Analytical approaches to resilience

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Contents

1 Introduction

This report is the second deliverable, frameworks strengths and weaknesses, for project

"Resilience study: Invitation to tender for an exercise to facilitate expert frameworks for the resilience of the UK's economic infrastructure"

It is produced by University College London[1] (UCL) for the National Infrastructure Commission[2] (NIC) and the original proposal was revised according to NIC needs, and expert input on 3rd April.

The following report addressed two objectives:

1. Address the following types of analytical approaches: qualitative, semi-quantitative, indicator-based, top-down economic, probabilistic risk-based, performance loss[3], stress-testing, consequence-based, minimum standard.
2. For each framework, answer the following questions: sources describing approaches; input data; system-based; which questions these approaches could answer; is its primary use related to monitoring or to decision-making?

The proposed categories indicate a broad interest of the NIC in analytical approaches to resilience.

Different principles of classification were used to form this list. For example, *qualitative* is related to qualitative-quantitative epistemological dichotomy of data and methods, *performance loss* is related to the estimation of resilience value on system's output, while *stress-testing* is related to experimentation on the (configuration of) system if it would work in certain conditions.

The proposed list of categories indicate that this list might be extended, both within the existing principles of classification and incorporation of other principles of classification. For example, *probability* is a branch of mathematics that allows to simulate the world in the absence of a sufficient deterministic cause-effect relationships; a probabilistic model may be used for the same purpose as a heuristic model.

A structured description is introduced and used to describe both analytical approaches to resilience and the proposed categories. This work assumes that the 'analytical approach' is a class of things that can be described within a set of qualities, and an individual approach can be described with values of these qualities. A quality in this set must directly or indirectly address at least one category or research question, while this description provides an overview of answers this approach could answer. Eight qualities are used to describe analytical approaches to resilience: (1) *object* of analysis, (2) principle of analytical *decomposition*, (3) applicability to *infrastructure*, (4) *aspects* of object for resilience, (5) types of *sources* of information, (6) methods of information *processing*, (7) *scale* of the object of analysis, and (8) *temporal* perspective relative to a disastrous event. This is further discussed in Section 0 (p. 6) and Section 5.1 (p. 51).

A semi Systematic Literature Review (SLR) was conducted to find the academic and grey literatures (on Scopus and Google Scholar databases respectively). Keywords were determined based on past experience of SLR and resilience studies.

[1] https://www.ucl.ac.uk/
[2] https://www.nic.org.uk/
[3] The original name was 'resilience loss' in context to the previous report [64] to the NIC which contains an overview of resilience assessment approaches with the emphasis on performance-based assessment. With a system having resilience as an emergent property, the change in the system may result in a change of resilience value, which is produced by a resilience assessment approach. Resilience loss is addressed with approaches that deal with the changes in the systems, an example of such approach is provided in the paper on resilience toolbox [63], currently under review. Therefore, 'resilience loss' seems is replaced with 'performance loss'.

The search strategies included:

1: ((resilien*) AND (assess* OR evaluat* OR criteria*) AND (nation* OR region*) AND (infrastructure*) AND (“best practice*” OR benchmark* OR standard*))

The first search strategy has been applied in Scopus data base with the following limitations TITLE-ABS-KEY ((resilien*) AND (assess* OR evaluat* OR criteria*) AND (nation* OR region*) AND (infrastructure*) AND ("best practice*" OR benchmark* OR standard*)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "DECI") OR LIMIT-TO (SUBJAREA , "MATH")). This search was done on 19 March 2019 16:25 PM and the total search result was 89 papers which reduced to 25 papers after topic and abstract reviewing. Topic and abstract reviewing were carried out to choose the most relevant papers that align with the objectives of the proposal.

2: (resilience OR resilient) AND (assessment OR evaluation OR criteria) AND (national OR regional) AND (infrastructure) AND ("best practice" OR benchmark OR standard)

The second search strategy applied in google scholar on 20 March at 16:12 PM. The result was 348000 papers. Topics and abstracts of papers in the first 11 web pages has been reviewed to identify the most relative ones. The google scholar papers were not very recent but they were highly cited papers. However, we had the most recent papers from the Scopus data base, which was a complement to google scholar result. Furthermore, a separate google search was conducted to identify the existing national tools and frameworks for resilience assessment. The result includes CERT Resilience Management Model (CERT®-RMM), The Australian Natural Disaster Resilience Index, The Regional Resilience Assessment Program (RRAP).

Section 3 (p. 9) contains structured descriptions of approaches, while Section 0 (p. 47) contains structured descriptions of the categories.

2 Properties of resilience approaches

An analytical approach may be described with a set of properties (quality or characteristic) having specific values (values of predicates in predicate logic). If no approach is fitting to the needs, then new one may be assembled or an existing may be modified by changing values in one or multiple properties.

Understanding of this set, each property in this set, and possible values of each property allows to understand an analytical approach, how it is used, what it allows to observe, and what would be missing in observation. Each property is described with a sub-section (from 2.1 to 2.8) that contain rationale, examples of values, and speculations on questions this property allows to address.

2.1 Object of analysis

An analytical approach requires an object of analysis. This property allows to address an abstract (a system) or concrete (National Grid the power grid operator, an organisation) thing. The limitations are intuitively evident, an organisation-based approach may not be directly applied for analysis of a social-ecological system. Examples of values are listed below; no definitions are provided for each value:

- system, socio-technical system, social-ecological system;
- community, society, city, country;
- organisation, infrastructure, economy.

Authors of many of the reviewed approaches used the word 'system' to name the object of resilience assessment. The International Council of Systems Engineering (INCOSE) defines [1] 'system' as a *construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected.*

2.2 System's decomposition principle

The INCOSE definition shows that a system consists of elements (sub-system, components, and the latter is used int his document), and a system has system-specific qualities (properties, characteristics, performance; 'aspect' is used in this document). Therefore, two principles of decomposition are selected: • component-based system's decomposition and • aspect-based system's decomposition. This property and its values provide insights into mechanics of data collection and processing.

A component-based decomposition assumes that an 'object of analysis' is a composition of interacting parts on two or more levels of decomposition, with observations and conclusions made on a functional, constructional, spatial or temporal characteristic of the system's components, their quantities and interactions.

An aspect-based decomposition assumes that an object is described as a set of qualities its components do not have or are (partially) meaningless at the level of individual components. A limited set of qualities is assumed, and an approach addresses these qualities and does not address other qualities.

2.3 Infrastructure

Infrastructure is the key type of objects in this study. Some approaches are infrastructure-specific, other infrastructure-generic. The following list contains examples of infrastructures referenced by approaches within this description, alphabetically sorted:

- buildings, communications, critical products, digital communications, electric, energy, finances, food, generic, government, healthcare, information technology, natural gas, smart city, solid waste, supply, transportation, transportation (interregional), transportation (intraregional), water, wastewater, '--'.

2.4 Aspect

An aspect is a quality of the world's objects that an approach works with and represents. Aspects may require an elaborate compound hierarchy of qualities, thus the list below contains few examples from different approaches for illustration purposes only:

- specified social resilience, general social resilience, specified technical resilience, general technical resilience;
- health and wellbeing (minimal human vulnerability, diverse livelihood and employment, effective safeguards to human health & life); economy and society (sustainable economy, comprehensive security & rules of law, collective identity & manual support); infrastructure and environment (reliable mobility & communication, effective provision of critical services, reduced exposure and fragility); leadership and strategy (effective leadership & management, empowered stakeholders, integrated development planning);
- tight/loose coupling, complex/linear interactions;
- preoccupation with failure [of all sizes]; reluctance to simplify operations; sensitivity to operations; commitment to resilience; underspecification of structures/deference to expertise.

This property has an intuitive clarity for its use, e.g. a system's quality 'tight/loose coupling' is different to 'health and wellbeing'; therefore, an approach that operates on the former is not suitable for addressing the latter, unless it addresses both.

2.5 Sources

This property names types of sources of information about the object of interest. Each type of information source, or a method of information collection has own specifics of application, required resources, advantages and limitations. The research and engineering community written volumes on research and engineering methodologies. Examples of these types are given below, in an alphabetically sorted list:

- 1-to-1 discussions, case study, census data, desk study, descriptions, economic data, experts, field measurement, focus groups, group work, household surveys, institutional surveys, interviews, land use maps, operations, questionnaire of Likert-type questions, remote sensing, stakeholder interviews, statistics, surveys, workshops.

2.6 Methods of processing information

Data and information on aspects are collected from the sources for transformation into resilience value. This transformation requires at least one step yet usually have many steps, sometimes an elaborate process with multiple alternatives and path on some stages. This sub-section lists methods of this transformation:

- a combination of methods, flood depth-damage rate curves, influence diagrams, mathematical models, modelling, network model, numerical taxonomy, principal component analysis, probabilistic models, reporting, statistical techniques, weighted aggregation

2.7 Scale

Micro-, meso-, and macro- are useful prefixes for a systematic extension objects of interest that allows to encode its scale. For example, Rose [2] has used these prefixes for describing 'economy', with microeconomic—individual behaviour of firms, households, or organizations; mesoeconomic—economic sector, individual market, or cooperative group; and top down economic—all individual units and markets combined, including interactive effects. These prefixes are used to define type- and aspect-specific scale of the object of interest:

- micro, meso, macro.

2.8 Temporal

This property addresses temporal aspect of a resilience approach, using a disastrous event as an origin point of relative temporal coordinates. The ENCORE Network Plus proposed five values: (1) during the event, (2 and 3) before and after the event, (4 and 5) long before and long after the event. Each value has specifics that are applicable to characterisation of a resilience assessment approach that are described in Objectives column of Table 1.

Table 1. A tabular representation of the resilience diagram of ENCORE Network Plus [3].

Time period	Objectives	System state	System function	Event feature
Long before	Identify possible events, know system weaknesses, plan response and restoration, prepare resources	Normal	Awareness, planning, and preparation	predisposition
Before	Monitor system, monitor threats, ensure resources are available, switch to alert state if a threat is detected	Alert	Monitor, detect, recognition	precursors
During	Stop effect propagation, core goals, manage cascade failures	Emergency	Containment, mitigation	effects
After	Resume normal operations, reverse alert/emergency, manage delayed failures	Restoration	Repair, reconfigure, replacement	impact
Long after	Understand what happened, know why it happened, plan and implement actions to improve resilience	Recovery	Reflection, learning, improvement	outcome

3 Approaches

3.1 Consultation or research groups

3.1.1 City Resilience Index

City Resilience Index was created by The Rockefeller Foundation and Arup for assessment of resilience of cities [4]. A short description of City Resilience Index is shown in Figure 1.

Purpose	Input	Output
Assess city resilience. Could be for city monitoring and assessment of all cities in the country. Too complex for villages.	Qualitative and/or quantitative 152 variables (see Table 4).	A hierarchy of quantitative indices: 52 indicators, 12 goals, and 4 dimensions (see Table 3).

Figure 1. A short description of City Resilience Index.

An analytical passport of the index is shown in Table 2, data [4] is briefly described in Table 3, while examples of data variables are shown in Table 4. In addition to the dimensions and goals, City Resilient Index names seven characteristics of resilient systems that various city systems need: reflective, resourceful, inclusive, integrated, robust, redundant, flexible.

Table 2. Passport of City Resilience Index.

Property	**Value**
Resilience	capacity of cities to function, so that the people living and working in cities – particularly the poor and vulnerable – survive and thrive no matter what stresses or shocks they encounter [4]
Object	city
Decomposition	aspects
Infrastructure	--
Aspect	4 dimensions (health & wellbeing, economy & society, infrastructure & ecosystem, leadership & strategy) as well as 12 goals and 52 indicators are listed in Table 3; characteristics (reflective, resourceful, inclusive, integrated, robust, redundant, flexible)
Sources	surveys, interviews, group work, operations
Processing	a process utilising various methods, see [5], with the main methods being Likert-type questionnaires and statistics.
Scale	Meso, macro
Temporal	long before, before, during, after, long after

100 Resilient Cities, a nonprofit organization uses City Resilience Framework [6] to help cities around the world build resilience to the economic, social and physical challenges that are increasingly part of the 21st century. The information structure and its presentation stylistics allows to make an assumption that City Resilience Framework is a copy or a close adaptation of City Resilience Index.

100 Resilient Cities defines resilience differently to The Rockefeller Foundation and Arup, as *capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience* [6]. This difference in definition may affect the data collection or decision making; however, it unlikely resulting changes in indicators and variables listed in Table 3 and Table 4.

Table 3. Data of City Resilience Index [4].

Dimension	**Goal**	**Indicator**
Health and wellbeing	1. Minimal human vulnerability	1.1. Safe & affordable housing
		1.2. Adequate affordable energy supply
		1.3. Inclusive access to safe drinking water
		1.4. Effective sanitation
		1.5. Sufficient affordable food supply
	2. Diverse livelihoods & employment	2.1. Inclusive labour policies
		2.2. Relevant skills and training

Dimension	Goal	Indicator
		2.3. Local business development and innovation
		2.4. Supportive financing mechanisms
		2.5. Diverse protection of livelihoods following a shock
	3. Effective safeguards to human health & life	3.1. Robust public health systems
		3.2. Adequate access to quality healthcare
		3.3. Emergency medical care
		3.4. Effective emergency response services
Economy and society	4. Collective identity & mutual support	4.1. Local community support
		4.2. Cohesive communities
		4.3. Strong city-wide identity and culture
		4.4. Actively engages citizens
	5. Comprehensive security & rule of law	5.1. Effective systems to deter crime
		5.2. Proactive corruption prevention
		5.3. Competent policing
		5.4. Accessible criminal & civil justice
	6. Sustainable economy	6.1. Well-managed public finances
		6.2. Comprehensive business continuity planning
		6.3. Diverse economic base
		6.4. Attractive business environment
		6.5. Strong integration with regional and global economies
Infrastructure and ecosystems	7. Reduces exposure & fragility	7.1. Comprehensive hazard and exposure mapping
		7.2. Appropriate codes, standards and enforcement
		7.3. Effectively managed protective ecosystems
		7.4. Robust protective infrastructure
	8. Effective provision of critical services	8.1. Effective stewardship of ecosystems
		8.2. Flexible infrastructure
		8.3. Retained spare capacity
		8.4. Diligent maintenance & continuity
		8.5. Adequate continuity for critical assets and services
	9. Reliable mobility & communications	9.1. Diverse and affordable transport networks
		9.2. Effective transport operation and maintenance
		9.3. Reliable communications technology
		9.4. Secure technology networks
Leadership and strategy	10. Effective leadership & management	10.1. Appropriate government decision-making
		10.2. Effective co-ordination with other government bodies
		10.3. Proactive multi-stakeholder collaboration
		10.4. Comprehensive hazard monitoring and risk assessment
		10.5. Comprehensive government emergency management
	11. Empowered stakeholders	11.1. Adequate education for all
		11.2. Widespread community awareness and preparedness
		11.3. Effective mechanisms for communities to engage with government
	12. Integrated development planning	12.1. Comprehensive city monitoring & data management
		12.2. Consultative planning process
		12.3. Appropriate land use and zoning
		12.4. Robust planning approval process

The authors of this index state [4] that both qualitative and quantitative data might be used in this index. 'The Vietnam City Resilience Index' [5] lists[4, 5] variable for both qualitative and quantitative approaches, examples are shown in Table 4.

