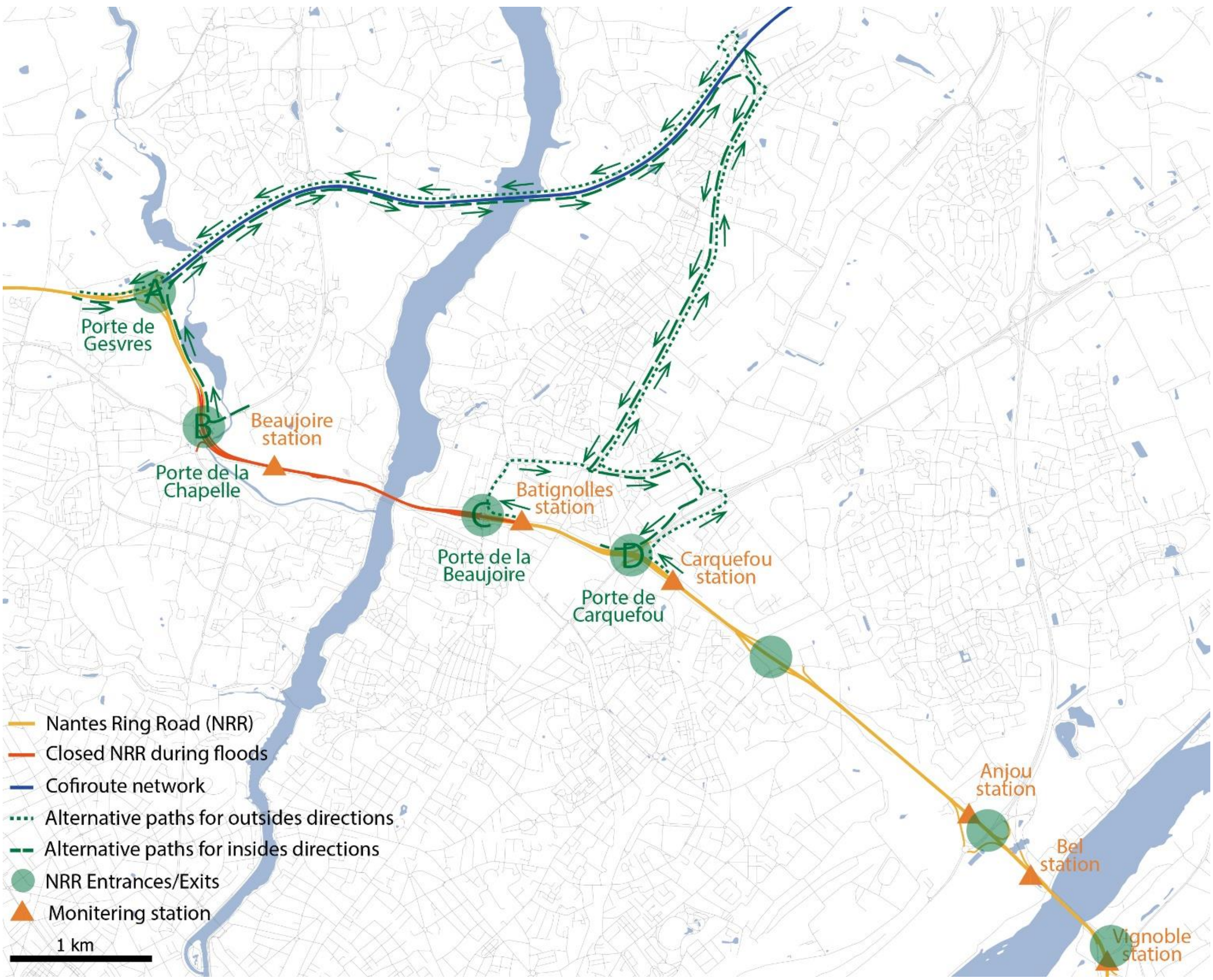


Fig. ~~10~~9. Road networks in presented example, adjusted from Cerema (2023).

4.1 Criteria setting

Studied scenarios should be defined before criteria setting. The first studied scenario refers to the NRR affected by flooding, for which DIRO suggests alternative roads when affected sections are closed (Fig. ~~11~~10, Initial scenario). The suggestion of alternative roads is thus the implementable action for the first scenario. For studying the side effects of the implemented action, it necessitates defining continuous scenarios, in which the implementable action affects NRR or its environment. In this example, since part of the Cofiroute network (Figure 9~~10~~, lines in blue) is alternative roads, Cofiroute network could be treated as an external system affected by the implementable action. The increase in traffic on the Cofiroute network due to the closure of NRR could have negative impacts, such as congestion, noise pollution, etc. (Cerema, 2023). Cofiroute network is an affected system in a continuous scenario (Fig. ~~11~~10, 1st continuous scenario). Moreover, the alternative pathways, which are longer than the initial pathways, produce more air pollution. The air environment in Nantes could be treated as another external system affected by the implementable action. Then, the air environment in Nantes is also an affected system in another continuous scenario (Fig. ~~11~~10, 2nd continuous scenario).

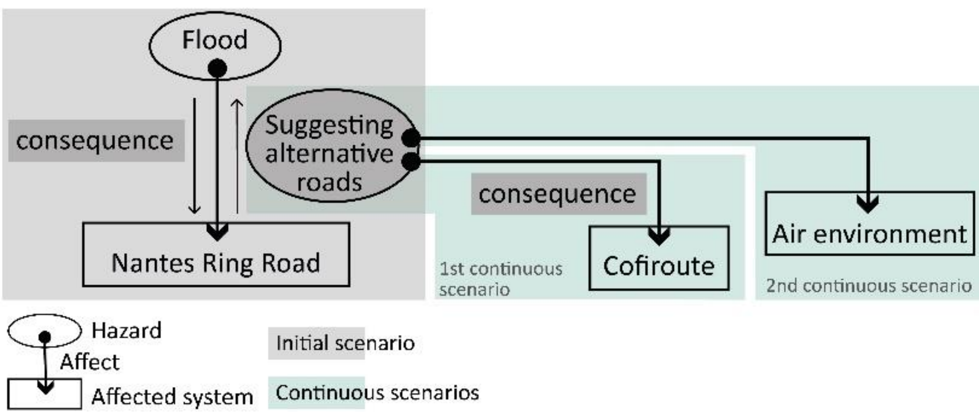


Fig. ~~11~~10: Initial and continuous scenarios of presented example, adjusted from Yang et al. (2023, b).

According to Form 1 (Section 3.1, Fig. ~~5~~4) and Form 2 (Section 3.2, Fig. ~~6~~5), identifying the main functions of target CI, as well as the function of its all components, is indispensable. This example, therefore, summarises all significant functions in Table 1 based on several existing studies (Yang et al, 2022; Yang et al. 2023, b) that investigated NRR resilience.

Table 1. The main functions of NRR, and the function of its all components~~All elements of NRR and their principal functions~~, source: Yang et al. (2022).

Categories	Internal components	Principal Functions
Main Function	Transport function	Serve individual and collective users in mobility: passenger, freight, postal, or auxiliary transport services (including medical services)

Human collective component	Managers	Ensure the daily operation of NRR, providing comfort and safety to users, through the management and maintenance of roads
	Project managers	Project management of investment operations (public or private) and management of the noise observatory of the NRR and of the flood-warning project for the eastern part of Highway Infrastructure
	State partners	Define and fund projects
	Safety observation	Produce and disseminate information on road safety
	Collective users	Organize mobilisation for different activities (posters, couriers, travellers, merchandise, health emergency services, etc.)
Human individual component	Individual users	Mobilise different activities (posters, couriers, travellers, merchandise, health emergency services, etc.)
	Individual staff	Work for affiliated institutions to ensure system functions
Physical non-human component	Rest areas	Supply energy and fuel to vehicles and provide material and spiritual needs to users in dedicated service areas
	Counting regulation	Provide information on road traffic
	Access regulation	Improve traffic flow on the Highway Infrastructure by controlling the injection of vehicles
	Green spaces	Protect water resources and enhance ecological transparency
	Maintenance and intervention centre	Provide support to state institutions (such as the police), cleaning, ordinary and extraordinary maintenance (road signs, lighting, localised damage, etc.)
	Drainage system	Remove surface water from the roads as quickly as possible (drainage) to ensure safety with minimum nuisance to users, implement effective subsurface drainage to maximise the lifecycle of infrastructures, minimise the impact of run-off on the external environment in terms of flood risk and water quality
	Road structures	Enable mobility by the construction of horizontal structures or structures in elevation or in excavation
	Vehicles	Transport passengers and goods on the ground
~~Main Function~~	~~Transport function~~	~~Serve individual and collective users in mobility: passenger, freight, postal, or auxiliary transport services (including medical services)~~

Initial scenario

Based on Form 1 (Fig. ~~5~~4), 3 sub-criteria are set for the "Damage to internal components" criterion: "damage to transport function (of NRR network)", "physical damage to individual users", and "physical damage to road structures". Then, for the criteria relating to the implementable action (Form 2, Fig. ~~6~~5), the desirable outcome and costs of selected implementable action need to be defined. The ideal outcome of the implementing action would be the increased transport function of the alternative routes. Thus, one sub-criterion is set for the "effectiveness of action" criterion based on Form 2: "increased transport function to alternative roads". The implementable action relies directly on two human components: the "managers" who plan it; and the "individual users" who use it. The material, economic, human or time resource costs refer therefore to the costs of "managers" and "individual users". ~~But~~However, according to the research team, no significant costs ~~is~~ are necessary for this implementable action. Thus, one sub-criterion could be set for the "effort for action" criterion based on Form 2: "time costs of individual users".

