RAMSES PROJECT

Grant Agreement n° 308497

WP 2: Taxonomy of architecture and infrastructure indicators

D2.1:

Synthesis review on resilient architecture and infrastructure indicators

Reference code: RAMSES – D2.1

This project has received funding from the European Union's Seventh Programme for Research, Technological Development and Demonstration under Grant Agreement No. 308497 (Project RAMSES).

Project Acronym: RAMSES

Project Title: Reconciling Adaptation, Mitigation and Sustainable Development for Cities

Contract Number: 308497

Title of report: D2.1: Synthesis review on resilient architecture and infrastructure indicators

Reference code: RAMSES – D2.1

Short Description:

The aim of this report is to identify and analyse resilience frameworks and corresponding indicators which are available to assess architecture and infrastructure resilience today. This state of the art will be instrumental to determine:

- The conditions under which architecture and infrastructure resilience can be defined and measured
- The attributes of appropriate indicators to guide actions and investments
- The suitable criteria to select and/or elaborate such indicators.

The deliverable is composed of contributions from research, business, design, planning and standardisation perspectives as well as major EU databases (EEA, ESPON Climate, RESPONSES, EVDAB, URBAN AUDIT). This input converges to highlight some common core issues. It is vital to define the purpose, usability, and suitability of indicators of resilience in general and for the RAMSES project in particular. Resilience indicators must be feasible, informative and cost-effective and at the same time deal with the very complex nature of resilience. Few operational indicators exist and most frameworks and indicators which have been proposed in the literature have not been used in practice. Instead best practice guidelines for good design and good organisation are increasingly perceived as efficient tools to encourage and promote resilience and deliver a level of reassurance not otherwise available through specific indicators.

The main messages from the draft report were presented and discussed in two workshops with stakeholder and research experts respectively, to identify gaps among current resiliency definitions and characteristics, to compare strengths and weaknesses in various assessment methodologies for cities, and to discuss priorities for resiliency indicators for urban architecture and infrastructure.

The links between theory and practice and the trade-offs between complexity and feasibility will be further developed through cooperation with case cities, amongst others in analysis of case study policy documents and insurance data for adaptation of urban architecture and infrastructure in cooperation with city stakeholders and experts. The resulting taxonomy of cross-scale indicators for resilient architecture and infrastructure, including qualitative as well as quantitative criteria, will be deployed in modelling of local context, identification of strategic design and planning interventions to increase urban resilience, and in transition strategies towards healthy, attractive and functional urban environments.

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Contributions: T6 ECO, CMF, ICLEI

Versioning		
Version	Date	Name, organization
0.1	01.05.2013	NTNU
0.2	13.05.2013	IVE
0.3	03.06.2013	NTNU
0.4	23.06.2013	NTNU + IVE
0.5	28.06.2013	IVE
0.6	04.07.2013	NTNU
0.7	19.07.2013	NTNU
0.8	25.07.2013	NTNU
0.9	01.08.2013	IVE
1.0	12.08.2013	IVE
1.1	23.10.2013	NTNU
1.2	15.11.2013	NTNU
1.3	02.12.2013	NTNU
1.4	06.12.2013	IVE
1.5	15.12.2013	NTNU

Quality check
Internal Reviewers: PIK, LSE

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1 Executive Summary

James Kallaos, Gaëll Mainguy and Annemie Wyckmans

The goal of WP2 "A taxonomy of resilient architecture and infrastructure indicators" is to provide guidance for assessing the quality and efficiency of architecture and infrastructure in terms of adaptation and mitigation actions.

Being the first deliverable of WP2, the aim of this report is to identify and analyse resilience frameworks and corresponding indicators which are available to assess architecture and infrastructure resilience today. This state of the art will be instrumental to determine:

- The conditions under which architecture and infrastructure resilience can be defined and measured
- The attributes of appropriate indicators to guide actions and investments
- The suitable criteria to select and/or elaborate such indicators.

Identification and discussion of resilience definitions and frameworks and corresponding requirements for urban architecture and infrastructure in this report are based on a critical review of literature gathered from scientific, economic and planning experts involved in climate change adaptation and costing, including state of the art research surveys and EU databases (EEA, ESPON Climate, RESPONSES, EVDAB, URBAN AUDIT). An internal review on best practices and risk management policy performed by IVE has served to refine assumptions and estimates, particularly on impacts involving the energy, transport and water sectors. The main messages from the draft report were presented and discussed in two workshops with stakeholder and research experts respectively, to identify gaps among current resiliency definitions and characteristics, to compare strengths and weaknesses in various assessment methodologies for cities, and to discuss priorities for resiliency indicators for urban architecture and infrastructure.

While composed of contributions from a variety of business, academic, design and planning perspectives, the review did provide a range of common core conclusions:

1. Resilience is the ability of X to anticipate, absorb, adapt to and rapidly recover from Y. These different abilities correspond to different temporal phases: A system resists and absorbs *during* and recovers *after* a stressful event, supported by adaptability efforts to anticipate, prevent and prepare the system *before* an event. These three phases correspond to different fields of expertise - vulnerability and risk management, crisis management, adaptation - which are confronted by different challenges and use different methods. Appropriate selection of methodologies to assess resilience depend on the adopted definitions and scope, the type of infrastructure of interest - in particular whether soft infrastructure is included or not, the perimeter, sectors and time horizon considered and last but not least, the purpose of the evaluation and corresponding recipients and target groups (cities, insurance companies, researchers, home owner organisations etc.).

2. To ensure resilient architecture and infrastructure, holistic and integrated design and management of the built environment is imperative. A common trait of many studies however is the use of resilience as a catch-all to describe any quality that may be perceived as green, sustainable, high performance, or otherwise desirable. Most assessment methods, as well as country level indicators and indices, utilize a comparative or relative approach, with no set limits or boundaries. Terms such as "resilient," "vulnerable" or "sustainable" are used to represent systems that may be only slightly closer to these goals than the status quo. Effort is rarely made to define the boundary conditions for these terms and assess whether the system meets these criteria. Core resilience characteristics such as redundancy, diversity, connectivity and cascading effects are rarely included.

3. Adaptation measures are available to make societies more resilient to the impacts of climate change. But decision makers need information and indicators to select the most

cost-effective investments. Prioritising among vulnerabilities and identifying opportunities for intervention require assessment frameworks for costs, design and planning, knowledge-based scenarios, benchmarking, and operational indicators. Review of scientific literature, standards, design guidelines and assessment schemes, along with testing of the review results in stakeholder and expert workshops, show however that few operational indicators exist. Instead, best practice guidelines are increasingly perceived as efficient tools to encourage and promote resilience and deliver a level of reassurance not otherwise available through specific indicators.

This review forms the basis for analysis of policy documents for adaptation of urban architecture and infrastructure in cooperation with cities, insurance companies, researchers and other stakeholders and experts. The resulting taxonomy of cross-scale indicators for resilient architecture and infrastructure, including qualitative as well as quantitative criteria, will be deployed in modelling of local context, identification of strategic design and planning interventions to increase urban resilience, and in transition strategies towards healthy, attractive and functional urban environments.

1.1 Indicators of Resilience

Resilience and Complexity

Resilience of buildings and infrastructure has been approached in theory and in practice by many different disciplines, stakeholders and schools of thought that have developed different methodologies and practices relevant to the class of problems they address. No single discipline deals with systems that range across all the possible scales of space and time. In particular, on the one hand engineers tend to develop outcome-based approaches to increase the resistance of hard infrastructure so that they do not fail. On the other hand, social scientists and policy makers are keen to develop process-based approaches to strengthen the adaptive abilities of communities and institutions to respond to and recover from failure. What is being considered should thus be clarified before analysing its potential resilience.

Resilience and Temporality

In particular, three different temporal phases of resilience poses serious methodological challenges: (i) Adaptability efforts to anticipate prevent and prepare a system take place before a disruptive event. (ii) A system resists and absorbs during and recovers after a stressful event respectively. These three phases (Figure 1) correspond to different field of expertise – vulnerability and risk management, crisis management, adaptation – which are confronted to different challenges and develop specific methods accordingly. The temporality issue is particularly relevant in the context of climate change where events and impacts can be distant in the future.