Table 4. An example of data sources of City Resilience Index. Quantitative and qualitative variables for 1.1. Safe & affordable housing indicator of the first goal Minimal human vulnerability.

Quantitative
1.1.1 Percentage of households having private houses in the city that are granted land use right certificates (a private house is that built on a land plot and owned by an individual household and is not apartment nor rented) 1.1.2 Average housing floor area per capita in inner-city area 1.1.3 Percent HHs living in permanent or semi-permanent house
Qualitative
Question 1.1. How do you assess the city's current housing situation? Assessment criteria, best case scenario (score=10): • The city's supply of high quality and affordable housing is able to meet demand of people of different walks of life. • All residents and organizations have security of tenure and property rights for what they legally own. • The poor and the low-income people have easy and quick access to city's financial funds to buy or upgrade their homes. • Citizens and agencies get consulted on housing design and construction standards by an authorized agency. • The urban planning and the issuance of housing construction permit works effectively in the way that only few people have to live in disaster-prone areas. • The city has an emergency plan for emergency shelter and temporary housing that can accommodate a big number of people in case of disasters. Assessment criteria, worst case scenario (score = 1): • The city is not able to supply high quality and affordable housing for most citizens, especially social housing for the poor and the low income. • Very few citizens and agencies have secured their tenure and property ownership. • The poor and the low income have no access to the city's financial sources for buying or upgrading their homes. • Citizens and agencies are not consulted on housing design and construction standards. • Urban planning and housing development policy is not available, or not effectively implemented, leading to a rampant violation of urban planning and construction discipline, and many people have to live in disaster-prone areas. • The city does not have an emergency plan for emergency shelter and temporary housing.

3.1.2 City Water Resilience Approach

Supported by The Rockefeller Foundation and The Resilience Shift, City Water Resilience Approach (CWRA) [7] is developed in collaboration by Arup[6], the Stockholm International Water Institute[7], 100 Resilient Cities[8] and the Organisation for Economic Co-operation and Development[9]. A short description of City Water Resilience Approach is shown in Figure 2.

[4] Quantitative variables for '2.5. Diverse protection of livelihoods following a shock' are missing in both the English and Vietnamese versions of the document. The position of the missing data in the end of the slide 52, and similar cases below, and taking into account the present descriptions, make the following hypothesis plausible: the data descriptors for 2.5. and other indicators were cut out or replaced with bottom margins by a PDF generation or presentation software.

[5] Public documents of all documents but 'The Vietnam City Resilience Index' (discovered within a limited search) on City Resilience Index list dimensions, goals, and indicators, yet do not list variables. This exception might be explained by an access rights' incident or specifics of a communist country.

[6] https://www.arup.com/perspectives/water

[7] https://www.siwi.org/what-we-do/city-water-resilience-framework/

[8] https://www.100resilientcities.org/

[9] http://www.oecd.org/water/

Purpose	Input	Output
Assess water system resilience. Similarly to City Resilience Index, could be used for monitoring and assessment of all major water systems.	Likely, input is similar to 3.1.1 City Resilience Index, i.e. qualitative and/or quantitative 150+ variables (see Table 4).	A hierarchy of quantitative indices: 53 sub-goals, 12 goals, and 4 dimensions (see Table 6). A high-level map of the city water system.

Figure 2. A short description of City Water Resilience Approach.

An analytical passport of the index is shown in Table 5, data is briefly described in Table 6.

Table 5. Passport of City Water Resilience Approach.

Property	Values
Resilience	Water resilience describes the capacity of cities to function in the face of water-related stresses so that those living and working within the city can survive and thrive [7].
Object	infrastructure
Decomposition	aspect, component
Infrastructure	water, potential applicability to other sectors
Aspect	in water research: basic service provision, flood risk, environment, economic, socio-cultural
Sources	surveys, focus groups, 1-to-1 discussions, operations
Processing	a process utilising desk study, workshops with stakeholders
Scale	Meso
Temporal	long before, before, during, after, long after

The Resilient Shift [8] is a global initiative to catalyse resilience within and between critical infrastructure sectors. It is funded by The Lloyd's Register Foundation, with Arup as host institution, working with a diverse network of grantees. The Resilient Shift focuses in resilience value described as *delivery and maintenance of critical functions of infrastructure in ordinary and extraordinary circumstances, while critical functions of infrastructure are the ability to sustain societal needs through protecting, connecting and/or providing essential services* [8]. There is no meaningful semantic difference between this and resilience definition from Table 5, excluding the narrow focus of the latter.

Table 6. Data of City Water Resilience Approach [7].

Dimension	Goal	Sub-goals
Leadership & strategy	Empowered communities	Active community engagement and participation around water issues
		Effective communication of government programmers and policies around water
		Support for civil society institutions working on water issues
		Support for social cohesiveness and strong community networks
	Strategic vision	Incorporation of expert and technical knowledge into decision-making around water issues
		Incorporation of local knowledge and culture into decision-making
		Long-term strategy development and action planning around water
		Incorporation of social, environmental and economic benefits into decision-making around water
		Political leadership around water resilience issues
	Coordinated basin governance	Proactive coordination between and within government agencies
		Proactive coordination between government, private sector and civil society
		Promotion of clear stakeholder roles and responsibilities
		Proactive coordination with relevant upstream stakeholders
		Proactive coordination around downstream impacts
Planning & finance	Effective regulation and accountability	Dissemination of accurate data
		Enforcement of design guidelines and construction standards for water infrastructure
		Enforcement of land use regulations and zoning

Dimension	Goal	Sub-goals
		Enforcement of transparent and accountable decision-making procedures
		Effective regulation and enforcement around qualities of water service provision
	Adaptive and integrated planning	Active monitoring and evaluation and evaluation of programmes
		Incorporation of redundancy into water sources, networks and assets
		Integrated planning across interdependent urban systems
		Integrated planning with agricultures and food supply chains
		Promotion of culture, processes and resource to enable innovation
	Sustainable funding and finance	Holistic assessment of social and environmental impacts of water programmes
		Promotion of transparent financial decision-making procedures and disbursement
		Provision of sufficient financial resources for maintenance and upkeep of water infrastructure
		Provision of sufficient financial resources for new water programmes and projects
		Water and sanitation pricing for cost recovery and demand management
Infrastructure & ecosystems	Effective disaster response and recovery	Comprehensive hazard monitoring, forecasting and early warning systems
		Coordination of disaster response and recovery preparation
		Ensuring adequate funds to government for disaster recovery
		Promotion of community capacity for preparedness and response to water hazards
	Effective asset management	Active monitoring and evaluation of water infrastructure
		Ensuring adequate human capacity for operations and implementation
		Promotion of diverse infrastructure for flood protection
		Promotion of reliable supply chains for water infrastructure
		Routine maintenance and upgrade of water infrastructure
	Protected natural environments	Active monitoring and evaluation of environmental resources
		Promotion of sustainable commercial water use
		Promotion of sustainable household water use
		Protection of critical aquatic habitats and ecosystems
		Protection of groundwater and surface water resources
Health & well-being	Equitable provisions of essential services	Provision of mental health services to reduce trauma around water hazards
		Provision of physical health services to reduce trauma around water hazards
		Provision of safe drinking water
		Provision of sanitation services
		Universal affordability of water sanitation services
	Healthy urban spaces	Application of water sensitive design principles to buildings
		Introduction and enhancement of urban water amenities
		Introduction of blue and green infrastructure to neighborhoods
		Urban land development and place-making around water landscapes
	Prosperous communities	Promotion of water-related hazard insurance and emergency savings for households and businesses
		Protections around climate-related displacement
		Provision of sufficient water quality and quantity for commercial uses
		Support for improved mobility through water-based transportation
		Support for livelihoods around water

No publication were found that lists variables for CWRA similarly to The Vietnamese City resilience Index [5] (see Table 4). The clear similarity in dimensions, goals and indicators/sub-goals between

Table 3 and Table 6, and Arup as (major) contributor leads to an assumption that CWRA utilises the same type of variables and methods of as City Resilience Index (see Table 4).

City Water Resilience Approach utilises a process [7] that consists of the following steps:

1. Understand the system: (a) Establish a core team; (b) Collect background information; (c) Multi-stakeholder inception workshop
2. Assess urban water resilience: (a) Research data collection; (b) Assessment and diagnosis process; (c) Findings report; (d) Validation workshop.
3. Develop an activation plan: (a) Interpretation of results; (b) Prioritizing; (c) Develop a Joint Action Plan.
4. Implement the action plan: (a) Develop a M&E mechanism; (b) Engage Facilitators and coaches; (c) Evaluation of the baseline assessment.
5. Evaluate learn and adapt: (a) Evaluate the implementation of resilience measures; (b) Analyse changes in context and stakeholders involvement; (c) Re-assess objectives for next period.

3.1.3 Wayfinder

The Wayfinder Guide [9] was created by an international group of resilience experts, from Stockholm Resilience Centre, Resilience Alliance and the Australian Resilience Centre. The Wayfinder project started in 2016 as a part of GRAID programme at SRC, Wayfinder was launched on September 12th, 2018. A short description the Wayfinder Guide is shown in Figure 3

Purpose	Input	Output
A pathway for collaboration of stakeholders via small workshops towards resilient social-ecological systems.	40 work cards for small workshops in 15 modules of 5 phases.	The final phases are about developing and implementing strategies, and establishing a learning-by-doing culture.

Figure 3. A short description of the Wayfinder Guide.

An analytical overview of the Wayfinder Guide is shown in Table 7.

Table 7. Passport of The Wayfinder's approach.

Property	Values
Resilience	capacity of a social-ecological system to sustain human well-being in the face of disturbance and change, by buffering shocks and adapting and transforming in response to change [10].
Object	system
Decomposition	component
Infrastructure	--
Aspect	social, ecological
Sources	focus groups, experts
Processing	a process utilizing various methods, including system dynamics
Scale	meso, macro
Temporal	long before, before, during, after, long after

The Wayfinder does not set variables, it rather provides an example of Sustainable Development Goals for consideration to participants for objectives of a Wayfinder project. 17 Sustainable Development Goals of the United Nations Development Programme [11] are described with facts and target goals that can be used in variable definition for a project. The Wayfinder suggests system dynamics for simulation modelling exercises, thus guides on variable definition of this simulation modelling technique also shape variable definition for a project.

Wayfinder is a guide for multiple organisations joining efforts to improve resilience of socio-economical systems. It consists of five steps [9] each having a number of modules supported by guiding cards describing focus points and questions to discuss:

1. Coalition: A) Getting people onboard; B) Designing the process; C) Initial system exploration; Evaluation, reflection and sense-making.
2. System identity: A) Understanding aspirations and sustainability challenges; B) System components and organization; C) Towards a systems model and a change narrative; Evaluation, reflection and sense-making.
3. System dynamics: A) Understanding social-ecological interactions across scales; B) Exploring option space; C) Looking at alternative future trajectories; Evaluation, reflection and sense making.
4. Strategies: A) Understanding social-ecological interactions across scales; B) Exploring option space; C) Looking at alternative future trajectories; Evaluation, reflection and sense making
5. Learning: A) Understanding social-ecological interactions across scales; B) Exploring option space; C) Looking at alternative future trajectories; Evaluation, reflection and sense making.

3.1.4 Australian Natural Disaster Resilience Index

Australian Natural Disaster Resilience Index [12, 13] is designed for assessing the resilience of Australian communities to natural hazards. It is developed [14] within the Bushfire and Natural Hazard Cooperative Research Centres programme of Australian Government. A short description of Australian Natural Disaster Resilience Index is shown in Figure 4.

Purpose	Input	Output
Assess disaster resilience at a national scale in Australia using a standardized approach.	Various statistical and operational data on indicators, indicators dimensions, themes and capacities (see Table 9).	State of Disaster Resilience report that contains indices for coping and adaptive capacity and lower level indices (see Table 9)

Figure 4. A short description of Australian Natural Disaster Resilience Index.

An analytical overview of this index is shown in Table 8, while Table 9 lists indicators and data sources of the index.

Table 8. Passport of Australian Natural Disaster Resilience Index.

Property	Values
Resilience	capacity of communities to prepare for, absorb and recover from natural hazard events, and the capacities of communities to learn, adapt and transform towards resilience. Importantly, this definition highlights not the actual realisation of resilience but the capacities for resilience [12].
Object	country, community
Decomposition	aspect
Infrastructure	generic
Aspect	coping capacity (social character, economic capital, infrastructure and planning, emergency services, community capital, information engagement); adaptive capacity (governance, policy and leadership; social and community engagement); each theme has indicators.
Sources	surveys, stakeholder interviews, census data, economic data
Processing	various statistical techniques
Scale	meso, macro
Temporal	long before, before, during, after, long after

Bushfire and Natural Hazards CRC published [15] one document on indicators and sources of the index. This document was published at the end of 2016, it is not clear if the lists of indicators and sources were updated.

Table 9. Indicators collected within the Australian Natural Disaster Resilience Index [15].