Continuous scenarios

According to Form 1 (Fig. ~~5~~4), for the first continuous scenario (Fig. ~~11~~10, 1st continuous scenario), the damage to the transport function of Cofiroute network could be considered a significant damage of implementable action, because the increased traffic in Cofiroute network brings congestion. Then, Form 1 (Fig. ~~5~~4) does not serve for the damage-related in the second continuous scenario (Fig. ~~11~~10, 1st continuous scenario), as the air environment in Nantes is not an infrastructure. "Damage to the air environment in Nantes" refers in particular to the additional air pollution caused by the increased travel distances via alternative roads. As a result, two sub-criteria are set for the “Damage of action” criterion: “Functional damage of transport function (of Cofiroute network)”; and “Air pollution”.

All sub-criteria for three-defined scenarios (Fig.~~11~~10) are listed in Table 2.

Table 2. Sub-criteria defined through Form 1 (Fig. ~~5~~4) and Form 2 (Fig.~~6~~ 5), resulting from consensus of stakeholders and managers.

Scenario	Criteria	Sub-criteria
Initial scenario	Damage to internal components of NRR	Damage to transport function (of NRR network)
		Physical damage to individual users
		Physical damage to road structures
	Effectiveness of action	Increased transport function to alternative roads
	Effort for action	Time costs of individual users
Continuous scenarios	Damage of action = Damage to internal components of Cofiroute network	Functional damage of transport function (of Cofiroute network)
	Damage of action = Damage to air environment in Nantes	Air pollution

4.2 Possible Indicators setting

In this example, a few indicators ~~could~~ can be found in the available resources for the defined sub-criteria (Table 2). Thus, the steps given in Form 3 (Fig.~~7~~6) are applied for creating indicators and defining indicator references. Before references definition, 17 possible indicators through ~~4~~four suggested dimensions (temporal, spatial, quantitative and qualitative) could be pre-set (Table 3).

Table 3. Possible indicators pre-set through part “A. Possible indicators pre-setting” in Form 3 (Fig.~~7~~ 6) , resulting from consensus of stakeholders and managers.

Criteria	Sub-criteria	Possible indicators (pre-set)				
		Temporal	Spatial	Quantitative	Qualitative	
Damage to internal componen ts (of NRR)	Damage to the transport function of NRR	Duration for unavailable functions	Length of road sections concerning unavailable functions	Reduced transport traffic number	Quality change of transport function	Type of roads sections losing functions

	Physical damage to individual users	No significant	No significant	Number of injured or killed passengers	Injury types
	Physical damage to vehicles	No significant	No significant	Number of destroyed vehicles	No significant
	Physical damage to road structures	Duration of destruction of physical structures	Size, scale or length of destroyed physical structures	No significant	Damage level of destroyed physical structures
Effectiveness of action	Increased transport function of alternative roads	No significant	No significant	Restored traffic	No significant
Efforts for action	Costs of individual users	Time costs of individual users	No significant	No significant	No significant
Damage of action	Functional damage of transport function of Cofiroute Network	Duration for domino effects	Length of road sections concerning domino effects	Reduced transport traffic number	Quality change of transport function
	Air pollution in air environment	No significant	No significant	Quantity of pollutant emissions	No significant

Then, after reviewing a large number of documents published by institutions related to flood management and road infrastructures (Appendix A), 5 of the 17 indicators mentioned in Table 3 are rejected because their references could not be defined. The description, reference, and resources of the remaining 12 indicators are listed in Tables 4, 5, 6, and 7.

Table 4. Possible indicators determined through part "B. Possible indicators determination" in Form 3 (Fig. ~~7~~6) for the "damage to internal components" criterion, resulting from consensus of stakeholders and managers.

Sub-criterion	Possible indicators		Reference	Damage score	Reference source	Description in original source
	Pre-set	Determined				
Damage to transport function	Duration of destruction of physical structures	Duration of the NRR close	No close	0	CGDD (2017)	Damage to the Var bridge and its consequences: Minor damage intensity: 3 days expected outage; Moderate damage intensity: less than 3 weeks planned outage; Moderate damage intensity: less than 3 weeks planned outage; Major damage intensity: less than 3 months expected outage;
			Close less than 3 days	1		
			Close between 3 and 30 days	2		
			Close between 30 and 120 days	3		
			Close between 120 days and 2 years	4		
	Quality change of transport function	Traffic flow on the affected NRR sections	Flow > 100 vehicles/6minutes	0	Cerema (2023)	Characterisation of road transport operation by flow rate: Flow > 100 vehicles/6minutes = high flow Flow between 50 and 100 vehicles/6 minutes = moderate flow Flow < 50 vehicles/6 minutes = low flow
			Flow between 50 and 100 vehicles/6 minutes	1		
			Flow < 50 vehicles/6 minutes	2		
	Type of roads sections losing functions	Importance of closed road sections	No flooded road structures	0	IGN (2023)	Importance of road section: Importance 1: The object is of national importance or influence, justifying its representation at scales of 1:1,000,000. Importance 2: The object is of regional importance or influence, justifying its representation at scales of 1:250,000. Importance 3: The object is of regional importance or influence, justifying its representation at scales of 1:100,000.
			Importance level 6	1		
			Importance level 5	2		
			Importance level 4	3		
			Importance level 3	4		
			Importance level 2	6		
			Importance level 1	7		

						Importance 4: The object is of inter-communal or cantonal importance or influence, justifying its representation at scales of 1:50,000. Importance 5: The object is of municipal importance or influence, justifying its representation at scales of 1:25,000. Importance 6: The object is of local importance or influence, justifying its representation at scales of 1:5,000.
Physical damage to individual users	Number of injured or killed passangers	Number of injured users	No injured passenger	0	SETRA (2005)	ZAAC (zone d'accumulation d'accidents corporels) is defiend through the number of accident for a road section length of 850 m and over a period of 5 years: Level 1: at least 4 accidents with injuries and 4 serious casualties; Level 2: at least 7 accidents with injuries and 7 serious casualties Level 3: at least 10 accidents with injuries and 10 serious casualties
			4 injured passenger for each 850m	1		
			7 injured passenger for each 850m	2		
			10 injured passenger for each 850m	3		
		Number of killed users	No dead	0	Defossez, (2009)	Human damage severity scale
			1 à 9 dead	1		
			More than 9 dead	2		
	Injury types	Injury grade of injured passengers	No injured passenger	0	Sécurité routière	In-patient casualties: Victims admitted to hospital as patients for more than 24 hours. Minor injuries: Victims who have received medical care but have not been admitted to hospital as in hospital for more than 24 hours.
			slightly injured	1		
			Serious injured	2		
Physical damage to road structures	Duration of destruction of physical structures	Duration of NRR flooding	0	0	Cerema (2016)	The duration of submersion could be classified as: less than 24 h-1 day from 24 to 48 h from 48 h-2 days to 4 days from 5 to 10 days more than 10 days
			Less than 24 h	1		
			24 h - 48 h	2		
			2 – 4 days	3		
			5-10 days	4		
			More than 10 days	5		
	Damage level of destroyed physical structures	Percentage of Pavement Damage	Insignificant Damage	0	Lu (2019)	Damage states can be categorized based on damage level such as collapse, major damage, moderate damage and minor damage, according to the percentage of pavement damage
			Minor Damage	1		
			Medium Damage	2		
			Minor Damage	3		
			Insignificant Damage	4		

Table 5. Possible indicators determined through part "B. ~~Possible indicators~~Possible ~~determination~~indicators determination" in Form 3 (Fig.~~7~~6) for the "effectiveness of action" criterion, resulting from consensus of stakeholders and managers.

Sub-criterion	Possible indicators		Reference	Recovery score	Reference sources	Description in original source
	Pre-set	Determined				
Increased transport function of alternative roads	Restored traffic	Percentage of traffic being restored on alternative roads*	0	0	No available	Non available
			0-30%	1		
			30%-60%	2		
			More than 60%	3		

*This indicator is intended to indicate the percentage of vehicles affected ~~and~~ using the alternative route to the total number of vehicles affected. Its reference is defined by the stakeholders and managers related to this study because it strongly depends on local conditions.

Table 6. Possible indicators determined through ~~part "~~part "B. ~~Possible indicators~~Possible ~~determination~~indicators determination" in Form 3 (Fig. 6)~~7)~~ for the "effort for action" criterion, resulting from consensus of stakeholders and managers.

Sub-criterion	Possible indicators		Reference	Cost score	Reference sources	Description in original source
	Pre-set	Determined				
Resources costs of individual users	Time costs of individual users	Additional time depend by each user in using alternative road	Less than 15 minutes	1	BFM business (2018)	82% of French people lose patience after 30 minutes of non-fluid driving, and 40% after just 15 minutes.
			15-30 minutes	2		
			More than 30 minutes	3		

Table 7. Possible indicators determined through part "B. ~~Possible indicators~~Possible ~~determination~~indicators determination" in Form 3 (Fig. 6~~7~~) for "damage of action" criterion, resulting from consensus of stakeholders and managers.