Figure 1: Temporal phases and corresponding characteristics of resilience

Definition of resilience, towards a consensus

Today, an ever increasing number of key institutional players are adopting the broadest and most comprehensive definition of resilience which blends all three dimensions: Resilience is the ability of X to anticipate, absorb, adapt to and rapidly recover from Y.

Interdependency

Most approaches today address the impacts of climate change effects focusing on loss or damage by sectors while lessons learned from historical disruptive events have dramatically shown the paramount importance of cascading effects. Modelling of architecture and infrastructure dependency provides a promising avenue for approaching complexity of the system and ensuring that vulnerabilities in one sector do not compromise others.

Uncertainties

Analysis and modelling are confronted with considerable uncertainties regarding climate system behaviour, but also future emissions, development trajectories and urbanization trends, in particular at the regional level. These uncertainties make it difficult, and sometimes impossible, to know exactly what the buildings and infrastructure should be adapted to. The past is no longer a reliable guide for the future as both the natural and the social spheres develop and are becoming increasingly dynamic and uncertain.

Indicators

Developing resilience indicators is a difficult task as they must address the typical challenges of assessment (to be feasible, informative, cost-effective etc.) and at the same time deal with the very complex nature of resilience. Review of research literature, codes and standards, design guidelines and assessment schemes shows that few operational indicators exist. In practice, different indicators have been proposed to assess proxy properties of resilience. They basically fall into two categories:

- Persistence, resistance, robustness can be assessed with outcome-based indicators which measure the effectiveness of action and policy
- Adaptability, responsiveness, ability to recover can be assessed with process-based indicators which monitor progress in implementation.

Table 1 summarises the main dimensions of resilient systems identified in literature and by RAMSES workshop participants (the latter's additional contribution *in italic*).

Characteristic	Description
Adaptability, flexibility	Capacity or ability to: • change while maintaining *or improving* functionality • evolve • adopt alternative strategies *quickly* • respond to changing conditions *in time* • *design open and flexible structures (in general)*
Connectivity, feedbacks, safe-failure	Functional interdependence of system components and processes (Effect of change in one part of the system on other parts of the system). Capacity or ability to: • absorb shocks • absorb cumulative effects of slow-onset challenges • avoid catastrophic failure if thresholds are exceeded • fail progressively rather than suddenly • fail without cascading impacts (domino effect) • *analyse and implement across spatial scales (city to site)* • *analyse as human-technology coupled system* • *identify lock-in effects and potential conflicts with mitigation* • *identify synergies with other city policies, added value assessment* • *balance clear distribution of responsibility with concerted action*
Dependence on local ecosystems	Local control over services provided by local and surrounding ecosystems. Maintaining health and stability of green and blue infrastructure, providing: • flood control • temperature regulation • pollutant filtration • local food production etc. • *bioclimatic design and management (adjusted to local conditions)*
Diversity	Spatial diversity - Key assets and functions physically distributed to not all be affected by a given event at any time • Functional diversity - Multiple ways of meeting a given need • *balance diversity with potential cascading effects*
Learning, memory, *foresight*	Individual and institutional. Capacity or ability to: • learn from past experiences and failures • use information and experience to create novel adaptations • avoid repeating past mistakes • accumulate, store, and share experience • *build on long-term cultural value and history of the city* • *integrate resilience in long-term development scenarios*
Performance	How well does the system perform in its role? • Functional capacity • System quality • *in an appropriate and efficient way* • *self-sustaining, reducing external dependencies* • *compared to others – "I want a bigger dike than my neighbours"*
Rapidity, responsiveness	Following a disruptive event, the capacity or ability to: • contain losses, including mortality and illness • reorganise

	• maintain and re-establish function • reinstate structure • restore basic order • avoid future disruption
Redundancy, modularity	The capacity or ability to: • substitute systems, or elements of systems • buffer from external shocks or demand changes • replace components with modular parts • *balance redundancy with potential cascading effects*
Resourcefulness	The capacity, ability, *resources and infrastructures* to: • identify (and anticipate) problems • establish priorities • mobilise resources • visualise, plan, collaborate and act • *re-evaluate* • *integrate resilience in governance and working processes* • *involve and co-create with citizens (e.g., crowd-sourcing and funding)*
Robustness	The capacity or ability to: • withstand a given level of stress or demand • without degradation or loss of function • *capacities that ensure sufficient margins*
Co-benefits	• Added value assessment of resilience • No/low regret measures

Table 1: Core dimensions of resilient systems, from RAMSES workshop participants and (Adger et al., 2005; Briguglio et al., 2008; Bruneau et al., 2003; Chang and Shinozuka, 2004; Chuvarayan et al., 2006; da Silva et al. 2012; Davis, 2005; Fiksel, 2003; Galderisi et al., 2010; Godschalk, 2003; ICSU, 2002; Longstaff et al. 2010a, 2010b; Maguire and Hagan, 2007; McDaniels et al., 2008; Reghezza-Zitt et al., 2012; Schultz et al., 2012; Tierney and Bruneau, 2007; Tyler and Moench, 2012; Van Der Veen and Logtmeijer, 2005; UN-ESCAP, 2008; Wilson, 2012)

Characteristics such as redundancy, diversity, connectivity and cascading effects are however seldom addressed; a common trait is the use of resilience as a catch-all to describe any quality that may be perceived as green, sustainable, high performance, or otherwise desirable.

1.2 Resilient architecture and infrastructure

Resilience of architecture and infrastructure is imperative for people's quality of life and the spatial quality of the environment that surrounds people in their daily life. In the RAMSES project architecture encompasses design and management of urban fabric ranging from buildings to public spaces, landscape and urban form. Infrastructure describes built assets (hard infrastructure) and all the institutions that are required to maintain the standards of living of a community (soft infrastructure). Infrastructure can be considered in terms of physical objects and networks or in terms of services. For users, assets owners and decision-makers the *services* that are provided are more important than the *structures* as such. This dual nature of resilience seems to run through all the topics in this work as illustrated by key differences and attributes listed in Table 2 below.

Hard infrastructure	Soft infrastructure
Resist	**Adapt**
Built	Social, economic, political
Focused	Comprehensive
Engineering/technical	Organizational
Industrial, operators	Institution, local authority
Quantifiable	Not (easily) quantifiable
Technological fix	Organizational fix
Structural measures	Non-structural measures
Outcome-based	Process-based
Sectoral	Non-sectoral

Table 2: Resilience characteristics for hard and soft infrastructures.

Even with imminent mitigation actions, society will undoubtedly be faced with a certain level of climate change impact. Changes in average climate variables, along with changes in the frequency and severity of extreme weather events, can be expected to have stark consequences for the built environment in the form of flooding, heatwaves, water scarcity and other impacts. Buildings and infrastructure, including roads and transport systems, energy, water, waste, vegetation and water bodies, and even public space, are designed to last for decades and are expensive to renovate or replace. As infrastructure assets have long operational lifetimes they are sensitive not only to the existing climate at the time of their construction, but also to climate variations over the decades of their use. For example, a substantial proportion of infrastructure built in the next five years, will still be in use long after 2030.

If there is no “perfect” operational framework which encompasses all the dimensions of resilience, in practical terms, asset owners, local authorities, regulators and insurers face these issues on a daily basis. From an operational point of view, resilient buildings and infrastructures should be well designed and well managed. In other words, resilience of is the result of good design and good organisation:

1. Norms of engineering designs, materials, and retrofit strategies have been developed to enhance the ability of buildings and infrastructure elements to withstand natural hazards. Many design and engineering standards already contribute to ensuring resistance and reliability of infrastructure. Revising design standards and building codes for the infrastructures to ensure that they are appropriate for the extreme conditions is a practical way to build resilience.
2. The design and engineering standards are intended to protect the physical integrity of the asset and are not sufficient to confer resilience of the system. Best practice guidelines are increasingly perceived as efficient tools to encourage and promote resilience and deliver a level of reassurance not otherwise available through specific indicators. Risk management and Business Continuity Management standards are generic and comprehensive approaches which provide frameworks, guidelines and process-based indicators to continually update and improve the abilities of an organization to overcome a disruptive event.