Theme	Indicator dimension	Indicators	Data sources
Coping capacity			
Social character	Immigration	Population arrived in Australia 2001 onwards	ABS 2011 Census
	Internal migration	Households with all or some residents not present one year ago	
	Language proficiency	Population speaks English not well or not at all	
	Need for assistance	Population with a core activity need for assistance	
	Family composition	One parent families Households with children	
	Sex	Sex ratio	
	Age	Population aged over 75 Population aged under 15 Median age of persons	
	Education	Ratio of certificate/postgraduate to high school education	
	Employment and occupation	Population unemployed Population not in the labour force Population managers and professionals	
Economic capital	Home and car ownership	Population owning home outright Population owning home with a mortgage Population renting Median rent Income to mortgage differential Car ownership	ABS 2011 Census
	Income	Median total family income Low income residents	
	Employment	Single sector employment dependence Businesses employing >20 people Retail and commercial establishments	
	Economy	Economic diversity index Population growth or decline	
Infrastructure and planning	Dwelling type	Caravan, marina, manufactured home, retirement village dwellings	ABS 2011 Census
	Building codes	Buildings constructed after 1980	Geoscience Nexis Database
	Planning for natural hazards	Disaster management planning	Analysis of disaster management plans
		Land use planning	Analysis of planning schemes
		Local government financial status	Department of Infrastructure and Regional Development
Emergency services	Health response workforce	Total medical practitioners Total registered nurses Hospital beds	Australian Institute of Health and Welfare
	Emergency response workforce	Police per capita	ABS 2011 census & Productivity Commission Report on Government Services
		Ambulance officers per capita	
		Fire and emergency service personnel per capita	Annual reports
		Fire and emergency service volunteers	

	Emergency response capability	Expenditure per capita: ambulance service	Productivity Commission Report on Government Services
		Expenditure per capita: fire and emergency services	
	Remoteness	Remoteness category	ABS
		Distance to medical facility	Regional Australia Institute
		Distance to nearest major highway	
		Distance to airport	
Community capital	Household support	Adults able to get support in times of crisis from persons outside the household	Social Health Atlas
		Adults who provide support to relatives living outside the household	
		Adults whose household could raise $2000 within a week	
	Access to services	Adults who had difficulty accessing services	
	Wellbeing	Adults with self-assessed health status of fair/poor	
	Unemployment	Jobless families with children under 15	ABS 2011 Census[10]
	Volunteering	Participation in voluntary work for an organization or group	
	Place attachment	Residence in area longer than 5 years	
	Crime and safety	Crime, offences against property	State crime data
		Crime, offences against the person	
		Adults who feel very safe/safe walking alone in the local area after dark	Social Health Atlas
Information and engagement	Community engagement and hazard education	Emergency service agency expenditure on community engagement	Annual reports & budgets
		Emergency service agency community engagement strategy	
	Telecommunications	Mobile phone coverage	Department of Communications
		Broadband access	
Adaptive capacity			
Governance, policy and leadership	Institutional character	Capacity for institutional learning	Annual reports, policy documents, organization plans & budgets
		Leadership style	
		Resource levels	
		Capacity for institutional innovation	
	Policy and legislation	Age of legislation and/or policy	Legislation, policy documents, strategic plans
		Uptake of resilience strategic directions	
	Research and development	Expenditure on research and development	Annual reports and budgets
		Presence of research organizations	Regional Institute of Australia
Social and community engagement	Skills for learning	Participation in continuing adult education	ABS 2011 Census
		Population with university level education	
	Social engagement	Change in net migration rate	ABS data
		Life satisfaction	NATSEM via AURIN database
		Generalized trust	
		Having a say and local governance	Regional Wellbeing Survey
		Equity and inclusion	
		Informal social connectedness	
		Community involvement	
		Sense of belonging	
		Community economic wellbeing	
		Community leadership and collaboration	

[10] The original table (in [15]) has vertical allignment in Data source(s) column, which in combination with the multiple indicators related to a data source, made it difficult to relate an indicator to its data source in this (the footnote) and other cases.

3.1.5 Resilience, Adaptation and Transformation Assessment

Resilience, Adaptation and Transformation Assessment (RATA) framework [16] provides a method to characterize a system, identify controlling variables, analyse the current state and future desired states of an agroecosystem and evaluate its condition with respect to resilience, adaptive capacity and transformability. A short description of Resilience, Adaptation and Transformation Assessment is shown in Figure 5.

Purpose	Input	Output
Understand resilience, adaptation and transformation of agro-ecosystems to meet the Sustainable Development Goals (more in [11]). However, the RATA is a preliminary framework.	Indicators from Table 11 collected via qualitative and quantitative sources.	A systematic and consistent overview of the state of agro-ecosystems via specific and generic indicators.

Figure 5. A short description of Resilience, Adaptation and Transformation Assessment.

It is described in Table 10, while examples of variables and data sources are listed in Table 11.

Table 10. Passport of Resilience, Adaptation and Transformation Assessment framework.

Property	Values
Resilience	ability of a system to maintain high-level objectives (e.g. sustainability, rural livelihoods, ecosystem services) in the face of unknown changes or disturbance. The term resilience can be coupled with aspirational goals, or system futures which are seen as desirable or 'good' (e.g. maintain the resilience of ecosystem services), so long as it is clear that it is not the resilience per se that is desirable [16]
Object	system, social-ecological
Decomposition	component and aspect
Infrastructure	food
Aspect	category-specific indicators
Sources	desk study, statistics, descriptions, remote sensing, field measurement, hosehold surveys, land use maps, institutional surveys, etc.
Processing	an established process
Scale	meso, macro
Temporal	long before, before, during, after, long after

Table 11. Examples of indicators and sources of Resilience, Adaptation and Transformation Assessment framework [16].

Indicator	Source of information
Postulated indicators for specified resilience of irrigated rice	
Levels of fossil energy use and greenhouse gas emissions	--
Levels of agrochemical use	--
Effectiveness or irrigation infrastructure	--
Area cleared for upper catchment agriculture	--
Storage capacity of upland dams	--
Potential indicators of general resilience – current levels and trends	
Public trust in the integrity of governance	Existing social surveys; published international indices, e.g. Transparency International
Ability to change laws when new circumstances require it	Commissioned work to assess the flexibility of legislation
Openness to criticism and new ideas	Commissioned work to compare Thailand with other nations
De-centralization of power and the resources to govern	Commissioned work to assess the current governance structure
School educational levels	Published international indices, e.g. World Bank 2012
Numbers of university graduates	Published international indices
National research capability	Commissioned work to assess capability

Integration of scientific and local knowledge	Commissioned work to assess the integration
Indicators well defined and linked to theory	Quick desk study
Indicators at time and spatial scales suited to system behaviour	Quack desk study
Strong feedback to research, governance and management	Commissioned work to assess the effectiveness of linkages
Long-term funding for data collection and analysis	Size of budget relative to tasks, and duration of commitment
Land uses	Develop an index of land-use diversity. Satellite imagery would produce data rapidly
Input markets	Data will probably be held by the Thai Government
Output markets	Data will probably be held by the Thai Government
Gender roles	Statistics probably available
Cultures	Statistics probably available
Money	Statistics probably available
Energy	Statistics probably available
Potential indicators of general resilience at the focal scale – current levels and trends	
Ecosystem diversity and productivity of native vegetation rangelands	Remote sensing, field measurement
Connectivity of transhumance routes	Household surveys and land use maps
Seasonal migration opportunities	Household surveys
Participation in farmer-led institutions	Household surveys, institutional surveys, associations, political parties
Participation in farmer-led institutions	Household surveys, institutional surveys, associations, political parties
Human Development Indicators and Gender Inequality Indices	UNDP, access to education, health, communication services
Capital reserves	National accounts, availability of insurance/banking, grain stores, livestock census
Institutions governing access to shared resources	Household surveys, National laws, local policies
Example of a set of specified resilience indicators	
Index of sustainability with respect to fallowing	--
Index of sustainability with respect to herbage intake	--
Other indicators of farm-scale nutrient balance	--
Distribution of household economic self-sufficiency index	--

The Resilience, Adaptation and Transformation Assessment (RATA) procedure [16] includes four elements: (A) System Description; (B) Assessing the System; (C) Adaptive governance and management; (D) Multi-stakeholder engagement. Each element consists of sub-elements.

3.1.6 Resilience Assessment Framework

Resilience Assessment Framework [17] provides an integrated view on resilience assessment, addressing a broad variety of issues including human factors, security, geo-politics, sociology, economy etc., and increased vulnerability due to changing threats. Various indicators are collects for further analysis. A short description of Resilience Assessment Framework is shown in Figure 6. Table 12 provides a structured description of Resilience Assessment Framework.

Purpose	Input	Output
Assess three types of resilience of critical infrastructure, structural, interrogative, transformative/adaptive.	A multitude of qualitative and quantitative indicators (see Table 13 and the related text).	Resilience matrix, resilience cube, resilience ratings & benchmarking, critical elements of infrastructure (see more in [17]).

Figure 6. A short description of Resilience Assessment Framework.

Table 12. Passport of Resilience Assessment Framework.

Property	Values
Resilience	ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruption [18]
Object	infrastructure
Decomposition	aspect
Infrastructure	financial, energy, healthcare, transportation, production, water, ICT, general
Aspect	system/physical, information/data, societal/political, cognitive/decision-making, operation/business
Sources	experts, surveys, operations, statistics
Processing	an established workflow
Scale	meso, macro
Temporal	long before, before, during, after, long after

Resilience Indicator database [18] is a part of Resilience Assessment Framework. This database contains indicators and issues for resilience assessment. By February 6 2019, the database stored 2723 approved from 3039 indicators in total and 799 approved from 844 issues in total. Examples of indicators and issues are shown in Table 13.

Table 13. Examples of indicators and issues from the Resilience Indicator database [18]. Provider column contains organisations who suggested indicators and issues, namely, Bay Zoltan Alkalmazott Kutatasi Kozhasznu Nonprofit KFT (BZN), European Virtual Institute for Integrated Risk Management (EU-VRi), European Dynamics SA (ED), Applied Intelligence Analytics Limited (AIA).

ID	Type	Name	Infrastructure	Threat	Phase
4	Indicator	Can appropriate security controls requested in any case?	Transportation	All/Any	All
8	Indicator	Are aviation security measures sufficient to secure EU/EEA bound air cargo?	Transportation	All/Any	All
…	…	…	…	…	…
1004	Issue	Incident investigation	All/Any	All/Any	--
1005	Indicator	Completeness of investigation procedures	All/Any	All/Any	Anticipate / Prepare
…	…	…	…	…	…
1793	Indicator	Test bed that mimics a production environment	ICT	Cyber attack	Understand risk
1794	Issue	Number of penetration tests	ICT	Cyber attack	Understand risk
…	…	…	…	…	…
5077	Indicator	KPI-Traffic public transport flow rail & light rail train flows	Transportation	--	--
5078	Indicator	KPI-Traffic Road Network Vehicle Flows by vehicle class car flows	Transportation	--	--

3.1.7 Resilience Dividend Valuation Model

Resilience Dividend Valuation Model [19] was developed in a partnership of the RAND Corporation and the Rockefeller Foundation. This model estimates the net benefits of a resilience project. The term resilience dividend describes the net benefits associated with the absorption of shocks and stressors, the recovery path following a shock, and any co-benefits that accrue from a project, even in the absence of a shock. A short description of Resilience Dividend Valuation Model is shown in Figure 7. Table 14 provides a structured description of Resilience Dividend Valuation Model.

Purpose	Input	Output
Estimate the realized or potential resilience dividend from a project.	Statistical or operational quantitative data on assets and environment.	Resilience dividend values and key findings to guide thinking about the probable outcomes of resilience investment and

		how valuable these outcomes might be to stakeholders.

Figure 7. A short description of Resilience Dividend Valuation Model.

Table 14. Passport of Resilience Dividend Valuation Model.

Property	Values
Resilience	capacity of a system—a household, a community, an organization, or a coupled natural-human system—to prepare for disruptions from outside of the system, to recover from shocks and stresses, and to adapt and grow from a disruptive experience [19].
Object	household, community, organization, coupled natural human system
Decomposition	component, aspect
Infrastructure	--
Aspect	resource, behavior, institution, monetary
Sources	survey, operation, statistics
Processing	Mathematical mode
Scale	micro, meso, macro
Temporal	long after

Data on stocks and goods/services are collected from participants at resilience dividend valuation of these participants. Examples of data collected for two projects are introduced in Table 15, communities resilience to floods conducted by Oxfam in Nepal and households resilience to typhoons by Institute for Social and Environmental Transition-Vietnam (ISET) of Da Nang city.

Table 15. Examples of data collected for an Oxfam Nepal and projects [19].

Oxfam Nepal	ISET Da Nang, Vietnam
Assets (both productive and consumptive) for 2013 and recall data for 2010. Crop production by crop type for the 2013 season and recall data of crop choice (yes/no for 8 crops and an “others” category) in 2010. Livestock data in 2013 and recall data in 2010. Adoption of alternative crop production activities between 2010 and 2013. Behavioral decisions regarding private protection measures taken by the household between 2010 and 2013. Crop production area in 2010 and 2013. Self-reported soil fertility change (increase or decrease) between 2010 and 2013. Income changes between 2010 and 2013. Knowledge of community-level activities regarding floods in 2013. Distances to river, roads, and markets. Loss data from the 2012 event including (categorical crop losses livestock losses, and damage to structures). Access to credit and savings in 2013. Other forms of income beyond agriculture in 2013. Whether they received an early warning about the 2012 storm. What actions they took following the early warning in 2012. Opinion data on community leaders’ ability to help in times of stress in 2013.	1) ISET, along with Hue University, conducted a random selection household assessment from May to June 2012 that included demographic and economic conditions information, construction conditions of homes, household assets, and historical information regarding a household’s experience, if any, with Typhoon Xangsane (2006) and Typhoon Ketsana (2009). 2) Limited outcome data for beneficiary households of resilient housing construction and loans and savings program from 2011 to 2014 were provided by ISET. The data contain some descriptive information on household members and information such as the condition of houses before rebuild or repair, loan and savings amounts, and whether construction was completed. 3) Pre-intervention data from 2016–2017 on household needs assessment were also provided for ISET’s current work with the Women’s Union to analyze the incentives needed to scale up resilient housing in Da Nang. The assessment includes household demographics, socioeconomic conditions, current housing quality and storm-resistant features, information on damage and costs from past storms, any renovations made to the house specifically for storms, and questions about life satisfaction, social interactions, and perceptions of resilience capacity.

3.1.8 Critical Infrastructure Resilience Platform

EU-CIRCLE [20] is a pan-European framework for strengthening Critical Infrastructure resilience to climate change. A short description of Critical Infrastructure Resilience Platform is shown in Figure 8.

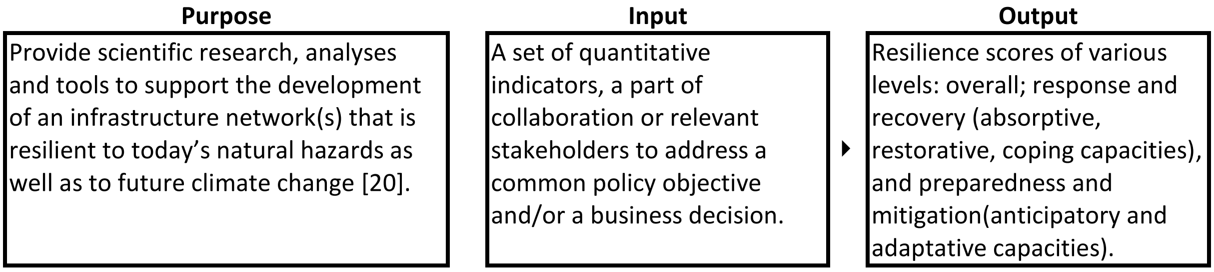

Figure 8. A short description of Critical Infrastructure Resilience Platform.