Sub-criteria	Possible indicators		Reference	Damage score	Reference sources	Description in original source
	Pre-set	Determined				
Damage to transport function of Cofiroute Network	Quality change of transport function	Traffic state on the alternative roads	fluid	0	Nantes metropole	~~Nnates~~Nantes metropole has defined the traffic situation as follows: Lane occupancy rate less than 20%: Fluid Lane occupancy between 20% and 30%: Dense Occupancy rate between 30% and 40%: Saturated Lane occupancy rate above 40%: Blocked
			saturated	1		
			dense	2		
			blocked	3		
Air pollution in air ~~environnement~~environment	Quantity of additional pollutant emissions	Percentage of additional CO2 emission for each path through alternative road	0-93%	1	phys.org	Due to 380 billion tons of CO_2 as the remaining carbon budget, there is a 50% chance the planet will reach the 1.5℃ global average temperature rise in just nine years. when the remaining carbon budget increases 93% to 732 billion tons or 224% to 1230 billion tons, the global average value of temperature rise could become 1.5℃ and 2℃.
			93-224%	2		
			more 224%	3		

References definition should be based on available resources. However, some references need to be modified and adjusted before their deployment for indicators setting. For example, for the qualitative indicator "importance of flooded section" (in Table 4), its reference could be defined based on the "importance levels of roads" defined by the Institut national de l'information géographique et forestière (IGN). The level of damage caused by flooding increases with the importance of the road (Table 8).

Table 8. Damage reference defined by road importance level, adjusted by IGN (2023).

Damage level	Importance level of flooded sections	Description
Catastrophic damage	Importance 1	The object is of national importance or influence, justifying its representation at scales of 1:1,000,000.
Very heavy damage	Importance 2	The object is of regional importance or influence, justifying its representation at scales of 1:250,000.
Heavy damage	Importance 3	The object is of regional importance or influence, justifying its representation at scales of 1:100,000.
Moderate damage	Importance 4	The object is of inter-communal or cantonal importance or influence, justifying its representation at scales of 1:50,000.
Slight damage	Importance 5	The object is of municipal importance or influence, justifying its representation at scales of 1:25,000.
Negligible damage	Importance 6	The object is of local importance or influence, justifying its representation at scales of 1:5,000.

In this example, the difference between the two indicators, "duration of the NRR close because of submersion" and "traffic state on the alternative roads" needs to be further explained. They are both used for describing damage to transport function. The "duration of the NRR close because of submersion" indicator is for NRR function, as it relates to NRR closed road sections. Meanwhile, the "traffic state on the alternative roads" indicator relates to alternative roads, which have certainly a change of traffic state due to increased traffic flows. It shows that the definition of indicators must be contextualised.

4.3 Available data analysis

The example relates to flood hazards and road infrastructures. In France, relevant institutions are presented in Appendix A, while the possible data resources could can be found in the open data websites shown in Appendix B. Moreover, the partner DIRO provides a large number of data on traffic flow on the NRR network. The indicator "Percentage of Pavement Damage" is rejected due to lack of data. All usable indicators and their available data resources are set through Form 4 (Fig. 78) and listed in Table 9. The main data sources refer to:

- The traffic flow per six minutes monitored by 18 channels in four stations on NRR, collected by DIRO: four channels in four stations (Beaujoire, Batignolles, Carquefou, and Vignoble) for both two directions, whereas Anjou station has only two channels for the internal direction. Collected data are relevant to two periods: 1) the first is from 14 to 20 January 2019 and is considered a normal situation; and 2) the second is from 31 January to 07 February 2020 and is considered a flooding situation. 62,676 data of traffic flow are involved.
- The BDTOPO from IGN on the department of Loire-Atlantique, which includes a 3D vector description (structured in objects) of road infrastructures.
- Documents from relevant local institutions, like DIRO, Cerema, Nantes Metropole.

Table 9. Available data verified through Form 4 (Fig. 78), resulting from consensus of stakeholders and managers.

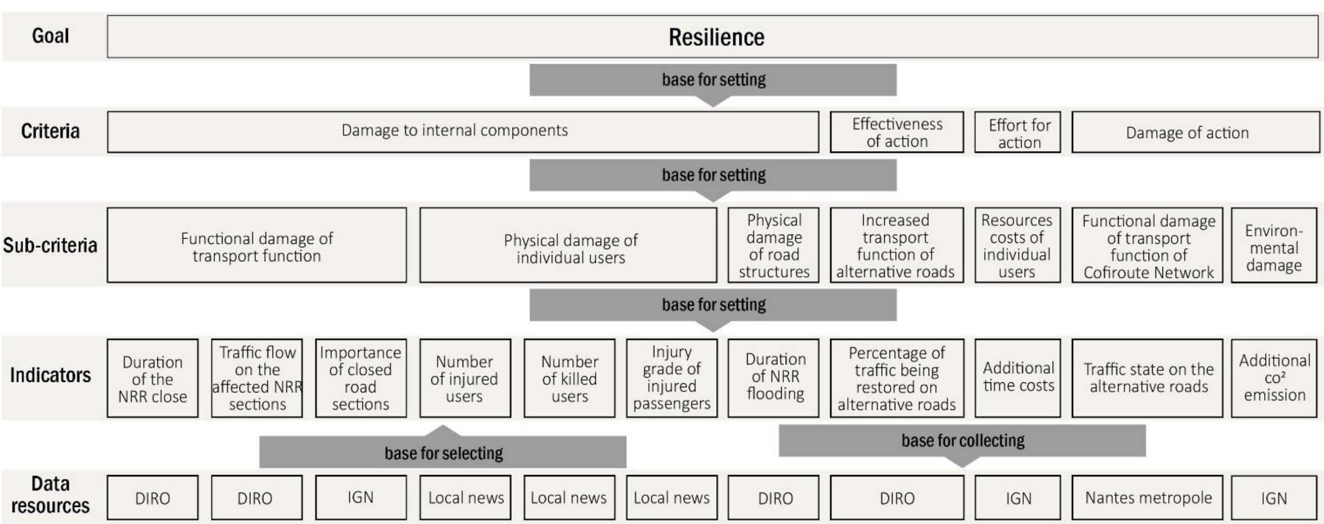
N°	Indicators	Data resources
1	Duration of the NRR close	DIRO
2	Traffic flow on the affected NRR sections	DIRO
3	Importance of closed road sections	IGN
4	Number of injured users	Local news
5	Number of killed users	Local news
6	Injury grade of injured passengers	Local news
7	Duration of NRR flooding	DIRO
8	Percentage of traffic being restored on alternative roads	DIRO
9	Additional time costs	IGN
10	Additional co2 emission	IGN
11	Traffic state on the alternative roads	Nantes metropole

4.4. Result of part 2: an indicator system for studied example case

As shown in Fig. 2, an indicators system contains criteria, indicators and data. After Criteria & Indicators setting, and data selection, the indicators system for the studied CI, Nantes Ring Road network, is built as show in Table 10 and Fig. 1211. The sub-criteria in this indicator system are set based on four general criteria. The indicators in this system are set in terms of sub-criteria and the availability of data resources.

Table 10. Criteria, sub-criteria, indicators and data resources for studied example, created by authors.

Criteria	Sub-criteria	Indicators	Data resources
Damage to internal components	functional damage of transport function	Duration of the NRR close	DIRO
		Traffic flow on the affected NRR sections	DIRO
		Importance of closed road sections	IGN
	Physical damage of individual users	Number of injured users	Local news
		Number of killed users	Local news
		Injury grade of injured passengers	Local news
	Physical damage of road structures	Duration of NRR flooding	DIRO
Effectiveness of action	Increased transport function of alternative roads	Percentage of traffic being restored on alternative roads	DIRO
Efforts for action	Resources costs of individual users	Additional time costs	IGN
Damage of actions	Functional damage of transport of Cofiroute Network	Additional co2 emission	IGN
	Environmental damage	Traffic state on the alternative roads	Nantes metropole



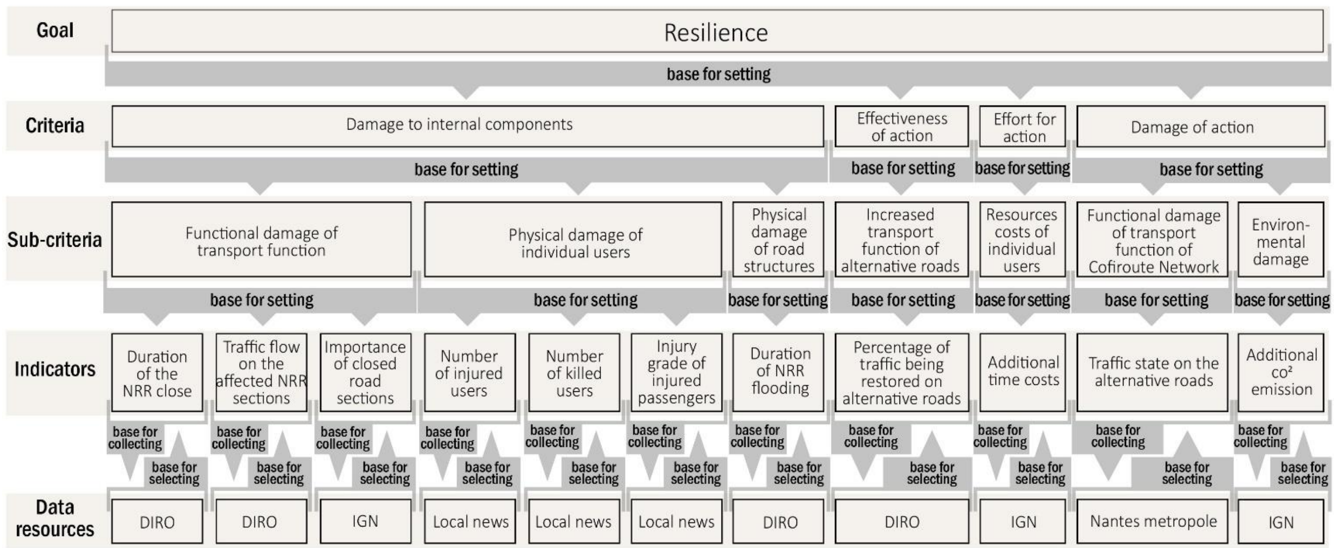


Fig. ~~12~~11. Indicator~~s~~ systems for studied example built based on the developed guide (Fig. ~~9~~8), created by authors.