Modelling of architecture and infrastructure dependency provides a promising avenue for approaching complex systems and ensuring that vulnerabilities in one sector do not compromise others, and a useful assessment framework for resilient architecture and infrastructure should particularly recognize three main categories of dependencies: geographical, physical and logical (Brown, 2010; Rinaldi et al., 2001). Modelling interdependent infrastructures is however a complex, multifaceted, multidisciplinary problem and capacities for analysing potential impacts from an interdependent or systems approach have developed only recently (Wilbanks et al., 2012). In addition particular attention should be devoted to define uncertainties and time horizon in the models.

1.3 Design and assessment frameworks for resilient architecture and infrastructure

Increasing network resilience involves three related capabilities – providing *absorptive capacity* so that the network can withstand disruptions, providing *adaptive capacity* so that flows through the network can be accommodated via alternate paths, and providing *restorative capacity* so that recovery from a disruptive event can be accomplished quickly and at minimum cost (Turnquist and Vugrin, 2013).

Prioritising vulnerabilities and identifying opportunities for intervention requires assessment frameworks for costs, design and planning, knowledge-based scenarios, benchmarking, and operational indicators. The nature and focus of methodologies developed to assess and measure resilience however depend on the adopted definitions and scope, the type of infrastructure of interest – in particular whether soft infrastructure is included or not, the perimeter, sectors and time horizon considered and last but not least, the purpose of the evaluation and corresponding recipients and target groups (cities, insurance companies, researchers, home owner organisations etc.). The range of potential evaluation needs and the number of specific challenges precludes the elaboration of a one-size-fits-all set of indicators for infrastructure resilience.

To our knowledge, the work of Vugrin et al. (2010, 2011, Turnquist and Vugrin 2013) is currently one of the most advanced attempts to provide a quantitative basis for resilience. Their measurement of system resilience costs consists in the quantification of two parameters:

- **Systemic impact** (*SI*) which is the difference between targeted and disrupted system performance,
- **Total recovery effort** (*TRE*) which is the efficiency with which the system recovers from a disruption. The TRE is measured by analysing the amount of resources expended during the recovery process (Vugrin and Camphouse, 2011).

Increasing network resilience involves three related capabilities – providing *absorptive capacity* so that the network can withstand disruptions, providing *adaptive capacity* so that flows through the network can be accommodated via alternate paths, and providing *restorative capacity* so that recovery from a disruptive event can be accomplished quickly and at minimum cost (Turnquist and Vugrin, 2013).

In principle, incorporating resilience principles and metrics into standards and codes could provide a monitoring framework for improvement of practices, and a consistent approach across sectors and countries. Review of research literature, codes and standards, design guidelines and assessment schemes and corresponding testing of the review results in stakeholder and expert workshops however show that few operational indicators exist. Instead, best practice guidelines are increasingly perceived as efficient tools to encourage and promote resilience and deliver a level of reassurance not otherwise available through specific indicators.

A number of publications provide design recommendations for a climate change adapted built environment, including a wide range of case studies and measures for grey and green infrastructure, categorised according to climate change impacts. Grey infrastructures can be defined as “construction measures using engineering services”, while green infrastructures are “vegetated areas and elements such as parks, gardens, wetlands, natural areas, green roofs and walls, trees etc. contributing to the increase of ecosystems resilience and delivery of ecosystem services" (EEA, 2012a, p. 7).

These design measures show how morphological factors and socio-economic activity can alter exposure and impact at local scale in cities, and how appropriate architecture and infrastructure design can mitigate these effects. Vulnerability risks and costs can for example be considerably reduced when designing the built environment with inherent flexibility for adaptation to climate change, prioritising passive and local solutions, and providing redundancy of solutions (diverse supply options). In addition, it is recommended to prioritise low-regret options providing a range of co-benefits for climate change mitigation as well as quality of life; for example, green areas and water bodies can provide storm water management, delay the urban heat island effect, and create local leisure facilities for the urban population, accessibly by non-motorised or public transport. Costs can further be reduced when adaptation measures are timed according to upcoming windows of opportunity such as building retrofits, urban renewal, densification or development (EEA, 2012a).

1.4 Next steps: case cities

This material forms the foundation of systematic analysis of RAMSES case cities across the world. Analysis of relevant municipal policy documents will be combined with interviews with key municipality representatives, similar to the review method used in the Norwegian Cities of the Future programme (Rambøll 2012). In addition to urban planning and development policies, regulations and generic checklists for project development used by city officials will be taken into account.

For this work the Local Government Self-Assessment Tool (LGSAT), developed by UNISDR, will be taken as a base to study these documents and assess the degree of maturity with which cities are aware of, and dealing with resilience related issues. In particular, for each document it will be evaluated whether:

- Resilient architecture and infrastructure indicators are mentioned and taken into account in the executive summary, introduction or conclusion (a sign of its significance)
- Resilient architecture and infrastructure indicators are mentioned and taken into account in the goals and strategies described in the document (a sign of operationalisation)
- Specific impacts and urban areas are described in detail
- Cost assessment of vulnerability and potential measures has been performed
- The proposed measures are legally binding
- The methodology for assessing and monitoring resilient architecture and infrastructure indicators is clear
- Resilient architecture and infrastructure indicators are integrated in checklists for project development used by city officials (urban, neighbourhood and building scale) (based on Rambøll 2012)

Selection of key municipal documents and the relevance of the results will be checked in cooperation with city officials. The results will be tested for relevance in other cities during stakeholder and expert workshops. In addition efforts toward more resilient urban architecture and infrastructure will be investigated for their impact on insurance cost structure and the corresponding assessment method used; this review can be performed among key private insurance companies and project developers in case cities, during stakeholder and expert workshops.

2 Introduction

James Kallaos and Annemie Wyckmans, with Rolf André Bohne and Floriana Ferrara

Before the report embarks on an in-depth discussion of resilience, resilience indicators and their relation with urban architecture and infrastructure, Chapter 2 clarifies and disentangles frequently misunderstood and mixed up concepts of resilience, sustainability and vulnerability.

2.1 Resilience and vulnerability

Resilience can be facilitated through redundant, distributed components and design for safe failure – whereby the system is designed so that failure of a component can be absorbed by a network and does not propagate (cascading or escalating through the system). This requires localised, knowledge-based and integrated cross-scale indicators of resilience for design and management of urban architecture and infrastructure.

The human cardiovascular system is comprised of a vast network of vessels and organs. The capillaries in our extremities are both exposed and vulnerable to injury. They are heavily networked and redundant, allowing us to tolerate a certain amount of peripheral damage and continue performing at an acceptable level, and have a high capacity for recovery (healing); they exhibit most if not all of the characteristics that define resilience. Failure of the smaller networked capillaries has lower consequences than failure of larger vessels: they are less critical. As the scale increases from capillaries up to arterioles and venules, and then smaller vessels and larger vessels, both vulnerability and resilience decrease, while criticality increases. Larger vessels have less redundancy, and less capacity for recovery from damage, yet they are less exposed by being deeper within the tissue, muscle, or bone, and less sensitive by being thicker and more elastic. Highest level organs such as the heart, aorta, or brain, are the most critical systems in the body. They lack redundancy and have little recovery capability. These organs are not particularly resilient, but they are protected by solid bone, reducing their exposure and sensitivity, and therefore vulnerability. The human cardiovascular system provides an interesting and easily grasped outline of the interactions between vulnerability and resilience, showing how they are related and how they are not. In short, vulnerable systems need more resilience, and non-resilient systems need to limit their vulnerability.

We have a limited capacity to influence the vulnerability and resilience of the organ systems that make up our bodies. We make decisions daily regarding the protection of critical resources based on real and perceived threats. The choice of protection level (decreasing vulnerability through sensitivity and exposure reduction) tends to increase with increasing criticality, and decreasing resilience. Motorcycle riders wear hard protective helmets – while police wear bulletproof vests. The choice of wearing a vest and helmet are in turn based on the criticality, vulnerability, and resilience of the underlying body systems. Protecting the head and torso to reduce vulnerability are direct consequences of the high criticality, high vulnerability, and low resilience of these areas. (To be specific, while a bulletproof vest is a protective element, it is made up of both protective and resilient elements – a hard metal plate to defend against high level threats, and a tight mesh of resilient fibres to dissipate the energy of lower level, or residual threats.)