Table 16 provides a structured description of the approach of Critical Infrastructure Resilience Platform.

Table 16. Passport of Critical Infrastructure Resilience Platform.

Property	Values
Resilience	Resilience (for this and definitions below, see p. 141 in [21]). The sufficient ability of an object to continue its operational objective in the conditions including harmful impacts and the ability to mitigate and/or to neutralize those harmful impacts. Critical infrastructure resilience. The ability of a critical infrastructure to continue providing its essential services when threatened by a harmful event as well as its speed of recovery and ability to return to normal operation after the threat has receded. Critical infrastructure resilience to climate change. The ability of a critical infrastructure to continue providing its essential services when it is exposed to threats associated with coming out from the climate change harmful events as well as its speed of recovery and ability to return to normal operation after those threats has receded.
Object	infrastructure
Decomposition	component, aspect
Infrastructure	energy, transportation, digital communications, water, wastewater, solid waste
Aspect	population, economy, technology, climate
Sources	operations, descriptions
Processing	modelling
Scale	macro
Temporal	long before, before, during, after, long after

Resilience indicators are described in the project deliverable D4.5 Resilience indicators [22]. Examples of resilience indicators are given in Table 17.

Table 17. Examples of resilience indicators of Critical Infrastructure Resilience Platform [22].

Indicator	Type	Input / Estimation	Related to
1.1.1. Number of hazards related to asset or network (awareness)	number	End-user /	asset, network, network of networks
1.2.1.1. Procedures are documented	yes/no	End-user /	asset, network, network of networks
…	…	…	…
2.1.1. Number of assets fully damaged (beyond reparability)	number	/D3.4 [23]	network, network of networks
2.1.2. Number of assets partially damaged	number	/D3.4 [23]	network, network of networks
…	…	…	…
5.4.3. Reputation is increased by implementing climate change adaptation options	yes/no	end-user/	asset, network, network of networks
5.4.4. Decisions on adaptation adopt due to market forces	yes/no	end-user/	asset, network, network of networks

3.1.9 Resilience to Nature's Challenges

Resilience to Nature's Challenges is an initiative taken by New Zealand to develop and apply new scientific solution to transform the response, recovery and 'bounce-back' from New Zealand's wide diversity of natural hazards. This initiative contains multiple programmes including [24] Infrastructure and Built-Environment Solutions. A short description of Resilience to Nature's Challenges is shown in Figure 9 and structured description in Table 18.

Purpose	Input	Output
Transform response, recover and 'bounce-back' from a wide diversity of natural hazards of New Zealand. Client Value Index for post-disaster reconstruction contracting service is an example of the means above.	Most likely, a combination of quantitative and qualitative methods would be used to fill values from Table 19.	Nine PMBOK categories (time, cost, quality, integration, scope, human resources, communications, risk, procurement) split into terminal and instrumental category.

Figure 9. A short description of Resilience to Nature's Challenges.

Table 18. Passport of Infrastructure and Built-Environment Solutions, RNC.

Property	Values
Resilience	--
Object	infrastructure
Decomposition	aspect
Infrastructure	construction, and other
Aspect	time, cost, quality, integration, scope, human resource, communication, risk, procurement
Sources	surveys, interviews, focus groups
Processing	statistical techniques, reporting
Scale	micro, meso
Temporal	long before, after, long after

The research proposal [25] for this initiative contains the list of researchers, including those in infrastructure program. Some of the publications of these researchers [26] contain resilience indicators, with the most clear on indicators being Client Values Index within contracting services in post disaster situations [27, 28]. These indicators are listed in Table 19.

Table 19. Client Value Index for post disaster reconstruction contracting services, categorised by nine objectives of Project Management Body of Knowledge (PMBOK) [27, 28].

Type	PMBOK category	Values
Terminal	Time	Shorter contract time
		Timeliness
		Delivery speed in construction process and lead time
	Cost	Lower contract price
		To budget delivery/appropriate to budget
		Value for Money
	Quality	Higher standard of quality
		Information system adequacy
		Accuracy of decision making and process
		Improved organizational culture
Instrumental	Integration	Commitment to constant client satisfaction
		True friendship/partnership with all parties
		Closer relationship/flexibility in relationship
		Building a trust based relationship
		Long-term business relationship
		Continuous learning & improvement
		Minimized construction aggravation, dispute & conflict
		Efficient problem resolution procedure
	Scope	Efficiency of construction methods & techniques

		Appropriate tangibles (site facilities, documentations, claims & reports)
		Competency
		Understanding client
		Accuracy of variations/invoices & claims
		Potential for innovation & creativity
	Human resource	Internal teamwork development
		Productivity of staff
		Efficiency of leadership & coordination
		Employee empowerment
		Perceived prosocial behavior
	Communication	Communication technique & documentation
		Accessibility & responsiveness
	Risk	Security, health & safety
		Environmental protection
		Providing necessary guarantees/assurance
		Financial stability during a relationship
		Maintaining reliability through risk management
	Procurement	Availability of resources (material, labor, & plant)
		Capability of sourcing
		Willingness of use of local resources

3.1.10 Resilience Measurement Index

Argonne National Laboratory [29] created Resilience Measurement Index for assessment of critical infrastructure systems or assets to support decision-making for risk management, disaster response, and business continuity. A short description of Resilience Measurement Index is shown in Figure 10 and structured description in Table 20.

Purpose	Input	Output
Capture the fundamental aspects of resilience for critical infrastructure with respect to all hazards, support decision-management related to risk management, disaster response, and maintenance of business community.	Quantitative and qualitative answers to questions. Questions belong to so called 'level 6' (see Table 21).	Weighted aggregations for all levels from 5 to 1 (see Table 21). Each element of each category could support decision making.

Figure 10. A short description of Resilience Measurement Index.

Table 20. Passport of Resilience Measurement Index.

Property	Values
Resilience	ability of an entity - e.g., asset, organization, community, region - to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance [29].
Object	infrastructure
Decomposition	aspect
Infrastructure	electric, natural gas, communications, information technology, water, wastewater, transportation, critical products
Aspect	preparedness (awareness, planning), mitigation measures (mitigation construction, alternate site, resources mitigation measures), response capabilities (onsite capabilities, offsite capabilities, incident management & command center characteristics), recovery mechanisms (restoration agreements, recovery time)
Sources	focus groups, surveys
Processing	weighted aggregation
Scale	micro, meso
Temporal	long before, before, during, after, long after

The RMI is based on multi-attribute utility theory and decision analysis principles. The index has a hierarchical structure of six levels. Table 21 lists level 1 to level 4 components of the index.

Table 21. Components of Resilience Measurement Index [29]; IST stands for Infrastructure Survey Tool.

Level 2	Level 3	Level 4	IST sections
Level 1: Preparedness			
Awareness	Resilience operations	Business continuity manager Emergency management manager Information technology manager	Resilience management profile Dependencies information technology
	Information sharing	General information sharing Information technology management dependency	Information sharing Resilience management profile Dependencies information technology
Planning	New planning measures	Planning and preparedness	Security activity history and background
	Business continuity plan	Characteristics Training/Exercises Content	Resilience management profile
	Emergency operation plan or Emergency action plan	Characteristics Training/Exercises Content	Resilience management profile
	Cyber plan	Characteristics Training/Exercises Content	Dependencies information technology
Level 1: Mitigation measures			
Mitigation construction	Natural hazards	Retrofit measures Long-term plans Deployable mitigation measures	Natural hazards
	New mitigation measures	Infrastructure upgrades/redundancy	Security activity history and background
	Standoff distance	--	Racking/Deliver/Standoff
	Significant asset/area mitigation	Time before severe impact Degradation with backup	Significant asset(s) and area(s)
Alternate site	--	--	Resilience management profile
Resource mitigation measures	Electric power	Sources Alternates and backups Impact prevention	Dependencies Electric power
	Natural gas	Connections Alternates and backups Impact prevention	Dependencies Natural gas
	Communications	Connections Alternates and backups Impact prevention	Dependencies Communications
	Information technology	Connections Alternates and backups Impact prevention	Dependencies Information technology
	Water	Sources Alternates and backups Impact prevention	Dependencies Water
	Wastewater	Discharge services Alternates and backups Impact prevention	Dependencies Wastewater
	Transportation	Alternates and backups and Impact prevention for Rail, Air, Road, Maritime, Pipeline	Dependencies Transportation

	Critical products	Alternates and backups and Impact prevention for Chemicals, Fuels, Byproducts/Wasters, Raw materials	Dependencies Critical Products
Level 1: Response capabilities			
Onsite capabilities	New response measures Incident management capabilities	Communications and notification Incident response Immediate onsite response Significant onsite response	Security activity history and background Resilience management profile
Offsite capabilities	First preventers / responders interaction	Written MOU/MOA Onsite visits Communications	First preventers / responders
	Resource service level agreements	Contingency/business continuity plans (Electric power, Natural gas, Communications, Information technology, Transportation, Critical products, Water, Wastewater)	Dependencies
	Equivalent number of dependencies	--	Dependencies
Incident management & command center (IMCC) characteristics	Local emergency operation center involvement	--	Resilience management profile
	Facility IMCC characteristics	Primary IMCC Backup IMCC	Resilience management profile
Level 1: Recovery mechanisms			
Restoration agreements	Information sharing	MOU/MOA existence MOU/MOA activation After-action reporting	Information sharing
	Resources restoration agreements	Provider priority plan for restoration (Electric power, Natural gas, Communications, Information technology, Transportation, Critical products, Water, Wastewater)	Dependencies
Recovery time	Significant asset/area recovery	Time to recover Specialised materials	Significant asset(s) and area(s)
	Resources recovery	Time before full resumption of operations (Electric power, Natural gas, Communications, Information technology, Transportation, Critical products, Water, Wastewater)	Dependencies

The RMI levels 5 and 6 questions were developed from the following standards on resilience and business continuity:

- British Standards Institute 25999 Standard on Business Continuity (BSI, 2010);
- NFPA 1600 Standard on Disaster/Emergency Management and Business Continuity Programs (NFPA, 2010);
- ANSI/ASIS SPC.1-2009 Standard on Organizational Resilience (ASIS, 2009); and
- ISO 22301 Societal Security – Business Continuity Management Systems – Requirements 06-15-2012 (ISO, 2012).

Table 22 provides an example of calculation of a level 5 index using level 6 yes/no questions.

Table 22. An example for levels 5 and 6. Business continuity plan exercises index [29].

Business continuity plan exercises components (level 6)	**Answer**	**Value**	**Level 6 weight**	**Weighted index**

Tabletop (practical or simulated exercise) - does not include external responders.	Yes	100	0.131	13.1
Tabletop—includes external responders.	No	0	0.161	0
Functional (walk-through or specialized exercise) - does not include external responders.	Yes	100	0.196	19.6
Functional - includes external responders.	No	0	0.241	0
Full-scale (simulated or actual event) - does not include external responders.	No	0	0.285	0
Full-scale - includes external responders.	No	0	0.343	0
Exercise or actual event results are documented; corrective actions are identified and reported to executive management.	Yes	100	0.255	25.5
Level 5 Business continuity plan exercises index (BSCPEI)			**Value:**	**58.2**

BCPEI is calculated from the data in Table 22 using the equation below.

$$BCPEI = \sum_{i=1}^{7} a_i \times Z_i$$

where:

$BCPEI$ is Business continuity plan exercised index, level 5, ranging from 0 to 100;

a_i is scaling constant (weight) indicating the relative importance of possibility $i \in [1, 7]$ for business continuity plan exercises; and

Z_i is value of component i of business continuity plan exercises (0, if not present, or 100, if present).

3.1.11 Flood Risk Measurement for Communities

Zurich Flood Resilience Alliance [30, 31] developed and used the Flood Risk Measurement for Communities (FRMC), with a structured description provided by Table 23. A short description of Flood Risk Measurement for Communities is shown in Figure 11.

Purpose	Input		Output
Measure flood risks of communities (villages) and guide communities towards a higher resilience against flood risks.	A set of qualitative and quantitative questions.	▸	Quantitative indices for seven categories listed in Table 24.

Figure 11. A short description of Flood Risk Measurement for Communities.

Table 23. Passport of Flood Risk Measurement for Communities.

Property	Values
Resilience	ability of a community to pursue its development and growth objectives, while managing its flood risk over time in a mutually reinforcing way [30]
Object	community
Decomposition	aspect
Infrastructure	--
Aspect	financial, human, natural, physical, political, social, process and institutions
Sources	interviews, workshops
Processing	mathematical model
Scale	micro, meso
Temporal	long before, before, during, after, long after

According to MacClune et al. [31] this approach collects data using a set of questions, with a large yet incomplete number of questions given in their work. An earlier and full version of this set was made available by Saxena [32], this set is shown in Table 24.

Table 24. Indicators of Flood Risk Measurement for Communities [31, 32].