5. Discussion

5.1 A practical guide for building indicator systems

The developed guide requires a multi-criteria analysis, a setting of numerous indicators and an investigation of available data. The built indicator systems may be considered complex with a large number of contents, and it may increase the application complexity of indicator systems to a certain extent. Nevertheless, there is no doubt that CIs resilience is a complex object, but not a complicated one. A complicated object, i.e. one with a certain amount of disorder, can be simplified, whereas a complex object should not be simplified. “Complexity varies according to a number of parameters, including the multiple uses to which it is put, the number of participants involved, its geographical dispersion, and the spatial and temporal scales considered” (Barroca and Bethelot, 2016). Since CIs resilience is a complex object, complex indicator systems seem~~s~~ inevitable for CIs resilience assessment. The more complex an indicator~~s~~ system, the more it requires detailed knowledge of real cases in diverse dimensions (geographies, socio-economic, environmental, technical, etc.). At the same time, the higher the need to increase the autonomy of local managers, which the developed guide in this study provides.

A consideration of the conditions of real cases may be one key ~~for~~ to advancing CIs resilience application. This consideration brings the uniqueness of each case that could be realised by the specificity of sub-criteria and indicators. Just as teaching a man to fish, rather than simply giving him fish. Rather than predefining sub-criteria or indicators for all potential resilience scenarios of CIs resilience, the guide for building indicator systems developed in this study enables CIs to set specific sub-criteria and indicators based on concrete situations. This guide is a tool flexible, adapting itself to different case studies and different kinds of CIs. The developed guide provides a wide margin of autonomy for CIs managers or stakeholders who need support and guidance to build indicator systems. The autonomy also brings the possibility of continuous updating or optimising of building indicator systems. Changes in the external environment may lead to changes in the setting and weighting of criteria, and indicators. For example, the sub-criteria of “Environmental damage” and the indicator of “Additional CO^2 emission” has become important in recent years because of the development of environmental concern. In addition, the criteria and indicators relating to implementable actions are another key for advancing the application of CIs resilience assessment. Even though many existing theories or models for CIs resilience assessment are valuable, the discussion about the effects of implementable actions is not sufficient in current studies. The present study insists that, for advancing CIs resilience application, it is necessary to consider the cost-effectiveness and side effects of implementable actions.

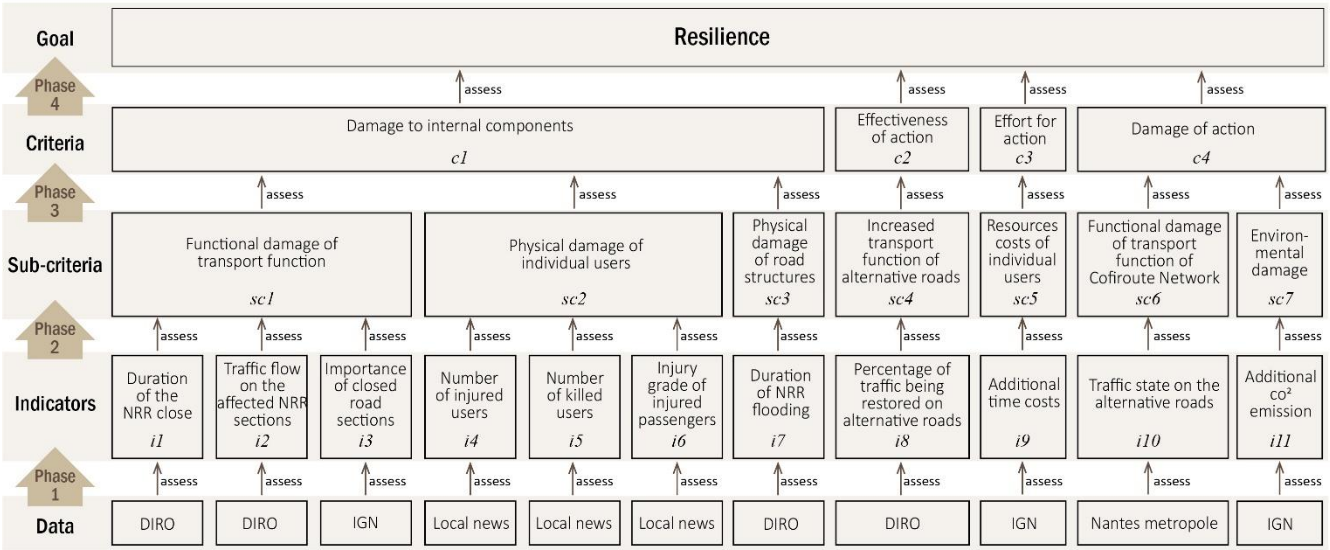
Meanwhile, the autonomy of this guide can also be interpreted as a weakness. Managers' experience or knowledge may be so limited that they overlook invisible factors. From a holistic perspective, a collaborative exchange between different stakeholders can reduce this shortcoming. The examples in this study demonstrate exactly the kind of cooperation between local operators, university scientists, and local researchers. Whereas a significant investment in human resources at the same time may reduce the cost-benefit of collaborative management. Research in the field of management is therefore needed for better use of built indicator systems.

In addition, the developed guide that promotes the practical use of resilience indicators could further contribute to the application of CIs resilience. The current studies of the CIs resilience aim to develop more effective and sustainable infrastructure management strategies for CIs through the concept of “resilience”. In other words, one of the desired developments in resilience research is to put resilience-based theories, tools, and models into practice. Thus, CIs resilience studies need to consider the application of the concept of “resilience” in practical risk management. According to Cambridge Dictionary, an application is a way in which something can be used for a particular purpose. A practical application of CIs resilience is therefore a way in which CIs resilience can be used for real risk management. Although CIs resilience has gained considerable attention in the research literature during the last decade, there remain relatively few resilience studies with application in real-life infrastructure (Hosseini; 2016; Meerow et al., 2016; Hernantes et al., 2019; Heinzlef et al., 2022; Esmalian et al., 2022; de Magalhães et al., 2022; Barroca et al, 2023; Rød, 2020). The obstacle to applying the CIs resilience concerns two major limitations: 1) the absence of applied tools; 2) the lack of an organisational aspect (Weichselgartner and Kelman, 2015; Hernantes et al., 2019 ; Heinzlef et al., 2022; Rød et al., 2020; Yang et al., 2023, b). The guide developed in the present study is firstly a practical tool that can be applied in concrete scenarios, as demonstrated by the example case presented. The fact that the criteria setting is based on organisational perspectives has been also emphasised. The developed guide could contribute to transforming the concept of “resilience” into an object of practical value, in the broader sense of 'use'.

5.2 Assessment demonstration

This study aims furthermore to discuss the possibility of assessing CIs resilience by the built indicator system in section 4 (Fig.~~12~~11). As presented in the introduction, ~~shown in Fig. 1,~~ resilience could be assessed based on indicators, and indicators could be assessed based on reliable data. The resilience assessment process based on this built indicator system, for the studied scenarios (Fig.~~11~~10) focusing on Nantes Ring Road, includes potentially 4 phases (Fig. ~~13~~12):

1. Indicator assessment based on collected data;
2. Assessment of the level of sub-criteria based on indicators;
3. Assessment of the level of criteria based on the level of sub-criteria;
4. Resilience assessment based on the level of criteria.