Moving up from the level of systems, to organs, to organisms, the injury or death of a single organism does not represent system failure - up to a certain level of population loss, the system (e.g. group, herd, or community) can survive. In all cases, a resilient system can tolerate or absorb a certain amount of damage, and heal or recover. Beyond the resilience capacity of the system considered, the resilience scale moves up one level. The scale of the assessment determines the assessment of resilience. Failure is scale based – the failure of a single component is not the same as system failure; different thresholds exist at different scales for what constitutes acceptable performance, and what constitutes a failure.

Similar to vulnerability and resilience, critical systems can only be defined at a specific scale. The heart and brain are critical systems in the human body, but that one individual may not be critical to the survival of the group, or of the larger society.

Applying the hierarchical resilience framework to the built environment, architecture and infrastructure, we can see that vulnerable systems should either reduce their vulnerability (exposure and sensitivity), or increase their resilience.

The resilience of a community will be a function of the resilience of individual components (physical and social), as well as the fabric or network that binds them. An optimization strategy should involve the protection or relocation of vulnerable assets, and the addition of resilient characteristics (absorption, redundancy, and recovery capacities) for those systems that remain vulnerable. The relationship between vulnerability and resilience is often discussed and often confused. While the concepts are linked, they are not subsets of each other, nor are they opposites – the absence of vulnerability does not equate with resilience (Manyena, 2006, p. 443).

Reduction in vulnerability and increase in resilience can be synergistic, however – both work to limit the extent of damage inflicted by a hazard. Reducing vulnerability can help prevent the resilience capacities of a system from being surpassed, and reduce the time and effort required for recovery. Vulnerability can be diminished by reducing potential impacts from a hazard, through location (reducing exposure) or protective design (reducing sensitivity). Vulnerability and resilience are related concepts, but vulnerability has "meaning only in relation to a specific hazard" while resilience is an intrinsic characteristic of complex systems (Manyena, 2006; Tyler and Moench, 2012, p. 317; Vugrin et al., 2010). Resilience can be facilitated through redundant, distributed components and design for safe failure – whereby the system is designed so that failure of a component can be absorbed by a network and does not propagate (cascading or escalating through the system).

Many of the problems with defining vulnerable or resilient systems are semantic. From the many varying definitions of resilience, there is a need to adopt a definition appropriate to the project under consideration (Attoh-Okine et al., 2009). A lack of comparability between different discussions of resilience often derives from a lack of attention to the scale of the assessment. With the same data and the same results, different conclusions can be drawn depending on the chosen scale.

A review of the literature shows a need to outline the difference between robust systems and resilient systems, depending on the scale one investigates. Tyler and Moench (2012), for example, suggest that robust systems use the strength of individual components to maintain functionality, while a resilient system maintains function in spite of failures or disruptions in individual components. Three elements of urban resilience have been elucidated:

- Systems and networks – resilient systems exhibit flexibility, diversity, redundancy, modularity, and safe failure (avoidance of failure cascades or escalations)
- Individual and organizational agents – resilient agents exhibit responsiveness, resourcefulness, and capacity to learn
- Social rules and conventions – representing the links between systems and agents (Tyler and Moench, 2012).

A common trait of many studies is the use of resilience as a catch-all to describe any quality that may be perceived as green, sustainable, high performance, or otherwise desirable. Many lack internal consistency with their definitions, and fail to explain whether they are describing system characteristics that may help a system to be resilient, or properties that should be used to assess resilience. Many include parts of adaptive capacity or vulnerability within resilience. While these concepts may reflect on resilience by reducing vulnerability, and therefore the magnitude of the threat a system must absorb or recover from – they do not describe resilience itself. A reduction in vulnerability and the magnitude of the threat is good practice, and will increase the likelihood that the resilience level inherent to the system will not be surpassed. It does not however, increase the resilience.

Strength at resisting a threat is not resilience, and should be assessed separately. Take an unreinforced concrete wall in a flood zone. Vulnerability depends on potential impacts, which in turn are a function of exposure and sensitivity – the wall is exposed, and sensitive to a threat above a certain magnitude. Based on strength, the wall can resist the threat up to a threshold, at which point it fails catastrophically – unreinforced concrete is strong yet brittle. It exhibits little resilience: once the threshold is met and failure is reached it retains little functionality. Once breached, the failure may propagate in a cascading or escalating manner. Reinforcing a concrete wall with a steel mesh may not increase the initial strength (threshold for failure), but it changes the nature of the failure. The wall now has a better chance of remaining intact, even with cracks or other damage. The brittleness is reduced by inclusion of the steel matrix, and chance of the failure propagating to other sections is diminished. While both systems are equally vulnerable, the reinforced concrete wall is more resilient after damage.

2.2 Resilience and sustainable development

Climate change will exert a large influence on the built environment and its future development. Not only will sea-level rise, droughts, wind, floods and related events challenge the robustness of the built environment, its institutions and inhabitants, but there will also be limited resources with which to repair, maintain and construct the built environment in the future. In order to face adaptation to climate change, one must first understand the action space for human intervention, or the "limits to growth" (Meadows et al., 1972). Rockström et al (2009) makes an attempt to quantify 9 of the limits to (human) growth, and by their estimates we have already overshot the limit for climate change (they suggest 350 ppm).

The resilience concept has been investigated for over 40 years showing a tight connection with sustainability. As observed by Common and Perrings (1992), the relevance of the concept resilience for sustainable development was on the table in the economic field since the late 1970s. Levin et al. (1998), quoted by Perrings (2006), refers to resilience as the preferred way to think about sustainability in social as well as in natural systems. Folke et al. (2005) state that the major challenge for research on sustainability is how to stimulate the emergence of multilevel and adaptive management systems that can secure the capacity to sustain the ecosystem services. By this perspective, cities function as part of socio-ecologycal systems, due to the fact that they are “demander” of resources but also provider of services, knowledge and capital.

Many of the mentioned authors (Perrings, Folke, Levin), devoted to investigate interdisciplinary issues affecting sustainability, gave life to the Resilience Network. In collaboration with the Beijer Institute and University of Florida, this research network later developed into the Resilience Alliance, a multidisciplinary consortium of research groups and research institutes that collaborated to explore the dynamics of socio-ecological systems (SES). The most important insights of resilience and sustainability in SES have been synthesized by Resilience Alliance in a report entitled "Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformation" (ICSU, 2002), in which resilience and adaptive capacity are described as key properties for sustainability. The report stresses also the importance of generating knowledge and coping with change in such a way as to create diversity of management options for responding to uncertainty and surprise, and implementing structured scenarios and active adaptive management processes.

The policies recommended by Resilience Alliance greatly emphasize concepts such as ecological thresholds, uncertainties and surprise. Even the sustainability debate is permeated by uncertainty, so that the precautionary principle appears as an official recognition of pervasive uncertainty in some statutory law and is the reason for many major sustainability policies although it is vague, inoperative by itself and open to wide interpretation (Handmer and Dovers, 1996). In line with the above comments, Adger asserts that "the unfocussed aspirations for sustainability are captured in the notion of resilience" (2003, p. 2) and recognizes that "the message of resilience is more radical for policymakers than that of sustainability" (2003, p. 1). In such a way he attributes a more operational and pragmatic meaning to resilience with respect to sustainability.

The higher pragmatism embodied in the resilience concept explains the reason for which, from an operational point of view, it may be preferable to talk about indicators of resilience instead of indicators of sustainability. In such a way building resilience becomes a means of pursuing sustainability goals.

Anthropogenic climate change is a consequence of fossil fuel combustion, an undesired by-product of energy consumption. The built environment is a major consumer of energy and thus a significant contributor to the problem as well as the solution of climate change. The building and construction sector alone is responsible for 10-40% of countries' GDP, as well as 10% of employment (UNEP, 2009). The sector is not only the largest consumer of natural resources, in terms of both land use and materials extraction, but is also responsible for 30-40% of global primary energy use and greenhouse gas (GHG) emissions (Huovila et al., 2007).