ID	Indicator

Financial	
52	Percent Income Earners per HH (from demography tab)
52	Percent Agricultural occupations (of Income Earners) (from demography tab)
78	% Member of savings or credit groups
116	Percent of HHs who borrowed
81	Percent of those in need who couldn't borrow (of people who tried to borrow)
84	Avg. Interest Rate (%)
89	Average Total HH Income
100	% of HHs with Insurance
Human	
2	# of Death from Flooding (-.o5*# of deaths)
50	Percentage of 'vulnerable'
51	% of HH w/ 5+ years education
54	% of Household Migrants
55	Average Months way per migrant / year
56	% Migrating far away (India or another country)
Natural	
7	Length of Flood Events (total per year, in months) (= #6 x #7 / 12(
62	Average Ag. Land (all HH (crop tab)
64	Kgs Sugarcane
65	Kgs All cereals (including pulses)
71	Avg. months cereals lasted per year:
72	% HH's ag land NOT flooded
73	% of Agricultural Area submerged
74	Months per year submerged
75	Average % of ag land lost to floods
76	Average livestock units (all HHs)
Physical	
14	Condition of Feeder roads to/from village Very Poor: 1, Poor 2, OK: 3, Good: 4, Very Good: 5
18	Are bus services disrupted in the monsoon? Yes: 1, No: 0
19	Condition of Bridges Very Poor: 1, Poor 2, OK: 3, Good: 4, Very Good: 5
20	How many community managed boats?
43	% Households with cell phone
57	% of Households with access to LPG/cooking gas
58	Percent of HH using open defecation
91	Average rating of strength of home
92	Average distance to river (km)
94	Avg. cost to rebuild/repair (of HH damaged)
99	% House OR Other Damage
102	% With an evacuation center present
103	Avg. Condition of evacuation center
Political	
22	# of CC adaptation activities/works in the community
23	Is the gov. timely to respond to community needs following a flood event? Yes: 1, No: 0
24	Does the gov. provide provisions during flood events? Yes: 1, No 0
25	Does your political representative listen to your concerns? Yes: 1, No: 0
26	How often your rep. meet with the community? Rarely/never: 1, Sometimes: 2, Often: 3
Social	
21	Do you meet with Neighboring Villages to discuss flood prep. and response? Yes: 1, No: 0
104	% Where there's been a drill/simulation organized in community
105	Avg. HHs w/ family member a member of a citizen forum/DRR group/etc.
106	Avg. HHs w/ family member involved in flood related advocacy
109	Avg. # total village relatives (this or nearby ones)
110	Avg. # relatives in cities (migrants – help or hurt resilience score?)
Process and Institutions	

27	Is there an EWS in place? Yes: 1, No: 0
28	How many times has maintenance been done to the EWS?
30	How many days does it take to prepare for a safe response to a flood event?
32	Does your community have a TFT or other DRR related institutions? Yes: 1, No: 0
33	Are DRR institutions functional for flood risk reduction? Yes: 1, No: 0
34	Have you received any training on DRR and/or EWS? Yes: 1, No: 0
35	How many cross-border citizen forums exist? Yes: 1, No: 0
37	Do you receive information from the local government about flooding? Yes: 1, No: 0
38	Does the village have a conflict resolution mechanism? Yes: 1, No: 0
39	How often is conflict resolution mechanism used by village?
40	Do you have an emergency plan in place for the village? Yes: 1, No: 0
41	Did you respond according to the village emergency plan during an emergency? Yes: 1, No: 0
111	% of HH w/access to grain bank
112	% with community/CDMC emergency or saving fund
113	% of HH receiving early warnings about floods in the past (move this to social?)
115	% of those who heard EW but ignored it

3.1.12 CERT Resilience Management Model

Caralli et al. [33] provided a comprehensive description of CERT Resilience Management Model (CERT-RMM) that addresses operational resilience of organisations. This model is a convergence of security management, business continuity management, and IT operations management resulting in a mature process-driven approach for resilience assessment and enhancement. A short description of CERT Resilience Management Model is shown in Figure 12.

Purpose	Input	Output
Evaluate and achieve resilience management goals and support the organsation's strategic directions with this capability-focused maturity model for process improvement.	Qualitative and quantitative evaluation of business processes and operations.	Values and indices of CERT resilience management model's process areas.

Figure 12. A short description of CERT Resilience Management Model.

Table 25 provides a structured description of CERT-RMM, while Table 26 contains examples of metrics for individual process areas of an organization.

Table 25. Passport of CERT resilience management model.

Property	Values
Resilience	ability to adapt to risk that affects its core operational capacities. Operational resilience is an emergent property of effective operational risk management, supported and enabled by activities such as security and business continuity. A subset of enterprise resilience, operational resilience focuses on the organization's ability to manage operational risk, whereas enterprise resilience encompasses additional areas of risk such as business risk and credit risk [33].
Object	organisation
Decomposition	component
Infrastructure	generic
Aspect	services, business processes, assets, resilience requirements, strategies for protecting and sustaining assets and services, life-cycle coverage
	asset definition and management, access management, communications, compliance, controls management, environmental control, enterprise focus, external dependencies management, financial resource management, human resource management, human resource management, incident management and control, measurement and analysis, monitoring, organizational process definition, organizational process focus, organizational training and awareness, people management, risk management, resilience requirements development, resilience requirements management, resilient technical solution engineering, service continuity, technology management, vulnerability analysis and resolution

Sources	operations, workshops, descriptions
Processing	a comprehensive methodology
Scale	micro, meso
Temporal	long before, before, during, after, long after

Table 26. Examples of metrics in selected CERT-RMM process areas [33].

Process area	**Example metrics**
Knowledge and information management	Percentage of information assets that do not have stated owners or custodians.
	Frequency and timeliness of information asset backups; frequency of backup restoration testing
	Percentage of information assets for which encryption is required and not yet implemented
Technology management	Percentage of technology assets (software, hardware, systems) for which the cost of compromise (loss, damage, disclosure, disruption of access) has been quantified
	Percentage of technology assets for which some form of risk assessment has been performed as required by policy
	Number of unauthorized changes to technology assets during a stated time interval
Service continuity	Percentage of service continuity plans tested (and number of times tested by time period)
	Percentage of service continuity plans that failed one or more test objectives
	Percentage of high-value services and supporting assets that do not have service continuity plans
	Percentage of unmet recovery time objectives and recovery point objectives
Vulnerability analysis and resolution	Percentage of high-value assets that have been monitored, assessed, and audited for vulnerabilities within a stated time interval
	Percentage of vulnerabilities that have been satisfactorily remediated, by time interval
Resilience requirements definition	Percentage of services and assets for which resilience requirements have been defined and documented (or conversely, for which requirements are not stated or are incomplete)
	Elapsed time between identification of new assets and the development of resilience requirements for those assets

3.2 Individual researchers or projects

3.2.1 Essential services for socio-technical systems

van der Merwe et al. [34] developed a conceptual index for assessing the resilience of essential services produced by socio-technical systems. A short description of Essential services for socio-technical systems is shown in Figure 13 and structured description in Table 27.

Purpose	**Input**	**Output**
Conceptualise different aspects of resilience in complex adaptive socio-technical systems.	Expert opinions on indicators listed in Table 28.	Evaluation of different types of resilience at different levels of organizational management (see Table 28).

Figure 13. A short description of Essential services for socio-technical systems.

Table 27. Passport of essential services for socio-technical systems.

Property	**Values**
Resilience	capacity of complex adaptive socio-technical systems to sustain the production of essential services in the face of disruption and ongoing social, technological, and environmental change [34]
Object	socio-technical system
Decomposition	aspect
Infrastructure	generic
Aspect	specified social resilience, general social resilience, specified technical resilience, general technical resilience
	characteristics (reflective, resourceful, inclusive, integrated, robust, redundant, flexible)
Sources	various methods in sections 'Building XY resilience' and 'Assessing XY resilience'
Processing	a process utilising various methods in sections 'Building XY resilience' and 'Assessing XY resilience'

Scale	micro, meso
Temporal	long before, before, during, after, long after

This approach differentiates between (a) operational (daily procedures), tactical (management), and strategic (organisational transformation) leadership; and (b) resilience to specific and generic hazards, and resilience of technical and social systems. This approach differentiates between, specified technical resilience, specified social resilience, general technical resilience, general social resilience. Four types of resilience on three leadership levels form twelve areas of concern. The authors propose qualities for each area, 34 qualities in total; these qualities may be represented with indicators. The indicators are listed in Table 28.

Table 28. Quadrant-specific indicators of resilience at different organisational levels [34].

Type of resilience	Indicators of persistence at operational level	Indicators of adaptability at tactical level	Indicators of transformability at strategic level
Specified technical resilience	Infrastructure and assets well managed to required standards, including regular maintenance and tests of back-up technologies. Deploy standardized redundancy criteria, have redundant equipment available, and have efficient access to operational spares to restore network disruptions.	Technical standards are adaptively revised to incorporate learning; adaptive assessment approaches are applied, and a portfolio of technical investments exists for disaster risk reduction. Strategic spares are available for contingencies and response. Engineers consider build-back-better and failto-safe design philosophies.	Strategic commitment to invest in resilience, reserve margins, and self-healing capabilities. Decision making considers effects of decisions on resilience of critical processes. Adopt a modular substation design strategy; although initial cost is higher, it can allow standardization on spares and speeds up recovery.
Specified social resilience	Competent in decisions that require attention to detail and precision across multiple recurring iterations. Competent in execution of standard operating procedures, emergency roles and responsibilities, ability to execute preapproved response plans, and ability to participate effectively in simulation exercises.	Competent in semistructured decisions and ensuring efficient and effective use of resources through business planning, logistics coordination, and operational improvements. Contingency arrangements, response plans, and risk reduction strategies are systematically reviewed and adaptively revised to incorporate learning. Response structures effectively integrate across functions.	Competent in unstructured decisions that are complex, ambiguous, and far-reaching in scope, entail high levels of uncertainty, and often pertain to nonlinear risks in the external environment. Commitment to resilience through visible leadership in good-practice disciplines such as emergency preparedness and business continuity management. Ownership of contingency arrangements, knowing and testing established plans, and actively participating in emergency simulation exercises. Ability to anticipate and avoid “foreseeable, predictable, avoidable surprises”.
General technical resilience	Able to operate adaptive technology under pressure and maintain back-up and contingent systems components. Technical capabilities that allow operational flexibility often beyond the infrastructure itself.	Review asset condition monitoring practices and test results of deployed technologies that provide adaptive capacity and strengthen systems flexibility. Consider technology solutions beyond the infrastructure system.	Proactive investment in systems flexibility (in electricity supply, these include smart metering, smart grid, containerized mobile substations, demand-side products, and supply-side mix).

General social resilience	Monitor whether people feel empowered to act in the interest of safety and resilience if contrary to what is expected. Able to follow intuition based on deep experience in situations that necessitate that rules be broken. During extreme events, be comfortable to apply an incident command system to perform emergency operations, even under great pressure. Employ fail-to-safe scenarios in emergency exercises that stretch people beyond the plan.	Able to network and mobilize support through strong social networks, third-party agreements, and memorandums of understanding that have been established. Monitor for signs of restorative or retributive justice exercised in supervision. Identify heuristics used on the frontline, verify the validity to formalize and spread guiding heuristics to be used in crises. During extreme events, be comfortable to coordinate planning, be able to integrate situational awareness during the incident to provide a common operational picture of unfolding events, execute tactical command, mobilize resources, and coordinate logistics to support operations.	Actively build a culture of resilience and safety, with restorative justice in word and deed; the ability to anticipate and avoid predictable surprises. Evidence that they value and actively build social and psychological capital in their networks and through their leadership, practice adaptive management, and encourage decentralized self-organization during disruption. Strengthen external and internal connections in functions, across disciplines, and with other sectors. During extreme events, be comfortable to fulfill the incident commander role, be able to see the big picture, prioritize objectives, take decisions in spite of incomplete information, and recognize when a phase change is evident or a regime shift has taken place.

3.2.2 Normal Accident Theory

Perrow [35] (accessed via [36]) identified two system qualities that are present in high-risk technologies, 'interactive complexity' and 'tight coupling'. Interactive complexity and tight coupling open systems to accidents, thus Normal Accidents. NAT provides a general direction of enhancing resilience of a system by de-coupling components and simplification of interactions; in combination with a typology of coupling and connections, it would direct towards a smaller probability of Normal Accidents. A short description of Normal Accident Theory is shown in Figure 14.

Purpose	Input	Output
Manage the expected number of normal accidents by changing how tight/loose is coupling and how complex/linear interactions are.	Understanding of decision makers of structures of the systems and specifics of interactions.	Change (of the probability) of the number of normal accidents.

Figure 14. A short description of Normal Accident Theory.

Table 29 provides a structured description of Normal Accidents Theory (NAT).

Table 29. Passport of Normal Accidents Theory.

Property	Values
Resilience	as induced from the text: a resilient system copes or is not prone to Normal Accidents [36]
Object	system
Decomposition	components via principles
Infrastructure	generic
Aspect	tight/loose coupling, complex/linear interactions
Sources	--
Processing	--
Scale	micro, meso, macro
Temporal	long before, long after

NAT provides a general guidance of enhancing resilience of a system. An application of NAT for resilience assessment or enhancement assumes that a component-based decomposition is applied to this system, and that an additional approach may provide description of coupling and connectivity. Dolan [36] composed an infrastructure interdependency characterisation checklist, see Table 30.

Table 30. Infrastructure interdependency characterisation checklist [36].

Quality	Description	Possible states
Directionality	Whether the reliance of one element on another is mutual	Bi-directional, non-reciprocal
Order	Whether the relationship is direct or via an intermediary	First order, second order, higher order
Coupling	Whether the effects of the relationship are felt closely in time and spare or not	Loos, tight
Location	Whether the element of interest provides or receives a resource	Upstream, downstream
Type	The nature of the relationship, spatially or in terms of resource flow	Physical, digital, geographic, organizational
Interaction type	The degree of co-operation and structure of the relationship	Competition, symbiosis, integration, sill over
Functionality	Whether the relationship is an integral part of the function of the elements or not	Functional, non-functional
Necessity	Whether the relationship is unavoidable or required, or whether there is flexibility	Necessary, optional
Outcome	Whether the effect of the relationship on the element of interest in positive or negative	Benefit, dis-benefit
Life-cycle impact stage	The phase of the project during which the effects of the relationship are relevant	Planning, construction, operation, end of life, scenario
Geographic scale	The spatial distribution of the relationship or its effects	Project, local, national, international
Sectoral scale	Whether the relationship is contained within one infrastructure sector or not	Intra-sector, inter-sector

3.2.3 High Reliability Organisation

Models of High Reliability Organisations (HRO) [37] describe a subset of organisations having a high level of safety over long time periods. Dolan cites a statement that a HRO embodies the following five principles: (1) preoccupation with failure [of all sizes]; (2) reluctance to simplify operations; (3) sensitivity to operations; (4) commitment to resilience; (5) underspecification of structures/ deference to expertise. A short description of High Reliability Organisation is shown in Figure 15.

Purpose	Input	Output
Have an organization with a high level of safety over long periods of time.	Understanding of decision makers of topics and issues listed in Table 32.	Evaluations and (alternatives of) decisions for a high reliability organization.

Figure 15. A short description of High Reliability Organisation.

Table 31 provides a structured description of an approach that could be based on High Reliability Organisations.

Table 31. Passport of High Reliability Organisations.

Property	Values
Resilience	capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back [furthermore] resilience is not only about bouncing back from errors, it is also about coping with surprises in the moment [36]
Object	organisation
Decomposition	components via principles
Infrastructure	general

Aspect	(i) preoccupation with failure [of all sizes]; (ii) reluctance to simplify operations; (iii) sensitivity to operations; (iv) commitment to resilience; (v) underspecification of structures/ deference to expertise
Sources	--
Processing	--
Scale	micro, meso
Temporal	long before, long after

Dolan [36] summarised best practices towards higher resilience, see Table 32.