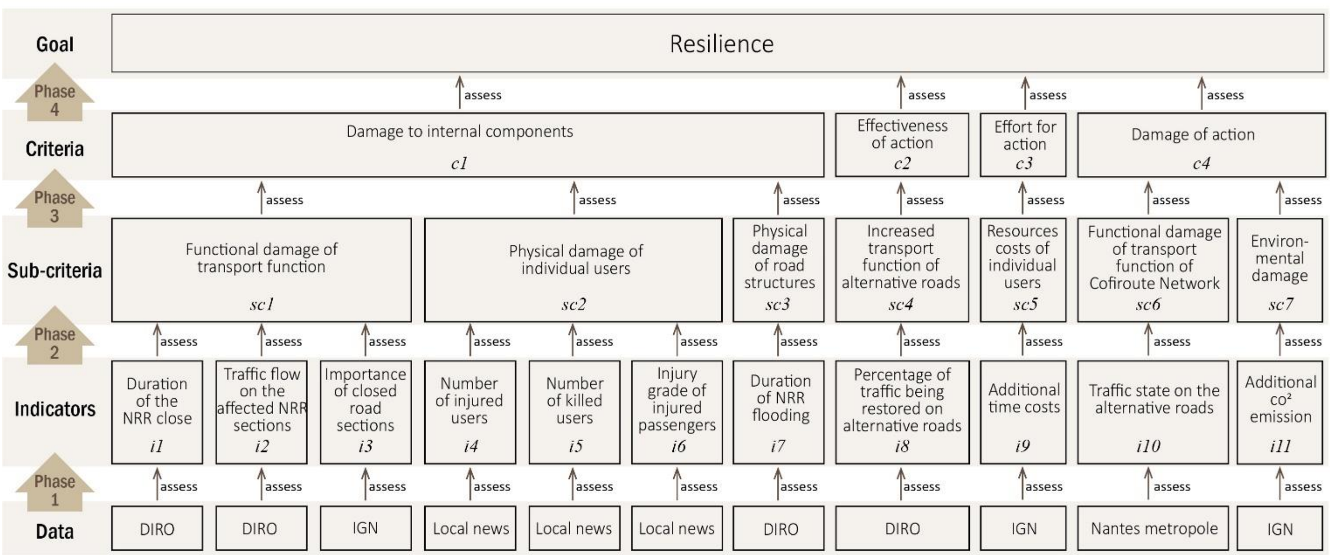


Fig ~~13~~12. Assessment process of Nantes Ring Road resilience based on the indicators systems developed in present study, created by authors.

It necessities in addition to determining assessment methods and weighting methods. As numerous methods are deployable, this example shows only some of them that are considered applicable and suitable for the built indicator system.

5.2.1 Criteria & Indicators weighting

The developed guide, involving a multi-criteria framework (Yang et al., 2023, b), could be associated with the ~~could associate to~~ Multi Criteria Decision Making (MCDM) approach. MCDM is a branch of operational research dealing with finding ideal results in complex scenarios including various indicators, conflicting objectives, and criteria (Kumar et al., 2017). Since MCDM requires a consideration of various perspectives, weighing methods is regarded as an important aspect in the MCDM methods step. The results of the multi-criteria decision-making method largely depend on such weights (Yusop et al., 2015). Weighting values accurately determine the relative importance of each factor significant to assessments (Singh and Pant, 2021). Even though most ~~of~~ MCDM studies highlight the weighting of criteria, this study will apply the weighting for all criteria and indicators. The weighting process in the MCDM approach is the most difficult task (Tervonen et al., 2009), even though weighting methods have been popular in recent years. A significant scientific system has therefore been developed and there are many available methods presented in a large number of studies. The relevant review articles are listed here and this study would not present in detail: Roszkowska, 2013; Johnsen and Løkke, 2013; Iwaro et al., 2014; Yusop et al., 2015; Singh and Pant, 2021.

Weighting methods could be simply divided into two categories, Subjective Weighting Methods, and Objective Weighting Methods. The former involves weights being derived from the decision maker's judgment, while the latter preference weights are obtained from mathematical algorithms or models (Yusop et al., 2015). Subjective Weighting Methods are more suitable for the present example that encourages CIs managers to build indicator systems according to specific requirements and judgments based on particular situations. Moreover, the present study selects the weighting methods that do not require additional software, and that do not require excessive simulation or mathematical skills that are difficult to be applied by managers in practice. The existing methods are numerous and it is difficult to show all of them. This section will use different methods to assess criteria levels and indicators for presenting some of the existing methods. All methods mentioned following are based on the study of (Yusop et al., 2015).

For the sub-criteria with only one indicator (indicators 7, 8, 9, 10, 11), indicators weighting is not necessary. For the resting sub-criteria, several weighting methods widely used for a small number of elements are suggested, as there are no more than three indicators for each sub-criterion in the example. Firstly, the ranking methods, such as rank sum and rank reciprocal, are the simplest approaches~~approach~~ for assigning weights. Generally, before calculating weights, the criteria are ranked in order from most important to least important. "In rank sum, the rank position r_j is weighted and then normalized by the sum of all weights. Rank reciprocal weights are derived from the normalized reciprocals of a criterion rank. The rank exponent method requires the decision maker to specify the weight of the most important element on a 0–1 scale. The value is then used in a numerical formula."(Yusop et al., 2015). The results of indicators weighting are shown in Table 11.

Table 11. Indicators weights, created by authors.

Sub-criteria	N°	Indicators		Straight rank	Rank sum $(n - r_j + 1)$	
					Weight	Normalised
Functional damage of transport function	1	i1	Duration of destruction of physical structures	2	2	0.33
	2	i2	Quality change of transport function	1	3	0.50
	3	i3	Importance of closed road structures	3	1	0.17
					6	1
Physical damage of individual users	4	i4	Number of injured users	2	2	0.33
	5	i5	Number of killed users	1	3	0.50
	6	i6	Injury grade of injured passengers	3	1	0.17
					6	1

Ranking methods are not ideal for weighting no more than two elements, as only two ranges are taken into account. Therefore, for criteria and sub-criteria weighting, another easy weighting method called the Point Allocation method, could be suggested. "In the point allocation weighting method, the decision maker allocates numbers to describe directly the weights of each criterion. The decision maker is asked, for example, to divide 100 points among the criteria. In many experiments, the analysts do not fix the total number of points to be divided but the subjects are asked to give any numbers they liked to reflect the weights. The more points a criterion receives, the greater its relative importance. The total of all criterion weights must sum to 100" (Yusop et al., 2015). Similarly, for the criteria with only one sub-criterion, weighting is not necessary. The results of sub-criteria weighting are shown in Table 12.

Table 12. Sub-criteria weights, created by authors.

Sub-criteria		Rank sum	
		Weight	Normalized
wsc1	Damage to transport function	30	0.3
wsc2	Physical damage to individual users	50	0.2
wsc3	Physical damage to road structures	20	0.2
		100	1
Wsc6	Functional damage to transport function of Cofiroute Network	80	0.8
Wsc7	Air pollution in air environment	20	0.2
		100	1

For criteria weighting, this study suggests the Direct Rating Method. This method requires a score, like the numbers 1–5, 1–7, or 1–10 used to indicate importance from a decision maker to represent the importance of each indicator. Yusop et al. (2015) argued: "Tthe rating method does not constrain the decision maker's responses as the fixed point scoring method does". It is possible to alter the importance of one criterion without adjusting the weight of another. This represents an important difference between the two approaches." Thus, the results of criteria weighting are shown in Table 13.

Table 13. Criteria weights, created by authors.

N°	Criteria	Importance (1 = least, 5 = most)					Level	Normalised weight	
		1	2	3	4	5			
1	Damage to internal components				X		4	wc1	0.308

2	Performance of action					X	5	wc2	0.384
3	Efforts of action		X				2	wc3	0.154
4	Damage of action		X				2	wc4	0.154
							13		1

5.2.2 Assessment methods and results

Resilience assessment, criterion level assessment and indicator assessment could all be quantitative, qualitative and semi-quantitative (Hosseini, 2016; Mebarki, 2017; Yang et al., 2023, a). Quantitative approaches offer domain-agnostic measures to quantify value across applications and structural-based modelling approaches that model domain-specific representations. Semi-quantitative approaches provide a general numerical description of the classification, without detailed formulae or models. Qualitative approaches refer to approaches without a numerical descriptor and based on people's judgments and analysis, like surveyed experts or operators.

In this study, the hierarchical references of set indicators make indicator~~s~~ assessment a semi-quantitative approach (Fig. 12. Phase 1). Based on the collected data, all indicators could be assessed. The values and levels of all indicators for the defined scenario are assessed in Appendix C. The result of the indicator~~s~~ assessment is show in Table 14.

Table 14. The values, scores and normalised scores of each indicators score, created by authors.