Human activities impact the natural environment in many different ways, directly and indirectly: through appropriation of existing stocks of land, energy, and materials, manipulation and intervention of flows of energy, water and resources, as well as through emissions, depositions, and changing concentrations of gases, particulates, and other materials. Many of these impacts occur in, or are the result of, human activities in settlements constituting a parallel, built environment. Human manipulation of the natural environment while constructing and maintaining the built environment are intertwined activities in the quest for sustainability. Anthropogenic climate change represents the completion of the feedback loop – sustainability now requires not only reductions in human impacts on the environment, but the assessment of uncertain changes in the natural environment to limit their effect on humans and the built environment.

Thus the questions of climate change adaptation, mitigation and sustainability converge very much into the design and management of the built environment, where the interplay between architecture and infrastructure will determine the success or failure. However, there is no consensus on a path to implementation. A plethora of different interpretations emerge as "…various stakeholders and institutions configure a fairly malleable idea to fit their own agendas" (Allenby et al., 2009, p. 10). This leads to large variability between different understandings, methodologies, and intentions regarding sustainability and resilience.

Regardless of the path to be chosen, an important element is quantified knowledge about the effects that human activities are having on the environment, and the effects of the environment on human activities. One approach to making this knowledge available and useful in the pursuit of resilience is with indicators.

3 Defining the scope

Gaëll Mainguy, with Ludivine Houssin, Georges Valentis, James Kallaos, Fernanda Pacheco, Floriana Ferrara and Annemie Wyckmans

Chapters 3 and 4 consist of a conceptual analysis of the theoretical literature and different frameworks which have been proposed to assess resilience. The complexity of the key elements is presented and discussed in the light of our issues (namely resilience, architecture and infrastructure, adaptation to climate change, indicators). Chapter 3 sets out the scope and the analytical framework for this work.

3.1 Challenges in framing resilience

The ability to critically measure resilience depends on the underlying conceptual framework guiding the analysis (Birkmann et al., 2012a). Yet, in contrast with its popularity in policy-making, resilience is a complex and ambiguous concept addressing multiple dimensions. There is no definitive consensus on resilience definitions and as we will see, attributes of resilience vary widely between studies making comparative analysis challenging.

At first glance, resilience is a simple notion: it is the ability of a system to absorb a disturbance and return to its normal state. But the devil is in the detail and different conceptions of ability, system, absorption, disturbance and normality –to mention the visible tip of the iceberg– have led to very different interpretations and frameworks. In addition, the concepts of resilience of complex systems have significantly evolved over the last two decades.

3.1.1 Resilience, one concept, (too) many possibilities

The methodology to assess and measure resilience directly depends on the adopted definition which belongs to a "broad, multifaceted, and loosely organized cluster of concepts, each one related to some aspect of the interplay of transformation and persistence" (Carpenter and Brock, 2008, p. 1).

Resilience is an overarching and generic concept for the ability of a system to anticipate, absorb, adapt to and rapidly recover from a disturbance. It is a broad property which could virtually characterize any system. Indeed resilience is commonly used to denote strength, flexibility and adaptability in many disciplines ranging from environmental research to materials science and engineering, psychology, sociology, economics and more recently in disaster planning and organizational management (for reviews, see (Birkmann et al., 2012a, 2012b; Martin-Breen and Anderies, 2011)). Accordingly, approaches to conceptualize resilience widely differs depending on their stated goals, their defined system of interest, the scale of analysis, the hazards or the phenomena identified as triggering events (e.g. Birkmann et al., 2012b, 2012b; Eriksen and Kelly, 2007; Lhomme et al., 2010; Martin-Breen and Anderies, 2011; Wang and Blackmore, 2009).

3.1.2 Resilience as Persistence: an ability to resist, absorb, recover

The roots of the word resilience can be traced back to the Latin word for "bouncing back", "*resilio, resilire*" which was also used in the sense of "recovery" (Lhomme et al., 2010).

Much of the early work on infrastructure resilience focused on understanding the mechanics of how components of infrastructure systems perform when subject to extreme forces or conditions. In mechanical engineering, to be resilient is to withstand a large disturbance without changing or becoming permanently damaged (resistance) and to return to normal quickly (elasticity). It is the simplest conception where resilience means resisting/enduring stress and bouncing back after stress (see Lhomme et al., 2010; Martin-Breen and Anderies, 2011). Engineering resilience provides a useful and rigorous way of formalizing resilience and the concept has been instrumental in setting up appropriate indicators, standards and norms for infrastructure.

Concrete example: The design standard IEC 61936-1, from the International Electrotechnical Commission, specifies that outdoor components of the electricity network should function between -25°C and +40°C at ambient air temperatures (IEC 61936-1, 2010). In addition, critical circuits should have two levels of redundancy so that the service can remain operational in case of minor event (Cabinet Office, 2011).

This mechanical conception can be applied if:

- There is only one equilibrium or normal state
- The object resists or returns to this state after a disturbance
- The type of disturbances is known (Holling, 2010).

Resilience is the systems' ability to resist various possible hazards, absorb the initial damage from hazards, and recover to normal operation (Lhomme et al., 2013; Ouyang and Dueñas-Osorio, 2012).

This simplest conception **corresponds to inanimate, physical objects** which can either withstand stress or recover by returning to the initial state of functioning.

This conception however does not apply well for complex and dynamic systems and networks such as living organisms, ecosystems and societies **where recovery does not necessary imply returning to the initial state.**

3.1.3 Resilience as an ability to adapt

In addition to the ability to "persist" – and sometimes instead of – resilience has been increasingly used to describe an ability to adapt. In fact, the very concept of resilience has been introduced in ecology as a reaction to the concepts of stability and equilibrium. In its seminal article, Holling described how fluctuations are essential to ecosystem functioning: ecosystems undergo periodic cycles of change and do not evolve toward a single stable climax state (1973). Since then, "resilience" has evolved into an intellectual framework for understanding how complex systems, such as societies and ecosystems, learn, adapt and re-organize over time[1].

These definitions of resilience which include notions of learning and adaptive capacity are particularly relevant for cities and infrastructures (Klein et al., 2003). If the design and engineering standards are usually intended to protect the physical integrity of the asset, they are not sufficient to confer a complete resilience of the system. From an operational point of view, resilient infrastructures should be well designed and well managed.

A key principle of managing complex adaptive systems, such as urban ones, is that novelty should be fostered and systems should be able to self-organize in response to crisis that disrupt normal regulatory mechanisms (Gunderson et al., 2008). Resilience results from the ability of organizations and individuals to anticipate the changing shape of risk before failures and harm occur. The performance of individuals and organizations must continually adjust (Hollnagel et al., 2006) and a large set of sub-components of resilience has to deal with governance (actors, institutions, organizations) (Birkmann et al., 2012a).

[1] For detailed reviews of theoretical differences between resilience conceptions and the increasing role played by the more inclusive definitions see (Birkmann et al., 2012a; Holling and Gunderson, 2002; Holling, 2010; Martin-Breen and Anderies, 2011).

Concrete example: The concept of flood risk management, promoted by the EU has become the new paradigm of reducing flood disasters in Europe. The Floods Directive tries to mitigate flood risks not only by structural, hydraulic engineering measures, but also by "non-structural measures" such as prevention, protection and preparedness (see Schanze et al., 2008, and references therein).

The determinants of the capacity to adapt have been widely debated in the literature and include issues as diverse as:

- The range of technological options for adaptation
- The availability of resources and their distribution across the population
- The structure of critical institutions
- The system's access to insurance
- The ability of decision-makers to manage information (see (Harley et al., 2008) for a detailed list and discussion).

A fundamental challenge in assessing resilience thus arises from this dense bush of coexisting meanings and interpretations which put resilience "in danger of becoming a vacuous buzzword from overuse and ambiguity" (Rose, 2007, p. 384).

Depending on authors, a resilient system must be redundant, diversified and efficient at the same time; autonomous and collaborative; stiff, flexible and adaptable; persistent and prone to change, and many other apparent contradictions which preclude the design of consistent operational methodology (Reghezza-Zitt et al., 2012).

Consequently, with very few exceptions, the term resilience is used as a general or descriptive sense and operational guidelines cannot be usefully derived from its definition, not to mention indicators (Tyler and Moench, 2012).

Yet, an ever increasing number of key institutional players[2] are adopting the broadest and most comprehensive definition of resilience which blends persistence and adaptability:

Resilience is the ability of X to anticipate, absorb, adapt to and rapidly recover from Y

These different abilities correspond to different temporal phases: A system resists and absorbs *during* and recovers *after* a stressful event. All three abilities depend on adaptability efforts to anticipate prevent and prepare the system which take place *before* an event.