Table 32. Best practices of HRO. All references in this table applied to the Dolan's report [36].

ID	Best practice	Section
H1	High reliability should be an aspirational goal, a clearly stated priority, and at the heart of decision making processes and operations.	Tables 4, 5
H2	High reliability is created by people, enabled by supportive organisational structures. The right people and organisational culture are needed to achieve High reliability	Section 3.1.1., Figure 2
H3	The principles of HRO (Table 7) can be characterised as actions to address one or both of the high-risk characteristics (coupling and interactions) identified by NAT.	Section 3.2
H4	HRO is a useful starting point for planning how to increase the reliability of any digitally connected infrastructure systems. However, HRO is not a panacea, it cannot eliminate normal accidents, but It can reduce the likelihood (therefore frequency) and impacts of normal accidents.	Section 3.1.2
H5	HRO principles, like any intervention in a complex system can unintentionally increase complex interactivity or tighten system coupling. Therefore, HRO can have unintended consequences that increase normal accident likelihood.	Table 5, 6
H6	Achieving High reliability is not a single, one-off action. HRO is not a menu of options, rather HRO requires full implementation of HRO principles as a suite of purposeful interventions that are continuously implemented, monitored and refined.	Section 3.1.2
H7	There is a trade-off between managing for an efficient system and managing for high reliability.	Section 3.1.1, Table 7
H8	HRO is focused on organisations. Implementing HRO principles in a complex or complex adaptive system where competing priorities abound, may not be feasible. HRO needs to be adapted for use in complex adaptive systems	Sections 2.2, 3.1.1, 3.5, Table 7
H9	High reliability (like systemic resilience) is a mindset (it requires mindful implementation of principles). Symptoms of mindlessness are warning signs that must not be ignored or normalised	Section 3.1.2, Tables 6, 7

3.2.4 PCA and NT processing Liker-type questionnaire

Shirali et al. [38] used Principle Component Analysis (PCA) and Numerical Taxonomy (NT) for processing data collected with Likert-type questionnaires from experts working in different parts of organisation. A short description of PCA and NT processing Likert-type questionnaire is shown in Figure 16.

Purpose	Input	Output
Quantify the most and the least resilient process/unit in a processing organization.	Likert-type questionnaire answered by experts of processes/units	Numerical ranking of the most and least resilient processes/units, both overall and aspect-related (see groups in Table 34)

Figure 16. A short description of PCA and NT processing Liker-type questionnaire.

Table 33 provides a structured description of PCA and NT for processing data from Likert-type questionnaires.

Table 33. Passport of PCA and NT for processing data from Likert-type questionnaires.

Property	Values
Resilience	The article [38] does not explicitly define resilience; however, provides two examples:

	(1) capability of a system to create foresight, to recognize, to anticipate the changing shape of risk before adverse consequences happen; (2) inherent ability of a system to adapt its functioning before and during disturbances, so that it can continue operations after a major mishap or in the presence of continuous stresses.
Object	system
Decomposition	component and aspect
Infrastructure	--
Aspect	top management, just culture, learning culture, awareness and opacity, preparadness, flexibility
Sources	focus groups, questionnaire of Likert-type questions
Processing	principal component analysis, numerical taxonomy
Scale	micro, meso
Temporal	long before, long after

This approach uses six groups of qualities, each group is measured with a set of Likert-type questions ranging from 5 to 15 questions in a group, 61 question in total. This questionnaire is given to a selection of experts, where groups are representing a sub-system of a system. The results are analysed using Principle Component Analysis and Numerical Taxonomy. The result provides a relative resilience ranking of sub-systems on six qualities.

Table 34. Examples of questions for Likert-type questionnaire.

Group	Question
Management commitment	1. My superior director appreciates my work. … 9. My superior manager gives me constructive feedbacks regarding work and safety/ resilience.
Just culture	10. If staffs have concerns about their safety/resilience and work, they can consult with their superiors. …
Culture of learning	21. If the system under my management fails, I am aware of the consequences. …
Awareness and opacity	36. The organization expects that I do several tasks simultaneously. …
Preparedness	47. Resilience safety culture and rules governing my organization and workplace are appropriate and they can also be used in the future. …
Flexibility	56. My access to the helping resources (facilities, time, etc.) is ideal for dealing with unexpected events. … 61. If the system collapses, it has the ability to restructure and return quickly to its original state (stable).

3.2.5 Disaster Resilience Index

Cutter et al. [39] proposed Disaster Resilience Index for measuring resilience of communities on federal level of the US. A short description of Disaster Resilience Index is shown in Figure 17.

Purpose	Input	Output
Measure baseline characteristics of communities that foster resilience. Monitor changes in resilience over time in particular places and compare one place to another.	Statistics on indicators, see Table 36.	Resilience and aspect-related scores per place (see Aspect row in Table 35).

Figure 17. A short description of Disaster Resilience Index.

Table 35 provides a structured description of Disaster Resilience Index, while variables and data sources of the index are listed in Table 36.

Table 35. Passport of Disaster Resilience Index.

Property	Values
Resilience	set of capacities that can be fostered through interventions and policies, which in turn help build and enhance a community's ability to respond and recover from disasters [39].
Object	community
Decomposition	aspect
Infrastructure	--
Aspect	social, economic, institutional, infrastructure, community capital
Sources	statistics
Processing	normalisation, weighted aggregation
Scale	meso, macro
Temporal	long before, long after

Table 36. Variables used to construct disaster resilience index by subcomponent [39]. Effect column indicates the effect of a variable values on resilience, '+' for positive and '-' for negative effect.

Category	Variable	Effect	Data source
Social resilience			
Educational equity	Ratio of the pct. population with college education to the pct. population with no high school diploma	-	U.S. Census 2000
Age	Percent non-elderly population	+	U.S. Census 2000
Transportation access	Percent population with a vehicle	+	U.S. Census 2000
Communication capacity	Percent population with a telephone	+	U.S. Census 2000
Language competency	Percent population not speaking English as a second language	+	U.S. Census 2000
Special needs	Percent population without a sensory, physical, or mental disability	+	U.S. Census 2000
Health coverage	Percent population with health insurance coverage	+	U.S. Census 2000
Economic resilience			
Housing capital	Percent homeownership	+	U.S. Census 2000
Employment	Percent employed	+	U.S. Census 2000
Income and equality	GINI coefficient	+	Computed from U.S. Census 2000
Single sector employment dependence	Percent population not employed in farming, fishing, forestry, and extractive industries	+	U.S. Census 2000
Employment	Percent female labor force participation	+	U.S. Census 2000
Business size	Ratio of large to small businesses	+	Country Business Patterns (NAICS) 2006
Health access	Number of physicians per 10,000 population	+	U.S. Census 2000
Institutional resilience			
Mitigation	Percent population covered by a recent hazard mitigation plan	+	FEMA.gov
Flood coverage	Percent housing units covered by NFIP policies	+	bsa.nfipstat.com
Municipal services	Percent municipal expenditures for fire, police, and EMS	+	USA Countries 2000
Mitigation	Percent population participating in Community Rating System for Flood (CRS)	+	FEMA.gov
Political fragmentation	Number of governments and special districts	-	U.S. Census 2002
Previous disaster experience	Number of paid disaster declarations	+	FEMA.gov
Mitigation and social connectivity	Percent population covered by Citizen Corps programs	+	citizen.corps.gov
Mitigation	Percent population in Storm Ready communities	+	stormready.noaa.gov

Infrastructure resilience			
Housing type	Percent housing units that are not mobile homes	+	U.S. Census 2000
Shelter capacity	Percent vacant rental units	+	U.S. Census 2000
Medical capacity	Number of hospital beds per 10,000 population	+	www.ahd.com
Access/evacuation potential	Principle arterial miles per square mile	+	GIS derived from National Atlas.gov
Housing age	Percent housing units not built before 1970 and after 1994	+	City and Country Databook 2007
Sheltering needs	Number of hotels/motels per square mile	+	Country Business Patterns (NAICS) 2006
Recovery	Number of public schools per square mile	+	gnis.usgs.gov
Community capital			
Place attachment	Net international migration	-	census.gov
Place attachment	Percent population born in a state that still resides in that state	+	U.S. Census 2000
Political engagement	Percent voter participation in the 2004 election	+	City and Country Databook 2007
Social capital-religion	Number of religious adherents per 10,000 population	+	Assn. of Religion Data Archives
Social capital – civic involvement	Number of civic organizations per 10,000 population	+	Country Business Patterns (NAICS) 2006
Social capital – advocacy	Number of social advocacy organizations per 10,000 population	+	Country Business Patterns (NAICS) 2006
Innovation	Percent population employed in creative class occupations	+	USDA Economic Research Service ers.usda.gov

3.2.6 Urban flood depth-economic loss curves

Wu et al. [40] used loss curve for assessing resilience of communities. Data are collected with field survey and household interviews. The population is differentiated on the basis of level of income and hazard intensity (e.g. a depth of flood water). A statistical 'loss curves' analysis is performed on this data. A short description of Urban flood depth-economic loss curves is shown in Figure 18.

Purpose	Input	Output
Evaluate disaster reduction capability, impact on types of assets, the flood depth with a maximum loss rate.	Household surveys for socio-economic data.	Disaster reduction capability, impact on types of assets, the flood depth with a maximum loss rate.

Figure 18. A short description of Urban flood depth-economic loss curves.

Table 37 provides a structured description of an approach based on urban flood depts-economic loss curves.

Table 37. Passport of an approach based on urban flood dept-economic loss curves.

Property	**Values**
Resilience	--
Object	village, town
Decomposition	aspect
Infrastructure	--, flood risk management
Aspect	receptors (residence, agriculture, industry, commerce, infrastructure); statistic unit (household, administrative village, factory, retail store, institution); different towns
Sources	surveys
Processing	flood depth-damage rate curves

Scale	meso
Temporal	long after

3.2.7 Inventory input-output Leontief's model for resilience

Galbusera et al. [41] proposed using interoperability input-output Leontief's model for resilience assessment and inventory optimisation during critical events. A short description of Inventory input-output Leontief's model for resilience is shown in Figure 19.

Purpose	Input		Output
Assess the ability of critical infrastructure to overcome shocks and optimize the preparedness for critical events, via analysis of economic relationships.	Econometric models that include parameters such as the total output of sector, ration between the contribution from one sector to another.	▸	Resilience estimated, system optimized for resilience.

Figure 19. A short description of Inventory input-output Leontief's model for resilience.

Table 38 provides a structured description of the interoperability Input-Output model for resilience assessment and inventory optimisation during critical events.

Table 38. Passport of interoperability Input-Output model for resilience assessment and inventory optimization during critical events.

Property	**Values**
Resilience	The article [41] does not explicitly define resilience, but references to dynamic economic resilience by Rose that can be found in Table 42.
Object	economy
Decomposition	component
Infrastructure	--
Aspect	inventory, economy
Sources	statistics, operations, modelling
Processing	mathematical modelling
Scale	meso, macro
Temporal	long before, during, long after

It is a mathematical model of intrinsic operability of a sector at time, planned outputs of a sector at time, inventory level of a sector at the end of time interval, repair coefficients describing the ability of a sector to recover production/service delivery capability, etc; these data might be collected from statistics and operations, or generated in a simulation model.

3.2.8 Probabilistic disaster resilience of communities

Chang and Shinozuka [42, 43] used probabilistic models to measure disaster resilience of communities. Resilience is quantified as the probability of meeting robustness and rapidity standard at an event, or a broader resilience as aggregation of resilience to a range of events. A short description of Probabilistic disaster resilience of communities is shown in Figure 20.

Purpose	Input		Output
Relate expected losses in future disasters to a community's seismic performance objectives.	Probability that the system will meet predefined performance standards in a scenario seismic event of a certain magnitude.	▸	Seismic capacity per scenario. Estimates of technical, organizational, social, or economic resilience (depends on measures, see Table 40).

Figure 20. A short description of Probabilistic disaster resilience of communities.

Table 39 provides a structured description for probabilistic disaster resilience of communities, while examples of performance measures and robustness and rapidity standards are given in Table 40.

Table 39. Passport of probabilistic disaster resilience of communities.

Property	Values
Resilience	ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes. Resilience has four main properties: robustness, rapidity, redundancy, and resourcefulness [42].
Object	system
Decomposition	aspect
Infrastructure	generic
Aspect	technical, organisational, social, economic
Sources	statistics, operations
Processing	probabilistic models
Scale	micro, meso
Temporal	long before, before, during, after, long after

Table 40. Example performance measures and standards.

Dimension of resilience (unit of analysis)	Performance measure	Robustness standard	Rapidity Standard
Technical (water system)	Network physical condition	≤1 major pump station loses function	<1 week until all pump stations and 99% of pipes intact
Organizational (water system)	Water service	<5% of population loses water service	<1 week until 99% of population has water service
Social (community)	Population living at home	<5% of population displaced from homes	<1 week until 99% of population living at home
Economic (community)	Economic activity	<5% of Gross Regional Product loss	<1 week until return to 99% of GRP

3.2.9 Multi-dimensional hurricane resilience

Ouyang et al. [44, 45, 43] describes an approach for multi-dimensional assessment of interdependent systems. The core of resilience assessment is a probabilistic model that uses data on system's structure, hazardous events, time, real and targeted performance. A short description of Multi-dimensional hurricane resilience is shown in Figure 21.

Purpose	Input	Output
Quantify the hurricane resilience of contemporary electric power systems.	Hurricane hazard model, component fragility model, power system performance model, system restoration model.	Quantified hurricane resilience.

Figure 21. A short description of Multi-dimensional hurricane resilience.

Table 41 provides a structured description of this approach.

Table 41. Passport of multi-dimensional assessment of hurricane resilience.

Property	Values
Resilience	joint ability to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation [45].
Object	system
Decomposition	component, aspect
Infrastructure	generic
Aspect	performance; technical, organisational, social
Sources	operations
Processing	mathematical models
Scale	meso, macro

Temporal	long before, long after

3.2.10 Avoided performance drop

Rose [2, 43] proposed resilience assessment that is based on the avoided drop in performance relative to the maximum drop in performance. Rose differentiates between static and dynamic resilience. For the static resilience, he proposes to use data on the economy-wide input-output multiplied, the maximum percent change in total output, estimated percent change in total output. For the dynamic resilience, he proposes to use the maximum percent change in direct output, and the estimated percent change in direct output. A short description of Avoided performance drop is shown in Figure 22.