N°	Indicators	Reference	Score	Score normalisation	Indicator value	Indicator score	Normalised score of indicator
1	Duration of the NRR close	No close	0	0	56h	1	0.25
		Close less than 3 days	1	0.25			
		Close between 3 and 30 days	2	0.50			
		Close between 30 and 120 days	3	0.75			
		Close between 120 days and 2 years	4	1			
2	Traffic flow on the affected NRR sections	Flow > 100 vehicles/6minutes	0	0	19.01	2	1
		Flow between 50 and 100 vehicles/6 minutes	1	0.5			
		Flow < 50 vehicles/6 minutes	2	1			
3	Importance of closed road sections	No flooded road structures	0	0	1.76	5	0.83
		Importance level 6	1	0.17			
		Importance level 5	2	0.33			
		Importance level 4	3	0.5			
		Importance level 3	4	0.67			
		Importance level 2	5	0.83			
		Importance level 1	6	1			
4	Number of injured users	No injured passenger	0	0	0	0	0
		4 injured passenger for each 850m	1	0.33			
		7 injured passenger for each 850m	2	0.67			
		10 injured passenger for each 850m	3	1			
5	Number of killed users	No dead	0	0	0	0	0
		1 à 9 dead	1	0.5			
		More than 9 dead	2	1			
6	Injury grade of injured passengers	No injured passenger	0	0	0	0	0
		slightly injured	1	0.5			
		Serious injured	2	1			
		0	0	0	60 h	3	0.75

7	Duration of NRR flooding	Less than 24 h	1	0.25			
		24 h - 48 h	2	0.5			
		2 – 4 days	3	0.75			
		More than 4 days	4	1			
8	Percentage of traffic being restored on alternative roads	0	0	0	92.92%	3	1
		0-30%	1	0.33			
		30%- 60%	2	0.67			
		More than 60%	3	1			
9	Additional time costs	Less than 15 minutes	1	0.33	6 min 5 s	1	0.33
		15-30 minutes	2	0.67			
		More than 30 minutes	3	1			
10	Traffic state on the alternative roads	fluid	0	0	dense	2	0.67
		saturated	1	0.33			
		dense	2	0.67			
		blocked	3	1			
11	Additional co2 emission	0-93%	1	0.33	152%	2	0.67
		93-224%	2	0.67			
		more 224%	3	1			

Then, ~~in order~~ to make judgments, the levels of each criterion (and sub-criterion) could be designed to show the extent of damage, cost, and recovery. Thus, for phases 3 (indicator to sub-criteria) and 2 (sub-criteria to criteria) in Fig. 12, the aggregated score of indicators should correspond to one level of criteria or sub-criteria. For ease of understanding, this study simply divides the criteria into five levels: 1 (value 0-2); 2 (value 2-4) ; 3 (value 4-6) ; 4 (value 6-8) ; 5 (value 8-10).Moreover, simple overlay operations with weights can be considered, because the sub-criteria and indicators derived from each criterion are part of its field (Table 15).

Table 15. The levels of sub-criteria and criteria.

Indicators				Sub-criteria				Criteria	
	Score	Weight	aggregated score		Level (score)	Weight	aggregated score		Level (score)
Duration of the NRR close	0.25	0.27	0.77	Functional damage of transport function	4 (0.77)	0.3	0.38	Damage to internal components	2 (0.38)
Traffic flow on the affected NRR sections	1	0,55							
Importance of closed road sections	0.83	0.18							
Number of injured users	0	0.27	0	Physical damage of individual users	0 (0)	0.2			
Number of killed users	0	0.55							
Injury grade of injured passengers	0	0.18							
Duration of NRR flooding	0.75	1	0.75	Physical damage of road structures	4 (0.75)	0.2			
Percentage of traffic being restored on alternative roads	1	1	1	Increased transport function of alternative roads	5 (1)	1	1	Effectiveness of action	5 (1)
Additional time costs	0.33	1	0.33	Resources costs of individual users	2 (0.33)	1	0.33	Efforts for action	2 (0.33)
Traffic state on the alternative roads	0.67	1	0.67	Functional damage of transport function	4 (0.67)	0.8	0.67	Damage of action	4 (0.67)

				of Cofiroute Network					
Additional co2 emission	0.67	1	0.67	Air pollution in air environment	4 (0.67)	0.2			

Next, the resilience of the studied CI (Nantes Ring Road) could be assessed (Fig. 12. Phase 4). Among existing methods, this study highlights a quantitative assessment method “probabilistic framework”, created by Mebarki et al. (2012), as an example. This method, originally created for assessing seismic vulnerability, builds mathematical models by analysing the probability of events occurring.

Furthermore, the unified theoretical approach for resilience, developed by Mebarki (2017), allows an engineering analysis for the resilience of any system, as it considers:

- The prior definition of the system, its components and sub-systems, and the expected utility functions or services, which the system should deliver. These functions or services can be described as a vector (case of multiple expected functions) or a scalar value (case of a unique function or service, or a weighted combination of the whole expected utility functions). The utility function, herein, is denoted R(t) as it depends on time.
- The evaluation of the utility function loss, which loss is denoted D_R with values ranging within the interval [0..1], i.e. no damage up to full damage respectively.
- The capacity of the system to recover at post-damage phase, where the recovering function is denoted $\square_a$, which depends on the dynamics of the system. Actually, the system can either recover, or go into worse evolution or remain at residual level with no more variation. This recovery function should be modelled by the physical behaviour or response of the system after some actions are provided.
- This recovery capacity (or worsening function) is also affected by the prior existence of available resources at internal level (within the system) or at external level (through interaction from outside the system). As it is a conditional aspect, it’s described by a probabilistic parameter denoted χ_r which is described as the combination of external or internal resources i.e. split up into two parts $\chi_{m,r}^{int}$ and $\chi_{m,r}^{ext}$.
- The capacity to manage the post-damage phase which capacity is described by a probabilistic parameter, denoted $\chi_{m,c}$.

In the present paper, the authors will consider the post-damage phase and will describe the effects of the adaptive options, which will influence therefore the recovery function Φ_a.

These adaptive options will be discussed in the present paper under various aspects:

- The efficiency of these actions in terms of recovery function
- The availability of the resources in order to set up these actions
- The secondary effects of these actions, their consequences on damage amplification as well as the cost for their setup and the expected cost of their secondary and side effects.
- The satisfaction of the multi stakeholders that are concerned by the system and its expected utility functions.

The formula details presents in Appendix D.

5.3 Limitation

The assessment framework replied to the method presented in this study aims precisely at assessing the resilience of a studied CI associated ~~to~~ with defined scenarios (Fig.~~11~~10). This approach, based on a scenario, considering both consequences and implementable actions, allows studying a CI facing a hazard with a global perspective. The objects of the presented example, both the hazard and infrastructure, remain unchanged. The values of resilience, criteria levels, and indicators change, if suggested alternative roads change. Thus, the scenarios with different alternative roads could be compared to find the better one. However, under other implementable actions, for example “creating dams”, the sub-criteria and indicators relating to “action” should be modified. The problem then arises that the values of resilience and general criteria, assessed by different indicators and sub-criteria, could not be compared. It results in the meaningless of the values of resilience and general criteria in the indicators-based assessment suggested in this study.

On the other hand, in practice, the value of resilience and general criteria, while important, is not the only significant part of the decision-making process, because resilience and general criteria are too abstract and do not contain concrete information. Only with sub-criteria and indicators in place, are CIs managers enable to understand the content of each scenario in its entirety. We can imagine now that two implementable actions are available, "Creating dams" (A), and "Suggesting alternative roads" (B). Option A has a much higher resilience value than B, since in the scenario where A is implemented, there is no significant "damage to internal components". And the "effectiveness of action" is high even though the "effort for actions" and "damage of action are both high". Based on this information, the choice of A is highly probable. ~~But~~However, a further analysis of the sub-criteria and indicators values shows that the resource costs of action A ~~is~~ are much higher than the city of Nantes can sustain. Action B becomes therefore more implementable. The set of specific sub-criteria and indicators could play a key role in practice management.

Another limitation of this guide refers to the suggested method for data collection. As it is based on existing available resources, for instance in the presented example, many pre-set indicators are rejected due to a~~le~~ lack of appreciable references or local data. Road infrastructures require the management of a large quantity of varied data (topographical, geospatial, geometric, etc.), which is often available in heterogeneous formats. Intelligent digital systems can improve data collection and integration. However, the construction and maintenance of digital data for~~of~~ road infrastructure in Europe are not enough due to an insufficient level of cooperation, inadequate information management and limited investment in research, technology and development (UNECE, 2021). Without true data, professional and particular simulation models, for example by digital twin, would be acceptable. A specific model targeting given scenarios may enable the production of ~~producing~~ useful data resources for practice management. But it ~~has~~ is a large time-consuming and high investment and is instead less effectivity and cost-efficient. Potential challenges relate to effective and convenient ways of data collection. On the other hand, for data managers, data resource building could take place from possible indicators. For serving the important indicators without available data, creating useful data resources presents a key task for local data institutions for ~~the purpose of a~~ continuous assessment.

6 Conclusion

Focusing on the indicators-based assessment of critical infrastructures resilience, this study develops a step-by-step guide for building indicator systems. The developed guide considers both the positive and negative effects of implementable actions. Three key phases (Fig. ~~9~~8) have been presented in detail for building indicator~~s~~ systems: criteria setting, indicators setting with references definition, and verification of data availability. In addition, this study provides an example to demonstrate how to use this guide. This example is based on a given scenario for the Nantes Ring Road (NRR) network: when the ring road is flooded and closed, the road network manager suggests alternative roads to the public. The results show that this guide enables to building of specific indicator systems tailored to real cases. Built indicator systems could furthermore assist CIs managers in their decision-making process as they involve the various interests of stakeholders.

Data availability

All raw data can be provided by the corresponding authors upon request.