3.2 Resilience of what?

3.2.1 Scale of Resilience from objects to systems

Resilience definitions and attributes vary whether they describe an isolated object or a system. As we have seen (§3.1.2), in the case of an object, the definitions are straightforward and can be used non-ambiguously to define indicators to measure the ability to absorb and resist a perturbation.

Many elements of critical infrastructure take the form of networks which provide service by allowing flows of water, passengers, information, electric power, fuels, etc. These networked infrastructures create many different dependencies within and between infrastructure sectors (see §0).

In these cases, systems and networks are at the same time:

[2] This definition is shared by Wilbanks and Kates (2010),, the IPCC (2012), UK Cabinet Office (2012a), Community and Regional Resilience Institute (CARRI), (2013), emBRACE project (Jülich et al., 2012), French Ministry of Defense (RFMD, 2008), and US National Climate Assessment (NCA) (NCADAC, 2013; Wilbanks et al., 2012) to name a few.

- a collection of agents and objects, and
- the relationships among those agents, between these objects.

In urban studies, it has been acknowledged that a neighbourhood can be damaged without necessarily affecting the functioning of the rest of the city and reciprocally a city can be resilient but not one of its neighbourhood (Sanders, 1992).

Consequently, different disciplines have generated different definitions of resilience, relevant to the class of problems they address, and no single discipline deals with systems that range across all the possible scales.

What is being considered should thus be clarified before analysing its potential resilience. In particular key distinction should be made between object and systems. This issue is particularly relevant in the case of infrastructure that can describe an object, a network, a system of objects or even a complex system of systems.

3.2.2 Architecture and the built environment

The built environment is the "collection of man-made or induced physical objects located in a particular area or region" (ISO 21929-1, 2011, p. 3) understood to encompass "all of the buildings, spaces and products that are created or significantly modified by humans" (Health Canada, 1997, p. 12) and in this context comprises:

- Buildings and structures
- Facilities and networks for communication
- Facilities and networks for transport
- Plants, facilities, and networks for water supply and wastewater treatment
- Plants, facilities, and networks for solid waste treatment
- Plants, facilities, and networks for energy production and distribution.

The building and construction sector alone is responsible for 10-40% of countries' GDP, as well as 10% of employment (UNEP, 2009). The sector is not only the largest consumer of natural resources, in terms of both land use and materials extraction, but is also responsible for 30-40% of global primary energy use and greenhouse gas (GHG) emissions (Huovila et al., 2007). Residential and commercial building operational energy consumption alone accounts for 29% of global, and 34% of European primary energy use (EIA, 2011). While there are many current initiatives that aim to reduce the impact of the built environment on the natural environment, according to the United Nations: "…there is still a clear lack of initiatives aiming at addressing global issues from a life-cycle perspective of the built environment" (Huovila et al., 2007, p. 1).

Architecture is a discipline that involves a broad variety of perspectives, dealing with "the creation, transformation and interpretation of the built environment and the articulation of space at various scales" (EAAE, 2012, p. 1), ranging from buildings to public spaces, landscape and urban design.

At the urban scale, components and parameters for architectural and spatial quality include infrastructure, urban form, proximity to facilities and functions, access to green areas, building typology and morphology, transition between different urban areas and city boundaries (Alexander et al., 1977; Gehl, 2011; Jacobs, 1961; Lynch, 1990, 1984; Rogers, 1997). At the building scale, examples include views, isolation and contact, internal and external arrangements, transition between public and private domains, and perceived density (Ashihara, 1981; Gehl, 2011; Rapoport, 1994; Weber, 1995).

Resilience of architecture is thus imperative for people's quality of life and the spatial quality of the environment that surrounds people in their daily life. In this context, quality is defined in a broad manner including also issues such as security and accessibility.

3.2.3 Infrastructure(s): Hard vs. Soft

The term *infrastructure* has been used in English since 1927 "to refer collectively to the roads, bridges, rail lines, and similar public works that are required for an industrial economy" (American Heritage Dictionary). This original meaning corresponds to the one in use today in Latin languages (French, Spanish, Italian etc.) where "*les infrastructures*" or "*las infrastructuras*" refer unambiguously to the *built* infrastructures. The plural is usually used to denote the existence of different sectors.

In English, this conception is rare today but can still be found. Noteworthy examples include:

- The **US National Climate Assessment** for which "infrastructures" (please mind the plural) correspond to *built* infrastructures such as: "*urban buildings and spaces, energy systems, transportation systems, water systems, wastewater and drainage systems, communication systems, health-care systems, industrial structures, and other products of human design and construction that are intended to deliver services in support of human quality of life."* (Wilbanks et al., 2012, p. 4).
- The report from the **Royal Academy of Engineering** which also focuses its analysis to built infrastructure. It is worth noting that infrastructure is used as a singular noun, particular systems being referred to as infrastructure assets or infrastructure sectors (RAEng, 2011).
- In a recent effort to devise more generic and consistent definitions of infrastructure, Fulmer has proposed: "the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance societal living conditions" (2009, p. 32).

Stricto sensu, hard infrastructure systems include both the fixed and tangible assets (built infrastructure), and the control systems and software required to operate, manage and monitor these systems. However in practice, "built" infrastructure and "hard" infrastructure are synonyms.

In addition to definitions of infrastructure that consider only physical (hard) artefacts, *infrastructure* is also found in English and German literature[3] with a more comprehensive meaning, which includes "soft" infrastructure as well. "Soft" infrastructure refers to all the institutions which are required to maintain the economic, health, and cultural and social standards of a country. Typical sectors covered by soft infrastructure include: the financial system, the education system, the health care system, governance as well as emergency services.

For instance, the report from the Royal Academy of Engineering, considers only four sectors: Energy, Transport, Communications and Water (RAEng, 2011).

Strikingly, on the same issue and published the same year, the UK cabinet Office defines (national) infrastructure as a complex mix of "networks, systems, sites, facilities and businesses that deliver goods and services to citizens, and support our economy, environment and social well-being" (Cabinet Office, 2011, pp. 11–12). Accordingly, the UK plan for infrastructure recognizes nine key sectors: food, energy, water, communications, transport, health, emergency services, government, and finance (Cabinet Office, 2011, 2010). In addition to these sectors, the UK government also considers other infrastructure of national significance such as civil nuclear facilities, hazardous sites, strategic companies and research organizations (Cabinet Office, 2011).

[3] **Note:** In German, as in English, the singular *Infrastruktur* is more common although the plural *Infrastrukturen* can also be found. The term can also describe either the hard or the soft infrastructure depending on the context.

In the same vein, the US Department of Homeland Security identifies 18 critical infrastructures: Agriculture, Banking and Finance, Food, Energy, Transportation, Public Health, Emergency Services, Information and Telecommunications, Chemical Industry and Hazardous Materials, Government, Defense Industrial Base, Monuments and Icons, Postal and Shipping, and Water.

Classification of sectors varies widely between studies but tends to recognize a central core of five key sectors:

- Energy
- Communications (ICT)
- Transport
- Water
- Health facility (to a lesser extent).

Table 3 provides a summary of the different conceptions of infrastructure mentioned in this report (Cabinet Office, 2011; RAEng, 2011; Wilbanks et al., 2012).

Source	**Language**	**Singular**	**Plural**	**Built-hard**	**Social-soft**
Origin	English	X		X	
UK, RAEng	English	X		X	
US, NCA	English		X	X	
UK, CO	English	X		X	X
Common usage	French		X	X	(X)
Common usage	Spanish		X	X	(X)
Common usage	German	X	X	X	X

Table 3: Summary of different conceptions of infrastructure. Sources: RAEng: (RAEng, 2011); NCA: (Wilbanks et al., 2012); CO: (Cabinet Office, 2011)

To add to the challenges to analyse the corpus, it should be noted that these hard and soft infrastructure concepts are not congruent with the hard and soft conceptions of resilience. In its proposition for an operational framework, Kahan et al, distinguishes:

- Hard resilience, which "addresses institutions and infrastructure and refers to their structural, technical, mechanical, and cyber systems' qualities, capabilities, capacities, and functions" (2009, p. 6), from

- Soft resilience, which "refers to the aspect of resilience related to family, community, and society, focusing on human needs, behaviors, psychology, relationships, and endeavors" (2009, p. 6).