Purpose	Input	Output
Assess economic resilience to natural and man-made disasters.	Time and volume data on system's output from a system or its model. Alternative measures to enhance resilience.	Static and dynamic resilience. Evaluation of measures to enhance resilience.

Figure 22. A short description of Avoided performance drop.

Table 42 provides a structured description of the approach based on avoided performance drop

Table 42. Passport of resilience assessment via avoided performance drop.

Property	Values
Resilience	Static economic resilience as the ability of an entity or system to maintain function (e.g., continue producing) when shocked […it is] primarily a demand-side phenomenon involving users of inputs (customers) rather than producers (suppliers). It pertains to ways to use resources available as effectively as possible. This is in contrast to supply-side considerations, which definitely require the repair or reconstruction of critical inputs [2]. Dynamic economic resilience as the speed at which an entity or system recovers from a severe shock to achieve a desired state. Dynamic resilience is more complex because it involves a long-term investment problem associated with repair and reconstruction [that] involves serious tradeoffs [2].
Object	organisation
Decomposition	aspect
Infrastructure	--
Aspect	economic
Sources	operations, interviews
Processing	mathematical models
Scale	micro, meso, macro
Temporal	long before, before, during, after, long after

3.2.11 Time-driven resilience for multi-hazard environments

Ayyub [46, 43] used time in assessing systems resilience in multihazard environments. The following time-based data items are used in his set of mathematical equations: time to incident, time to failure, time to recovery, and derived data items, disruption duration, failure durations, recovery duration. A short description of Time-driven resilience for multi-hazard environments is shown in Figure 23.

Purpose	Input	Output
Effective decision-making tool for multihazard environments,	Times to incident, failure, recovery, and their derivatives, e.g. disruption duration.	Resilience value.

Figure 23. A short description of Time-driven resilience for multi-hazard environments.

Table 43 provides a structured description of this approach of resilience assessment for multihazard environments.

Table 43. Passport of time-based systems resilience for multi-hazard environments.

Property	Values
Resilience	ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of the deliberate attack types, accidents, or naturally occurring threats or incidents. The resilience of a system's function can be measured based on the persistence of a corresponding functional performance under uncertainty in the face of disturbances [46].
Object	system
Decomposition	aspect
Infrastructure	generic
Aspect	time
Sources	operations
Processing	mathematical models
Scale	micro
Temporal	long before, long after

3.2.12 Performance over time for resilience assessment

Dessavre et al. [47, 43] analysed various approaches based on 'performance-over-time' concept.. If a system is insufficiently resilient, then the system under pressure of a hazard decreases the output value, with this under-delivery accumulating over time. Therefore, resilience value is a ratio of the delivery under disruption and the expected delivery. A short description of Performance over time for resilience assessment is shown in Figure 24.

Purpose	Input	Output
Characterise and visualise the resilience behavior of complex systems.	Performance and time data from a system or its model.	Resilience value.

Figure 24. A short description of Performance over time for resilience assessment.

Table 44 provides a structured description of this performance-over-time resilience assessment approach.

Table 44. Passport of performance over time resilience assessment approach.

Property	Values
Resilience	--
Object	system
Decomposition	aspect
Infrastructure	generic
Aspect	performance, time
Sources	operations
Processing	mathematical models
Scale	micro, meso
Temporal	long before, long after

3.2.13 Performance, duration and restoration

Vugrin et al. [48] developed a framework for assessing resilience of infrastructure and economic systems. Resilience calculation utilises data on system's performance, recovery duration, and recovery effort. Absorptive, adaptive and restorative capacities of a system are evaluated. A short description of Performance, duration and restoration is shown in Figure 25.

Purpose	Input	Output
Define infrastructure-specific resilience, measure resilience disruptive events, provide insight and direction for	Targeted and actual system's performance over time from a system or its model.	Optimal resilience, recovery-dependent resilience.

potential improvements in these systems.		

Figure 25. A short description of Performance, duration and restoration.

Table 45 provides a structured description of this approach, while examples of system performance metrics are given in Table 46.

Table 45. Passport of this resilience assessment approach using performance, duration and restoration efforts.

Property	Values
Resilience	ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels, given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) [48].
Object	system
Decomposition	aspect
Infrastructure	generic
Aspect	technical, environmental, ecological, economic, social, and organisational
Sources	operations, statistics
Processing	mathematical models
Scale	meso, macro
Temporal	long before, before, during, after, long after

Table 46. Examples of system performance metrics.

Critical infrastructure system	System performance metrics
Agriculture and food	Rates of and population exposure to food contamination; average consumer price of food
Chemical	Shipments to critical chemical-based commodities (e.g. pharmaceuticals)
Emergency services	Lives saved; average response time
Energy: petroleum, oil, and lubricants	Barrels of refined petroleum product transported to the Midwest; price of domestic refined products; profitability of energy companies
Information technology	Number and efficacies of cyber attacks
Public health and healthcare: H1N1 vaccine production, storage and distribution system	Rates of morbidity and mortality; cost per vaccine given
Transportation systems: highway	Average speed and cost of shipments; number of disrupted shipments
Communications	Number of dropped telephone calls

3.2.14 Operational model of infrastructure resilience

Alderson et al. [49] addressed infrastructure via a perspective of an operator who makes decisions for objectives within constraints. This allows optimisation of the decisions on infrastructure as a network, using resilience as one of the optimisation parameters. A short description of the operational model of infrastructure resilience is shown in Figure 26.

Purpose	Input	Output
Model an infrastructure system as a network of operations/functions and use it in attacker/defender optimization.	Operational/functional structure of an infrastructure system to build a model, dynamics of supply, see Data row in Table 48.	Operational resilience of infrastructure system. Understanding of operational context, an optimised infrastructure.

Figure 26. A short description of the operational model of infrastructure resilience.

Table 47 provides a structured description of the operational model of infrastructure resilience. Table 48 contains a part of mathematic formulation of the operational model, indices and sets, data, and decision variables of operator, attacker, and defender.

Table 47. Passport of operational model of infrastructure resilience.

Property	Values

Resilience	ability of a system to adapt its behavior to maintain continuity of function (or operations) in the presence of disruptions [49].
Object	infrastructure
Decomposition	component
Infrastructure	generic
Aspect	function/operation
Sources	operations, experts, descriptions
Processing	network model
Scale	meso
Temporal	long before, before, during, after, long after

Table 48. Datasets and decision variables of operator, attacker and defender.

Type	Operator	Attacker	Defender
Indices and sets	Nodes Undirected edge between nodes Directed edge between nodes	--	Set of additional edges available to be built
Data	Per unit cost of traversing arc [dollars/barrels] Upper bound on total (undirected) flow on edge [barrels] Damaged or undamaged edge [binary] Per unit penalty cost of traversing arc if damaged [dollars/barrel] Fuel supply at node [barrels] Per unit penalty cost for demand shortfall [dollars/barrel]	'Cost' to break edge [cardinality] Budge constraint on the number of simultaneous attacks [cardinality]	'Cost' to protect edge [cardinality] 'Cost' to build edge [cardinality] Budget constraint on the number of defenses [cardinality]
Decision variables	Flow on arc [barrels] Fuel shortfall at node [barrels]	1 if attacker breaks edge, 0 otherwise [binary]	1 if defender protects edge, 0 otherwise [binary] 1 if defender builds edge, 0 otherwise [binary]

3.2.15 Resilient cities with expert judgement

Chang et al. [50] proposed to characterize resilience of infrastructure systems with expert judgments, witch structured description given in Table 49. A short description of Resilient cities with expert judgement is shown in Figure 27.

Purpose	Input	Output
Characterise a community's infrastructure vulnerability and resilience in disasters.	Experts generate scenarios and summary of previous experiences. Expert interviews on disruption and recover, interdependencies, cross=sectoral expectations.	Detailed hazard scenario, service disruption diagrams, interdependencies diagrams.

Figure 27. A short description of Resilient cities with expert judgement.

Table 49. Passport of resilience cities via expert judgement.

Property	Values
Resilience	ability to absorb shocks (from extreme events, such as natural disasters) while still maintaining function (in terms of providing the basis for well-being of residents) [50].
Object	infrastructure
Decomposition	aspect
Infrastructure	electric, communications, water, transportation (intraregional), transportation (interregional), healthcare, government, natural gas, wastewater
Aspect	--
Sources	surveys, workshops, focus groups
Processing	reporting
Scale	meso, macro

Temporal	long before, long after

Expert judgements are collected during expert interviews according to an interview script. Examples of questions in the interview script for resilient cities via expert judgement are shown in Table 50.

Table 50. Examples of questions in the interview script for resilient cities via expert judgement.

ID	Question
1	Does your organization use a flood scenario for planning, and if so, how does it differ from this one?
3	Please use Table I to indicate how the flood scenario would affect your ability to provide services to consumers at various time points. Please consider only how the flood would affect your system (i.e., assume that other infrastructures do not suffer any damage or disruption). What is your rough estimate of the total duration of service loss? What do you expect to be the severity of service disruption?

Table I

Scenario	**Service disruption to your system (nature and severity)**		
	0 hours	**72 hours**	**2 weeks +**
Flood	☐ No loss ☐ Slight disruption ☐ Moderate disruption ☐ Severe disruption	☐ No loss ☐ Slight disruption ☐ Moderate disruption ☐ Severe disruption	☐ No loss ☐ Slight disruption ☐ Moderate disruption ☐ Severe disruption

ID	Question
13	Overall, how confident are you in your answers? Please fill out Table IV with a check mark for your level of confidence.

Table IV

	1 (not at all confident)	**2**	**3 (confident)**	**4**	**5 (highly confident)**
Your system					
Upstream sectors					
Earthquake-related questions					
Flood-related questions					

This approach has four major steps: (1) structuring and conditioning (develop basic hazard scenario, summarise previous experience); (2) expert interviews (infrastructure disruption and recover, infrastructure interdependencies, cross-sector expectations); (3) data synthesis (detailed hazard scenario, service disruption diagrams, interdependencies diagrams); (4) information sharing, feedback and revision (workshop, major regional concerns, summary reports).

3.2.16 Decision context for fostering resilience

McDaniels et al. [51] studied decisions that can be pursued within infrastructure systems to foster their robustness to hazards and rapidity of recovery. In this framework, a disaster management process and generic decision context for fostering resilience were mapped using flow diagrams. The elements of these diagrams encode key indicators for decision making. A short description of Decision context for fostering resilience is shown in Figure 28.

Purpose	**Input**	**Output**
Specify the factors that influence the resilience of infrastructure systems in terms of two dimensions, robustness and rapidity.	Literature review for *ex-ante* mitigation and *ex-post* adaptation opportunities, failures and failure interdependencies. Detailed interviews with stakeholders.	Infrastructure disaster management process. Decision context for fostering resilience in infrastructure systems.

Figure 28. A short description of Decision context for fostering resilience.

Table 51 provides a structured description of this framework.

Table 51. Passport of decision context for fostering resilience.

Property	**Values**

Resilience	capacity to absorb shocks while maintaining function [51].
Object	infrastructure
Decomposition	component
Infrastructure	generic
Aspect	aspects of planning & recovery: socio-technical context, pre-disaster planning, vulnerabilities, hazard, robustness
Sources	desk study, case study, interviews
Processing	influence diagrams
Scale	micro, meso
Temporal	before, during, after

3.2.17 Agile and resilient infrastructure

Massoud Amin and Horowitz [52] proposed to use agent-based modelling for adaptive multi-layer management of infrastructure. A short description of Agile and resilient infrastructure is shown in Figure 29.

Purpose	Input	Output
Holistic analysis of the national and global infrastructure development for increased agility and resilience for large-scale systems.	Models of national and global infrastructure systems.	Potentially, decisions based on alternatives and resilience values.

Figure 29. A short description of Agile and resilient infrastructure.

Table 52 provides a structured description of this proposal.

Table 52. Passport of agile and resilient infrastructure.

Property	Values
Resilience	--
Object	system
Decomposition	component and aspect
Infrastructure	generic
Aspect	layers: system management and policy; overall system and external systems; technical systems and human organization; subsystems and human sub-organisations; technology components and people.
Sources	--
Processing	agent-based modelling
Scale	micro, meso, macro
Temporal	long before, during

3.2.18 Cyber risk assessment with a test bed

Dondossola et al. [53] used a test bed of a power control system for assessment of cyber risks. This test bed is a software-hardware system specially designed to experiment with this diverse risk. Data are described in multiple volumes of well-structured documentation and standards. A short description of Cyber risk assessment with a test bed is shown in Figure 30.

Purpose	Input	Output
Assess power control systems, with a software-hardware test bed.	Software-hardware test bed of passive interconnected distribution grid.	Resilience and technical parameters of a scenario.

Figure 30. A short description of Cyber risk assessment with a test bed.

Table 53 provides a structured description of the cyber risk assessment with a test bed.

Table 53. Passport of cyber risk assessment.

Property	Values
Resilience	--
Object	system, power control

Decomposition	component
Infrastructure	electric
Aspect	communication, control
Sources	experiment
Processing	physical modelling, mathematical modelling, probabilistic modelling, reporting
Scale	meso
Temporal	long before, before, during, after, long after

3.2.19 Volcanic hazard impacts

Wilson et al. [54] studied volcanic hazard impacts on critical infrastructure. This was a desk study of a corpus of research publications and reports on volcanic hazards resulting in a compact and comprehensive publication on the topic. A short description of Volcanic hazard impacts is shown in Figure 31.

Purpose	Input	Output
Characterisation of hazards and vulnerabilities of exposed elements. In this paper, the focus is on volcanic hazards impacts.	Empirical (controller experiments, post-event damage assessment); judgement-based (expert elicitation); analytical (numerical modelling); hybrid.	Hazards characteristic, primary damaging characteristics, its intensity metrics. Vulnerability of different infrastructures to damages of various intensity.

Figure 31. A short description of the volcanic hazard impacts.

Table 54 provides a structured description of this approach.

Table 54. Passport of volcanic hazard impacts.