Author contributions

Conceptualization, Z.Y. and B.B.; methodology Z.Y., K.L.; investigation Z.Y.; writing—original draft preparation Z.Y. and A.M.; writing—review and editing B.B., A.M. and K.L.; visualization, Z.Y; Data Curation, H.D and L.L; supervision B.B. All authors have collaborated, read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A

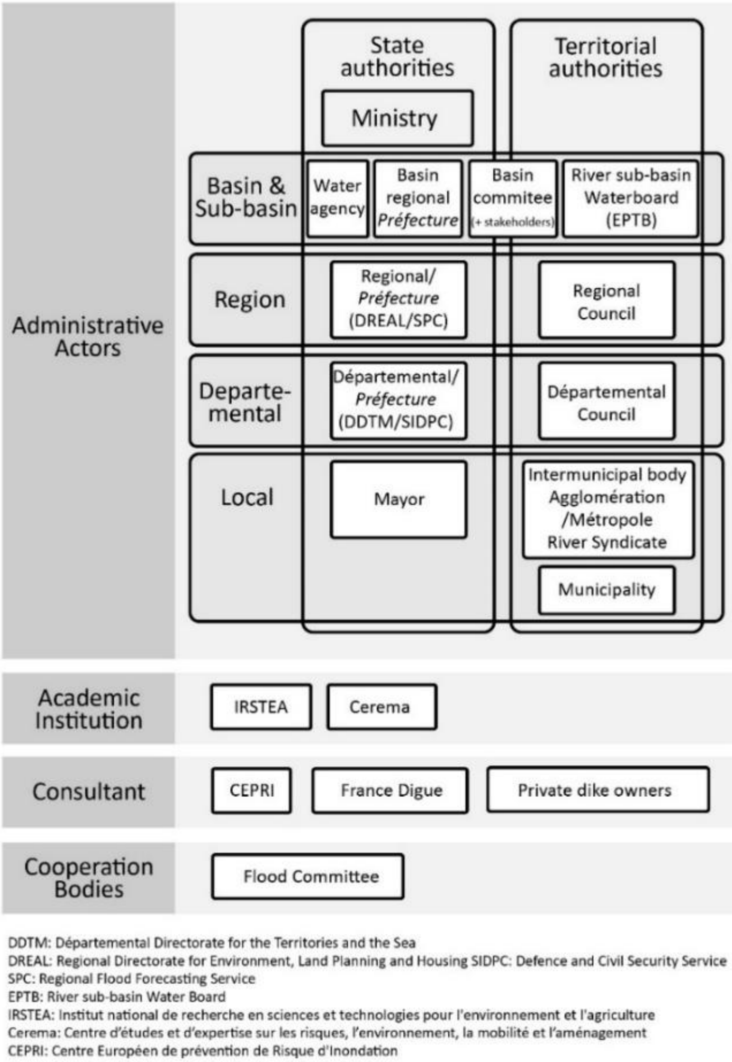

Fig. A1. Involved actors of flood management in France, source: Larrue et al. (2016) and Yang et al. (2021).

	Responsible public authority	Decision-maker	Construction services and road manager
Concession highways	State	Minister for Transport (Directorate-General for Infrastructure, Transport and the Sea DGITM)	Concession companies
Unconcessioned highways and national roads	State	Minister for Transport (Directorate-General for Infrastructure, Transport and the Sea DGITM)	Interdepartmental Road Directorates (DIR) Regional Project Management Service (SMO)
Departmental roads	Department	Departmental council	Department technical services
Municipal roads	Municipality	Municipal council	Municipal technical services

Fig A2. Involved actors of road infrastructure management in France, source: Yang et al. (2021).

Appendix B

Table B 1. Potentially usable open data websites, created by auteurs.

Organisations	Potentially applicable data	Link
Institut géographique national (IGN)	Geographic data in France	https://geoservices.ign.fr/catalogue
Data.gouv	Public data from the French State	https://www.data.gouv.fr/fr/
Institut national de la statistique et des études économiques (INSEE)	Statistics and economic studies collect, produce, analyse and disseminate information on the French economy and society.	https://www.insee.fr/fr/accueil
Ville de Nantes, Nantes métropole	Open public data provided by the City of Nantes and Nantes Métropole.	https://data.nantesmetropole.fr/pages/home/
CatNat	Database of natural disasters worldwide since 01/01/2001 Database of recognition/non-recognition of natural disasters by commune since 1982 Database of Natural Risk Prevention Plans (surveyed, prescribed or approved) by municipality	https://www.catnat.net/nos-bases-de-donnees

	Database of local emergency plans (Plans Communaux de Sauvegarde) by municipality Database of Municipal Information Dossiers on Major Risks Flood Zones Atlas database by municipality Flood Risk Territories database by municipality	
Climate central	An interactive map showing areas threatened by sea level rise and coastal flooding. Combining the most advanced global model of coastal elevations with the latest projections for future flood levels.	https://coastal.climatecentral.org/
Géorisque	Database on all types of risk in France	https://www.georisques.gouv.fr/donnees/bases-de-donnees

Appendix C

Indicator Assessment

Indicator 1 - Duration of the NRR close

According to an internal document of Cerema (2023), in February 2020, the maximum height of the Gesvres at the Jonelière station reached 251 cm and traffic ~~were~~ was closed with a disruption at lasted 56h.

Indicator 2 - Traffic flow on the affected NRR sections

Four monitoring stations and their 14 channels are involved in the affected section, Batignolles, Carquefou, Anjou, and Vignoble. The weights of the data monitored by 14 channels are calculated by the rank sum method and based on their distance ranking from the affected road and their average traffic flow: the channel closer to the affected section has a higher weight; the channel relate~~ing~~ to more traffic flow has a higher weight. The selected data are relating to the traffic flow between 7 am to 9 am (2 h) on Monday 3 February 2020 (flooding situation) and Monday 14 January 2019 (normal situation). These data have been selected mainly due to the limitations of the data available and their significance. They allow to make comparisons between flooding and normal conditions on the same day of the week. The average traffic flow of the relevant four monitoring stations is shown in Table C 1

Table C 1. Average traffic flow in normal and flooding situations, created by authors.

			Average flow in Normal situation	Straight rank	Weight	Average flow in Flooding situation
Vignoble	Inside direction	Channel 1	123.81	13	0.02	99.62
		Channel 2	108.43	14	0.01	82.86
	Outside direction	Channel 3	144.67	12	0.03	31.24
		Channel 4	200.67	11	0.04	169.33

Anjou	Inside direction	Channel 1	62.71	10	0.05	45.15
		Channel 2	135.52	9	0.06	59.43
Carquefou	Inside direction	Channel 1	113.29	5	0.10	23.29
		Channel 2	83.81	7	0.08	4.10
	Outside direction	Channel 3	79.14	8	0.07	0.00
		Channel 4	95.14	6	0.09	0.00
Batignolles	Inside direction	Channel 1	132.71	1	0.14	0.00
		Channel 2	111.52	2	0.13	0.00
	Outside direction	Channel 3	78.10	4	0.11	0.00
		Channel 4	97.42	3	0.12	0.00
Average			109.52			19.01

Indicator 3 - Importance of closed road sections

According to the BDTOPO of the department of Loire-Atlantique, the closed section has 29 parts, of which twenty are categorised as importance level 1, seven are categorised as importance level 3, and two are categorised as importance level 5. Consequently, the value of average importance is 1.76.

Indicators 4, 5 and~~,~~ 6 - Number of injured users, Number of killed users, Injury grade of injured passengers

According to the local document that describes~~descript~~ the studied flooding event, no injured, dead, or destroyed vehicles were caused by this flood event.

Indicator 7 - Duration of NRR flooding

According to Cerema (2023), NRR was inundated for 60 h (Fig. C). The duration of the NRR being flooded differs from the duration of the NRR being closed. ~~because roads~~ NNR do not need to be closed if the flooding does not affect the traffic function. The duration of the NRR being flooded is about the physical damage to road infrastructure, while the duration of the NRR being closed is related to the functional damage to road infrastructures.

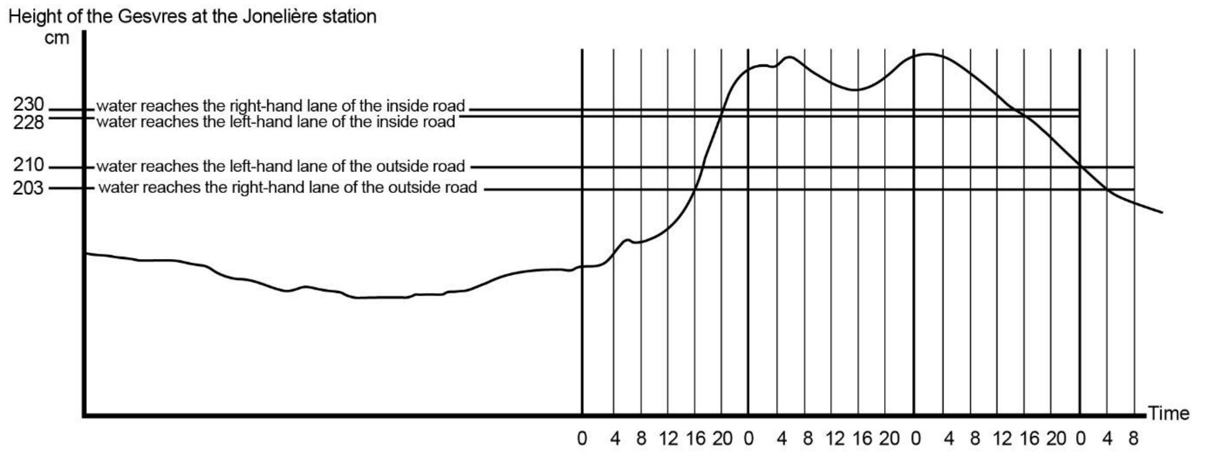

Fig. C. Duration of the NRR (inside and outside roads) being flooded, created by authors.