These definitions also overlap to some degree with the outcome resilience and process resilience.

Finally, different intergradations exist between hard and soft infrastructure, for instance: "the term "infrastructure" refers to both physical systems (such as water supply, sanitation, energy, transportation and communication services) and institutional systems (delivering healthcare, security, and fire control and other services)" (Hallegatte, 2011, p. 3).

To conclude, the attributes of the hard and soft infrastructure are very different and important sources of divergence in the literature.

In the rest of this study we will use the wording (hard, soft, plural, singular etc.) corresponding to the one used in the original publications. For the sake of consistency, we will sometimes refer to focused and comprehensive conceptions. We introduce the words comprehensive and focused to avoid words such as restricted, limited, broad, narrow and so forth, which might carry unintended appreciation of intrinsic value.

3.2.4 Infrastructures, services vs. structures

Considerations on physical structures should not conceal that for users, assets owners and decision-makers the *services* that are provided are more important than the *structures* as such.

In fact, performance of infrastructures is constantly assessed by owners and operators in many different ways. For example, normal service delivery can be measured in terms of the number of households being connected to the grid, the volume of water being delivered, the tonnage of freight being transported, the revenue generated by normal system operations etc.

Guaranteed Standards, or Standards of Services (SoS) are used in Infrastructure Asset Management to define the service that a customer is entitled to receive. Any public or private body operating in water, energy or transport must comply with obligatory SoS. SoS should be objectively measurable, so that performance can provide a sound foundation for Asset Management and enable the regulators to measure the performance of the organization.

A typical SoS includes service expectations, safety requirements, fault toleration levels, response / reconnection objectives and penalties for service disruption. A "minimum condition grade" is also usually provided by considering the consequences of a failure of the infrastructure asset.

SoS are usually set by national bodies, but are increasingly subject to international standardization.

Concrete example: ISO 50001 is a specification created by the International Organization for Standardization (ISO) for an energy management system (ISO 50001, 2011). The standard specifies the requirements for establishing, implementing, maintaining and improving an energy management system, whose purpose is to enable an organization to follow a systematic approach in achieving continual improvement of energy performance, including energy efficiency, energy security, energy use and consumption. The standard aims to help organizations continually reduce their energy use, their energy costs and their greenhouse gas emissions.

International Standards on water service management and assessment are under preparation within Technical Committee **ISO/TC 224** (ISO, 2013).

3.2.5 Interdependency

Many elements of infrastructure take the form of networks which provide service by allowing flows of water, passengers, information, electric power, fuels, etc.

These networked infrastructures create many different dependencies within and between infrastructure sectors. It is essential that these interdependencies are both understood and managed to improve the resilience of infrastructure (DEFRA, 2011; RAEng, 2011; Wilbanks et al., 2012). A useful classification for infrastructures recognizes three main categories of dependencies, geographical, physical and logical (Brown, 2010; Rinaldi et al., 2001).

3.2.5.1 Geographical dependencies

The first source of interdependency comes from the fact that infrastructures are often co-located: for instance, power cables may be laid beside communications cables along roads, adjacent to water and gas mains and above sewers. Elements are close enough to be damaged by the same event, failure of one form of infrastructure can lead directly to damage to another and damage can also occur inadvertently during repair infrastructure work (Brown, 2010; RAEng, 2011). Geographical dependencies can also exist on a large scale as disruptive events such as high winds and flooding are susceptible to create damage and injuries up to the regional level.

3.2.5.2 Physical dependencies

Secondly, physical dependencies describe systems which are physically connected and where one is dependent on the other to function (Brown, 2010). Major disruptive events have shown dramatically that the four core sectors (energy, Information Communication Technology (ICT), transport and water) are all interdependent to some extent and are all absolutely dependent on the provision of energy and ICT (see Table 5) (Perks et al., 2009; RAEng, 2011; Wilbanks et al., 2012; Zambon et al., 2010).

The energy and ICT sectors are now regarded as mutually dependent: Energy infrastructures – both supply and demand – are increasingly reliant on communication and control systems, which rely on energy. The loss of electricity supplies can disrupt communication and information services, which in turn also complicates emergency responses related to health and safety (RAEng, 2011; Wilbanks et al., 2012).

3.2.5.3 Logical dependencies

Thirdly, infrastructures can influence one another without being physically connected due to human decisions and actions (Brown, 2010). These logical dependencies can cause severe service disruptions inside and outside the perimeter of interest. Businesses in every sector of the economy rely on other firms to supply necessary inputs and services. Dependencies can even be international due to the increased globalization of supply chains. For example, flooding in Thailand or cyclones in South Korea would directly affect critical U.S. supply chains (Wilbanks et al., 2012).

Concrete example: Hurricane Katrina disrupted oil terminal operations in South Louisiana because workers could not reach work locations (disrupted transportation), nor could they be housed locally because of disruption to potable water, housing, and food shipments. In that case, the greatest economic impacts turned to be distant from the infrastructure where damages started (Myers et al., 2008).

Resilience in one sector is thus dependent on resilience in another, and climate change increases the risks of cascade failures where a breakdown in one system has knock-on effects on others.

Even though research capacities for modelling and analysing dependencies remain "scarce and spotty" (Wilbanks et al., 2012, p. 29), modelling of infrastructure dependencies provides a promising avenue for approaching complexity of the system and ensuring that vulnerabilities in one sector do not compromise others. Modelling infrastructure system interdependency will be presented in section 4.4.1.

Table 4 presents examples of interdependencies across the four main sectors.

Sectors	Energy	Transport	Water	Information and Communication Technology (ICT)
Energy	All sectors depend on energy to carry workforce to site	Transport for the fuel supply chain All sectors depend on transport to carry workforce to sites and distribute food	Water is required for cooling power stations and fuel refining All workplaces require water for staff	ICT for control and management system of electricity and gas Increasing dependence on ICT for sensing and reporting the condition of the infrastructure
Transport	Transport wholly dependent on fuel and increasingly electricity	All sectors depend on transport to carry workforce to sites and distribute food	All workplaces require water for staff	ICT for management of services and networks Increasing dependence on ICT for sensing and reporting.
ICT	ICT wholly dependent on energy for all services	All sectors depend on transport to carry workforce to sites and distribute food	Same as above	Same as above
Water	Water wholly dependent on energy for pumping, processing and control systems	All sectors depend on transport to carry workforce to sites and distribute food	Same as above	Same as above

Table 4: Examples of interdependencies across the four main sectors. The table should be read as follows: Sector 1 (row) depends on Sector 2 (column). Source: (RAEng, 2011; Wilbanks et al., 2012).

Accordingly, treating infrastructure as a holistic system is increasingly seen as essential to understand and manage the interactions between the elements of the infrastructure and capture the critical dependencies at the operational level.

3.3 Resilience to what?

Key messages: For infrastructure assets, the main threats presented by climate change are (i) damage or destruction from extreme events, (ii) floods, (iii) change in water availability, and (iv) and higher temperatures. However, analysis and modelling are confronted with considerable uncertainties regarding climate system behaviour, as well as future emissions, development trajectories and urbanization trends. These uncertainties make it difficult, and sometimes impossible, to know what the infrastructure should be adapted to. The time horizon is another key issue as short term and long term resilience can be different, and last but not least, the very nature of climate change adaptation makes metrics and policies largely untestable.

As infrastructure assets have long operational lifetimes they are sensitive not only to the existing climate at the time of their construction, but also to climate variations over the decades of their use. For example, a substantial proportion of infrastructure built in the next five years, will still be in use long after 2030. To increase the resilience of both new and existing infrastructure, methods are needed to prioritize vulnerabilities in the infrastructure system for effective planning.

3.3.1 Climate change impacts: determining the key risks

Most frameworks are based on a list of impacts to assess what infrastructure should be resilient to. This list requires the following information:

- the likely key impacts on infrastructure operations and operators
- the likelihood and frequency of natural hazards
- the linkage between different natural hazards
- the dependencies between infrastructures and essential services (Cabinet Office, 2011).