Property	**Values**
Resilience	ability of a system to absorb and recovery from the effects of a hazard [54].
Object	infrastructure
Decomposition	component
Infrastructure	electrical supply, water supply network, wastewater network, transportation, communications, buildings, critical components
Aspect	volcanic hazard: tephra falls, pyroclastic density currents, lava flows, lahars
Sources	desk study of various information source: empirical (controller experiments, post-event damage assessment); judgement-based (expert elicitation); analytical (numerical modelling); hybrid (combination of different approaches)
Processing	reporting
Scale	meso, macro
Temporal	long after, long before

4 Categories requested for description

4.1.1 Qualitative approaches

The key characteristics of these approaches that use qualitative information of the object of interest, usually in a form of a set of principles, rules or indicators. Absence of these descriptors (qualities) make the description of the object of interest incomplete or impossible. Traditionally, qualitative descriptors form a dichotomy with quantitative descriptors, those with numeric values, countable. However, a quantification of a qualitative descriptors is possible within the scope of a study for its objectives, and quantitative descriptors are directly associated with a quality, again, within the scope and scientific or engineering language. In this perspective, any resilience approach uses qualities and therefore is a qualitative approach.

From a pragmatic perspective and within this document, a qualitative approach is one that does directly use quantitative and produce quantitative resilience value. A short description of qualitative category is shown in Figure 32.

Purpose	Input	Output
Provide a holistic set of insights, a perspective for evaluation and decision making.	Principles, best practices	Patterns, recommendations

Key characteristics	A qualitative approach is one that does directly use quantitative and produce quantitative resilience value

Figure 32. A short description of qualitative category.

4.1.2 Semi-quantitative approaches

Semi-quantitative approaches. The key characteristics of these approaches is the use of quantification of qualitative data. Usually, a set of indicators is used, and one or multiple quantitative indices are calculated from these data. A short description of semi-quantitative category is shown in Figure 33.

Purpose	Input	Output
Resilience assessment of the object of interest, with a potential derivative use as monitoring or decision making.	Qualitative or qualitative and quantitative data on multiple indicators	Index or indices of resilience.

Key characteristics	Quantification of qualitative data.

Figure 33. A short description of semi-quantitative category.

4.1.3 Indicator-based approaches

Indicator-based approaches are semi-quantitative approaches that use qualitative or qualitative and quantitative data sets, and approaches that use a set of purely quantitative data. A short description of indicator-based category is shown in Figure 34.

Purpose	Input	Output
Resilience assessment of the object of interest, with a potential derivative use as monitoring or decision making.	Qualitative or qualitative and quantitative or quotative data on multiple indicators	Index or indices of resilience

Key characteristics	Are semi-quantitative approaches and those approaches that use purely quantitative indicators.

Figure 34. A short description of indicator-based category.

4.1.4 Top down economic approaches

Top down economic approaches address economic resilience of a country or use economic information to address resilience on a country scale. A short description of top-down economic category is shown in Figure 35.

Purpose	Input	Output
Resilience assessment of a country or on a country scale, could be focused on economic aspect.	Economic information or evaluation of economy-related.	Economic resilience of a country.

Key characteristics	Economic information or evaluation, on a top-down scale.

Figure 35. A short description of top-down economic category.

4.1.5 Probabilistic risk-based approaches

Probabilistic risk-based approaches use probabilities or probabilities and impact to address resilience. A short description of probabilistic risk-based category is shown in Figure 36.

Purpose	Input	Output
Resilience assessment of the object of interest, with a potential derivative use as monitoring or decision making.	Probabilities or probabilities and impact	Resilience value

Key characteristics	Probabilities or probabilities and impact for input data.

Figure 36. A short description of Probabilistic risk-based category.

4.1.6 Performance loss approaches

The key characteristic of performance loss approaches are input data used for resilience calculation, performance or performance and time or time data from a system or its model. A short description of performance loss category is shown in Figure 37.

Purpose	Input	Output
Resilience assessment of the object of interest, with a potential derivative use as monitoring or decision making.	Performance or performance and time or time data from a system or its model.	Resilience value

Key characteristics	Performance or performance and time or time data from a system or its model.

Figure 37. A short description of performance loss category.

4.1.7 Stress-testing approaches

The key characteristic of stress-testing approaches, considering the scale of infrastructure, is stress-testing of reasonable detailed models or replicas of infrastructure or its sub-systems. A post-disaster assessment of infrastructure may also be treated of stress-testing approach, on the most detailed model and a single occurrence of one scenario. A short description of stress-testing category is shown in **Error! Reference source not found.**.

Purpose	Input	Output
Resilience assessment of the object of interest.	A detailed model and scenarios	An evaluation infrastructure or its sub-systems

Key characteristics	Stress-testing of detailed models or replicas of infrastructure.

4.1.8 Consequence-based approaches

The key characteristic of consequence-based approaches is that a change or alternatives for a change may result in different resilience and other KPIs of a system, and therefore these approaches are decision-making support systems. A short description of consequence-based category is shown in Figure 38.

Purpose	Input	Output
Resilience assessment of the object of interest used to help in decision-making	Data required for this approach, could be qualitative or quantitative. A set of scenarios or alternatives.	Evaluations of scenarios.

Key characteristics	Resilience as a KPI used for decision-making.

Figure 38. A short description of consequence-based category.

4.1.9 Minimum standard approaches

The key characteristic of minimum standard approaches are the use of threshold values a system should deliver to be resilient. A short description of minimum standard category is shown in Figure 39s.

Purpose	Input	Output
Assessment whether the object of interest meets a predefined threshold value.	Threshold values	A comparison whether the system met its threshold value.

Key characteristics	Use of threshold values to qualify the system as resilient.

Figure 39. A short description of minimum standard category.

4.2 Approaches in categories

Table 55 contains approaches allocated in categories.

Table 55. Approaches in categories. '●' indicates whether an approach belongs to a category.

Approach	Qualitative	Semi-qual.	Indicator	Economic	Probabilistic	Performance	Stress	Consequence	Standard
3.1.1 City Resilience Index		●	●						
3.1.2 City Water Resilience Approach		●	●						
3.1.3 Wayfinder				●	●	●	●	●	
3.1.4 Australian Natural Disaster Resilience Index		●	●						
3.1.5 Resilience, Adaptation and Transformation Assessment		●	●						
3.1.6 Resilience Assessment Framework		●	●						
3.1.7 Resilience Dividend Valuation Model		●	●						
3.1.8 Critical Infrastructure Resilience Platform		●	●						
3.1.9 Resilience to Nature's Challenges		●	●						
3.1.10 Resilience Measurement Index		●	●						
3.1.11 Flood Risk Measurement for Communities		●	●						
3.1.12 CERT Resilience Management Model		●	●						
3.2.1 Essential services for socio-technical systems	●	●	●						
3.2.2 Normal Accident Theory	●		●				●	●	
3.2.3 High Reliability Organisation	●		●				●	●	
3.2.4 PCA and NT processing Liker-type questionnaire		●	●						
3.2.5 Disaster Resilience Index		●	●						
3.2.6 Urban flood depth-economic loss curves			●			●	●	●	
3.2.7 Inventory input-output Leontief's model for resilience			●	●		●	●	●	
3.2.8 Probabilistic disaster resilience of communities			●		●	●			●
3.2.9 Multi-dimensional hurricane resilience			●		●	●	●	●	
3.2.10 Avoided performance drop			●	●		●			
3.2.11 Time-driven resilience for multi-hazard environments			●			●	●	●	
3.2.12 Performance over time for resilience assessment			●			●	●	●	
3.2.13 Performance, duration and restoration		●	●			●	●	●	
3.2.14 Operational model of infrastructure resilience			●			●	●	●	
3.2.15 Resilient cities with expert judgement		●	●						
3.2.16 Decision context for fostering resilience	●								
3.2.17 Agile and resilient infrastructure		●	●		●	●	●	●	
3.2.18 Cyber risk assessment with a test bed			●		●	●	●	●	
3.2.19 Volcanic hazard impacts		●	●				●	●	

5 Discussion

5.1 On the description scheme

Eight qualities are used to describe analytical approaches to resilience: (1) *object* of analysis, (2) principle of analytical *decomposition*, (3) applicability to *infrastructure*, (4) *aspects* of object for resilience, (5) types of *sources* of information, (6) methods of information *processing*, (7) *scale* of the object of analysis, and (8) *temporal* perspective relative to a disastrous event. The relevance of these qualities for description of approaches and the questions these could address are given in Sections 2.1--2.8. Overall, the authors consider this method is useful yet has limitation limitations.

The validity of the structured description has been shared with experts but not rigorously tested. The values of each qualities are collected from a limited number of approaches; thus, an introduction of a new approach might introduce a new value into a quality. A further decomposition is required for (5) sources and (6) methods of information processing, with the description of strengths and weaknesses, templates and timetables and qualifications required for each source and method.

The set of qualities is most likely incomplete. For example, *hazard* is critical yet is missing in this list, while van der Merwe et al. [34] differentiate *use* of indicators as operational (persistence through operational control), tactical (integrated capabilities through management), and strategic (long-term perspective via transformation).

In addition to the above-mentioned improvements, further work may be related to an ecosystem of approaches covering the complete set of needs for resilience and a method for design a holistic approach for the objectives and constraints of an organisation.

5.2 Notable approaches

City Resilience Index (Section 3.1.1) and City Water Resilience Approach (Section 3.1.2) are clearly relative approaches for the similarity of dimensions & goals and involvement of Arup, which states four perspectives [55], namely, cities, energy, transport, and water. The existence of resilience indices for cities and water, specialised sister indices for transport and water are plausible.

Wayfinder (Section 3.1.3) is notable for its mature, well-documented and comprehensive process, and for incorporation of system dynamic simulation modelling into the process.

Resilience, Adaptation and Transformation Assessment (RATA) framework (Section 3.1.6) evaluates the condition of a system with respect to resilience, adaptive capacity and transformability.

Resilience Assessment Framework (Section 3.1.6) is notable for a large database of indicators and issues on various types of infrastructure sectors that might be a solid foundation for comprehensive conceptual study.

Resilience Measurement Index (Section 3.1.10) is notable for a holistic and thoroughly developed pragmatic approach with its six levels of hierarchy and equations for aggregating a higher level index from its lower level components.

CERT Resilience Management Model (Section 3.1.12) is notable for a mature business processes and software engineering-based approach towards resilient organisations.

Essential services for socio-technical systems (Section 3.2.1) is notable for a logically complete model of resilience addressing three levels of organisational management, operational, tactical and strategic.

Performance over time for resilience assessment (Section 3.2.12) is notable for its logical validity of the equation for resilience assessment.

Operational model of infrastructure resilience (Section 3.2.14) Is notable for solid theoretical foundation, as it is based on the conceptual and instrumental foundation of operations research. This exemplary research is useful for simulation modelling of infrastructure as network of nodes.

Volcanic hazard impacts (Section 3.2.19) is notable for a comprehensive and high-quality desk study of volcanic hazard impacts.

5.3 On the objectives of NIC

The NIC sets the following values [56] above all: sustainable economic growth across all regions of the UK; improve competitiveness; and improve quality of life. Therefore, for the NIC these are the foundational values for assessment, comparison, and recommendations for the infrastructure.

Sustainable economic growth across all regions can be decomposed as follows. The foundational concept is *economy*, which can be evaluated with indicators, such as *Gross domestic product* (*GDP*). *Economic growth* means that *GDP* (or another indicator or a set of indicators) at *time* t_2 is higher than at an earlier time t_1 for GDP delta Δ_{GDP}. *Sustainable growth* means that the *GDP delta* stays the same for t_1 & t_2 , t_2 & t_3, t_3 & t_4, …, assuming the time intervals of the same length between t_n & t_{n+1}; an alternative explanation that deltas must always be higher than zero. *Across all regions* means that *regional GDP* is growing in all regions yet has an unclarity whether all regions must have the same delta, or each region have own delta.

Improve competitiveness can be decomposed as follows. The foundational concept *competitiveness*. Department for Business, Innovation & Skills produced a paper 'Benchmarking UK competitiveness in the global economy' [57] that refers to an annual the WEF 'Global Competitiveness Report' [58] and the World Bank's 'Ease of Doing Business Ranking'. The paper also cited the OECD's [59] definition of competitiveness, '*the degree to which it can, under free and fair market conditions, produce goods and services which meet the test of international markets, while simultaneously maintaining and expanding the real incomes of its people over the long term*.' *Improve competitiveness* means that competitiveness at *time* t_2 is higher thasn at an earlier time t_1 for a delta Δ_C.

Improve quality of life is decomposed similarly to improve competitiveness. The ONS Measuring National Well-being (MNW) programme [60] publishes a report on well-being and quality of life, which is supported by monthly statistics [61]. However, the closest to a definition for 'quality of life' was found in a related 'European quality of life survey' [62] where 'quality of life' was defined by an enumeration '*subjective well-being, optimism, health, standard of living and aspects of deprivation, work–life balance*'; the statistics covers these sub-indicators.

Each value must be represented with a single or multiple indicators, representing an object or its status (e.g. GDP for economy). A decision on each indicator and their set must be made, by someone on the role to make this decision. This decision might be an intra-organisational or inter-organisational, the latter requires a consensus.

Each indicator must have a desired value and a valid method of evaluating an object for this value. If the current is unsatisfactory in comparison to the desired value, then the goal is set to transition from the current level to the desired level. This transition, for the purposes of this document, is limited to infrastructure and its resilience.

A set of indicator-related decisions must be made. This set includes decisions for each indicator and for all indicators. The latter requires a valid method for selecting alternatives, where one alternative has a 'better' value for one indicator, while another alternative has a 'better' value for another indicator, e.g. a Pareto-front.

Resilience is unnoticeable unless the infrastructure is under pressure of a hazardous event, whether actual or simulated. A hazardous event has a negative connotation, it is expected to depress economy instead of stimulating economy, similarly to competitiveness and quality of life.

Improvement of infrastructure for resilience may directly reduce the negative impact of a hazardous event on economy, competitiveness and quality of life, thus improving stability of economy, yet would not focus on a faster growth of economy or competitiveness by itself. The purpose of improvement of infrastructure for resilience is to avoid the decline of economy, decrease of competitiveness and quality of life.

Indicators allow useful to define the system as is; however, the complexity and spatial-temporal scale of infrastructure and investment into infrastructure requires quantitative computer-based simulation modelling to assess the potential of infrastructure to meet indicator targets in alternative futures (as discussed in [63]).

6 Summary

A schema for structured description was created and used to describe resilience approaches. Approaches were loosely grouped into those produced and used by consultancy/and research groups, and by individual researchers within smaller research projects. 12 approaches of the former group and 19 approaches of the latter group are described.

The structured description was also created to describe the proposed categories and answer the questions about these categories. The categories are described within the schema. Each category is illustrated by at least one of 31 observed approaches.

Notable approaches are named in the discussion section. This section also contains critique of the proposed schema and names directions for continuation of this research. Theoretical considerations on the objectives of the NIC and resilience approaches are provided.

7 References

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