Indicator 8 - Percentage of traffic being restored on alternative roads

In the ~~The~~ closed section shows in Fig. 9, according to Cerema (2023), there ~~are~~ were 4800 passages increased on the alternative path of inside direction on Sunday 2 February 2020 between 6 pm to 7 pm (1h). Therefore, the selected data ~~are~~ relat~~eing to~~ the traffic~~s~~ on NRR between 6 pm to 7 pm on Sunday 2 February 2020 (flooding situation) and Sunday 20 January 2019 (normal situation). Because of the road closure, traffic on all four monitoring stations ~~is~~ was affected and their traffic flow is shown in Table C 2 below. It can be seen that the closer the road is to the affected section, the more it ~~is~~ was affected. 5 166 passengers were lost in one hour in the inside direction of the NRR, of which 4 800 ~~are~~ were received by the alternative path.

Table C 2. Total traffic number in normal and flooding situations, created by authors.

Station	Direction	Channel	Total traffic in Normal situation	Total traffics in Flooding situation	Additional traffic on alternative road during closure
Batignolles	Inside direction	Channel 3	1 360	1	4 800
		Channel 4	667	0	
Carquefou	Inside direction	Channel 3	1 276	213	Reduced traffic on NRR during closure
		Channel 4	630	25	
Anjou	Inside direction	Channel 1	1 217	551	5 166
		Channel 2	728	279	
Vignoble	Inside direction	Channel 3	1 142	963	Percentage of traffic being restored
		Channel 4	647	469	92.92%
Total			7 667	2 501	

Indicator 9 and 11 - Additional time costs, Additional co2 emission

Based on the study of Yang et al. (2021), additional travel time and additional CO^2 emissions for each vehicle that passes the four alternative roads are shown in Table C 3. Moreover, this study adds the weight of each path is based on the total traffic of the original paths of both sides, in a normal situation. For example, a normal situation refers to 15 h 48 (0 am to 3.48 pm) on Monday 14 January 2019, which corresponds to a flooding situation, 15 h 48 (0 am to 3.48 pm) on Monday 2 February 2020. Thus, the weight of External direction (E) or Internal direction (I) may be defined as Eq. (1):

$$w\ (E,I) = \frac{T(E,I)}{TT}/2$$

"T" is the traffic inof internal or external directions. "TT" is the total traffic of both two directions. Consequently, the average additional travel time is 6 min 5 s and the average growth rate of CO^2 emission is 152%.

Table C 3. Additional travel time and CO_2 emission for each alternative path, adjusted from Yang et al. (2021). "F"=flooding situation, "N"=normal situation, "o"=outside direction, "i"=inside

Start and arrival point	Paths	Distance (m)	Travel time	CO_2 emission (g)	Traffic of two directions in normal situation	Total traffics	Weight
Outside direction, from C to A	No1	3 676	2 min 46 s (166 s)	610	Traffic of external direction : T(E) = 17 543	T=36 261	0.243
	Fo1	9 732	8 min 17 s (497 s)	1 615			
	/		5 min 31 s (331 s)	growth rate : 165%			
Outside direction, from D to A	No2	4 867	3 min 40 s (220 s)	808			0.243
	Fo2	10 536	9 min 00 s (540 s)	1 749			
	/		5 min 20 s (320 s)	growth rate : 116%			
Inside direction, from B to D	Ni1	3 605	2 min 42 s (162 s)	598	Traffic of internal direction : T(I) = 18 718		0.258
	Fi1	11 125	9 min 50 s (590 s)	1 847			
	/		7 min 8 s (428 s)	growth rate : 209%			
Inside direction, from A to D	Ni2	4 731	3 min 32 s (212 s)	785			0.258
	Fi2	10 151	8 min 53 s (533 s)	1 685			
	/		5 min 21 s (321 s)	growth rate : 115%			

Indicator 10 - Traffic state on the alternative roads

According to the private document of Crema (2023), during NRR closures, the alternative roads carriedy too much traffic and caused congestion, especially during the morning and evening rush hours. Furthermore, level normalisation is necessary for the indicators with a variable number of reference levels but corresponding to the same criterion (Table 14).

Appendix D

Resilience assessment formulas

1. Stakeholders and global satisfaction

Since various adaptive options can be setup, it's important to investigate their global cost as well as their efficiency, besides the satisfaction of the stakeholders. In fact, this satisfaction can be very subjective. However, there is also an objective way to quantify this satisfaction through statistics.

We propose then the following modelling Eq. (2):

$$E_{sh\_satisfaction} = E_{pa} \cap \bar{E}_{da}$$

Where:

- $E_{SH\_satisfaction}$ = event for which the stakeholders are satisfied, with probability of occurrence denoted $P(E_{SH\_satisfaction})$
- E_{pa}= Event of efficient action against the first hazard, with probability of occurrence denoted $P(E_{pa})$
- E_{da}= Event of damaging side effect of first action, with probability of occurrence denoted $P(E_{da})$. The complementary event is denoted $\bar{E}_{da}$, i.e. it is related to non-damaging side effects.

So that the probability of satisfaction can be written as Eq. (3):

$$P\left(E_{sh_{satisfaction}}\right) = P\left(E_{pa}\right).P\left(\{\bar{E}_{da}|E_{pa}\}\right) \xrightarrow{yields} P\left(E_{sh_{satisfaction}}\right) = P\left(E_{pa}\right).(1 - P\left(\{E_{da}|E_{pa}\}\right))$$

With Eq. (4) and Eq. (5):

$$P(E_{Pa}) = P\left(E_{availabilityOfRequiredResources}\right).P\left(\{E_{pa}|E_{availabilityOfRequiredResources}\}\right)$$

$$\xrightarrow{yields} P(E_{Pa}) = \begin{cases} 0 : \ if \begin{cases} P\left(E_{availabilityOfRequiredResources}\right) = 0\,.or. \\ P\left(\{E_{da}|E_{availabilityOfRequiredResources}\}\right) = 1 \end{cases} \\ 1 : \ if \begin{cases} P\left(E_{availabilityOfRequiredResources}\right) = 1\,.and. \\ \left(\{E_{da}|E_{availabilityOfRequiredResources}\}\right) = 0 \end{cases} \end{cases}$$

Remark: The limit cases for which the stakeholder has 0 or 1 as satisfaction probability correspond to Eq. (6):

$$P\left(E_{sh_{satisfaction}}\right) = \begin{cases} 0 : \ if \begin{cases} P\left(E_{pa}\right) = 0\,.or. \\ P\left(\{E_{da}|E_{pa}\}\right) = 1 \end{cases} \\ 1 : \ if \begin{cases} P\left(E_{pa}\right) = 1\,.and. \\ P\left(\{E_{da}|E_{pa}\}\right) = 0 \end{cases} \end{cases}$$

The advantage of such description thanks to probabilistic modelling is that the whole parameters are objective to which are assigned metrics. These metrics, probabilities herein, are obtained by either theoretical distribution modelling or by inquiries.

2. Global cost and decision-making

Targeting resilience supposes that, as described hereabove, several adaptive options, at the post-disaster stage, or the risk reduction options and preparedness, before any disaster occurs, can be set up. These options suppose that resources are available, are well managed and that their cost are acceptable.

It is then crucial to define the global cost on which will rely the decision-making. For such global cost, we propose the following Eq. (7):

$$C_g = C_0 + \left\{P\left(E_{componentsDamage}\right) * C_{consequenceOfDamagePriorToAdaptiveOptionsByActions_{\{a_1,..,a_i,..,a_{N_a}\}}}\right\} +$$

$$\left\{\sum_{i=1}^{N_a}\left[C_{setup_{action_{a_i}}} + \left\{\left(\left(1 - P\left(E_{pa}\right)\right) * C_{action_{a_i}}\right) + \left(\mathrm{P}\left(\mathrm{E}_{da_i}\right) * \mathrm{C}_{consequence_{action_{a_i}}}\right)\right\}\right]\right\}$$

Where:

- C_0: initial cost of the whole infrastructures from the design stage until the initial service and use
- N_a: number of adaptive options, in order to solve the disturbance of the service (traffic, etc)
- $C_{setup\_a_i}$: Cost of the adaptive option i.e. design, staff, equipment, overheads, and daily service
- C_{a_i}: socio-economic consequences of non-efficiency of the adaptive option (overcome the disturbance, consider the public perception…)
- $C_{consequenceOf\_a_i}$: indirect or direct socio-economic impact of the adaptive option secondary effects

It is worth to notice that the modelling described above concerns:

- The effectiveness of action as $\mathrm{P}\left(\mathrm{E}_{pa}\right)$
- The effort of action as $C_{setup_{action_{a_i}}}$
- The damage of action as $\mathrm{P}\left(\left\{\overline{\mathrm{E}}_{da} \middle| \mathrm{E}_{pa}\right\}\right)$

Therefore, the part concerning the damage ~~on~~ to internal ~~infrastructures~~ components is partly described through the loss of utility function. This damage as well as the transformation of the weights and metrics, presented in Table~~s~~ 14 and Table 15, will be normalized and transformed into objective probabilities. This process is still under development and will be further detailed in an upcoming paper.