In addition particular attention should be devoted to define uncertainties and time horizon in the models.

In Europe, amongst the 52 different impacts due to climate change which have been identified (EC, 2009; EEA, 2008; Harvey et al., 2009), 10 are particularly relevant for urban areas: higher temperatures, heat wave and health; decreased precipitation, water scarcity and drought; wildfires; heavy precipitation and fluvial floods; intensive precipitation and urban drainage; sea level rise and storm surge-driven flooding; saltwater intrusion into aquifers; mass movements and erosion; wind storms; vector-borne diseases (Schauser et al., 2010). The causes and effects of most issues are well documented in the literature although the details of the cause-effect chains for specific urban population groups or systems are often still unknown.

For infrastructure assets, there is a consensus that the main threats presented by climate change are:

- Damage or destruction from **extreme events**, which can damage or destroy hard infrastructures, such as transport infrastructure, thermal power plants, water networks, refineries and so forth,
- **Floods from sea level rise, coastal and river flooding**, because they directly affect power station and transport infrastructure used to deliver fuel to power stations,
- Change in patterns of water availability, and, to a lesser extent,
- Increased maintenance costs associated with **higher temperatures** (see (ESPON Climate, 2011; Neumann and Price, 2009; RAEng, 2011; Wilbanks et al., 2012).

Conceptual and data constrains limit the identification of the most important factors describing the sensitivity or adaptive capacity of a system. In particular, the climatic effects on urban systems present significant gaps (Schauser et al., 2010).

However, extreme events and floods are of major concern because they are likely to result in cascading effects and systemic failure (see §0).

3.3.2 Linkages between events

Natural hazards and in particular climate change impacts, tend to occur either simultaneously or consecutively. As flooding can result from melting snow, the major impacts on infrastructure may not necessarily be due to the natural event itself but to its secondary consequences. Reciprocally a damaging impact can result from different natural events. For example, flash flooding can result from a storm event or a rapid thawing of snow. Table 6 lists the links between different natural hazards and impacts identified by the UK National Risk Register (Cabinet Office, 2012b)[4].

Source	Initial consequences	Knock-on consequences
Storms and Gales	Strong winds (Gales) Tidal surge Snow Lightning Heavy Rainfall Tornadoes Hail	River and coastal flooding Surface water flooding Land instability Wildfire
Prolonged period of hot weather	Heat	Thunderstorms Drought Dust/Smog/haze Land instability Wildfire
Prolonged period of dry weather	Reduced Rainfall	Dust/Smog/Haze/fog Reduced ground water flow Water quality Land instability Drought Wildfire
Excessive cold with snow	Cold Snow	Ice Wind chill Fog Surface water and river flooding (snow melt)

Table 5: Linkages of natural hazards and climate change impacts (Cabinet Office 2011).

3.3.3 Climate change impacts: EU exposure profile

In the EU, the ESPON Climate project used the CCLM climate model to determine the general and regional climatic changes which are likely to occur within 30 years and establish the corresponding exposure profiles (ESPON Climate, 2011).

The key findings are:

- An increase of the **annual mean temperature** between 2 and over 4.1 degrees across EU territory
- A **decrease of average precipitation** in the southern territory up to 40% and more
- An **increase of average precipitation** in UK and Scandinavia, up to 40% and more
- A **decrease of days with snow cover** in Northern territories and Alpine countries
- A considerable **increase in exposure to river flooding** in Northern Scandinavia and Northern Italy and, to a lesser extent to selected regions in UK, Ireland, Hungary and Romania
- An expected **decrease in exposure to river flooding** in Easter Germany, Poland and Southern Hungary

[4] In addition to the natural hazards which are attributable to climate change, the UK National Risk Register also accounts for impacts of volcanic ash and severe space weather resulting from solar eruptions (Cabinet Office, 2012b).

- **Coastal flooding:** For most coastal regions changes in inundated area will be rather marginal. However significant increases in regional exposure to coastal storm surge events are expected for selected coastlines of the Netherlands, Germany, Denmark, Eastern UK, Western France, North-Eastern Italy and Romania.

(For a detailed presentation of exposure profiles, see (ESPON Climate, 2011). The list of corresponding indicators is given in Section 5.3.1.1).

It results from ESPON analysis that vulnerability is extremely heterogeneous. Large parts of Europe may not expect relevant impacts on their infrastructure while North-Western European coastal regions, which border the Atlantic Ocean, present remarkably high exposure profiles.

For cities, the European Database of Vulnerabilities for Urban Areas (EVDAB) presents key vulnerabilities of 305 EU urban areas (JRC, 2013). The adaptive capacity of cities is planned to be assessed by using country level adaptation investment data from the Directorate-General for Regional and Urban Policy (DG REGIO) cohesion fund report.

The **Floods Directive** requires Member States to draw up a Preliminary Flood Risk Assessment to identify the areas at significant risk and produce flood hazard and risk maps (EC, 2007). These maps are due by December 2013 and will include detail on the flood extent, depth and level for three risk scenarios (high, medium and low probability).

3.3.4 A climate of uncertainties

While there is overwhelming evidence that the world is warming, there are also considerable uncertainties surrounding the scale, timing and nature of how the climate might change. Analysis and modelling are confronted with uncertainties in future emissions, and with climate system behaviour, in particular at the regional and local level. These uncertainties make it difficult, and sometimes impossible, to know exactly what the infrastructure should be adapted to.

Concrete example: Historical records and regional climate models in the US have been analysed to estimate extreme precipitation and determine design parameters (Rosenberg et al., 2010). This work concludes that current drainage infrastructure may be inadequate to cope with increase in extreme rainfall. However, the range of variations of the different projections is too large to determine engineering design requirements (Rosenberg et al., 2010).

In other words, the risk is identified but the uncertainties preclude the design of an adapted response.

Detailed risk assessments must be made for infrastructure assets under the likely conditions they will be exposed to. However, the uncertainty related to the trajectories of development and urbanization affects the way risks are understood and managed.

Concrete example: Efforts to reduce greenhouse gas emissions are likely to create new interdependencies and vulnerabilities in the infrastructure system. For instance, it is likely that reduction in travel to work will increase reliance on and demand for bandwidth which will also increase energy consumption (RAEng, 2011). More generally, current decarbonising transport strategies rely heavily on electric mobility, expecting a smart grid to deal with different loads. This "smart" trend is likely to increase dramatically the dependence of all the other sectors on energy and ICT.

The linkages between different infrastructures will change notably in the coming decades, adding to the uncertainties to predict and assess the risks.

3.3.5 Temporality

Temporality is another key parameter which poses serious methodological challenges, in particular in the context of climate change.

Phases: We have seen that the different abilities of a resilient system correspond to different temporal phases: A system resists and absorbs *during* and recovers *after* a disruptive event while adaptability efforts to prevent and prepare the system take place *before* an event.

These three phases correspond to different fields of expertise - vulnerability and risk management, crisis management, adaptation - which are confronted with different challenges and develop appropriate methods accordingly.

Additional issues with temporality include:

- Sudden and persistent events can have different consequences
- Short term and long term resilience can be different
- Metrics and policies are largely untestable.

Sudden vs. persistent: Short-term effects must be distinguished from those that are sustained or persistent. Short term impacts, such as flash flooding, may have to be tolerated in some situations, while it may be more realistic to introduce counter measures economically for persistent effects, such as rivers running low or increased temperature (RAEng, 2011).

Short term and long term effects can be significantly different, even for the same impact. Some strategies may enhance infrastructure system resilience in the short term but at the expense of the resilience in the long run. For example, the study of a power transmission grid has shown that some resilience strategies may enhance infrastructure system resilience in the short term, but may compromise practical utility system resilience in the long run if not managed well (Ouyang and Dueñas-Osorio, 2012).

Metrics and learning process: Long timescales and uncertainties associated with climate change challenge the classical learning process. By definition, an infrastructure is resilient if many adverse effects of climate impacts can be avoided. However, since many of the impacts to be avoided - especially the most important ones - are expected to happen in a distant future[5], the effectiveness of policy and metrics may not be tested, evaluated and improved (see §0).

To conclude, temporality is a fundamental parameter which must be considered for determining the purpose of the evaluation and design indicators accordingly. The key issues about resilience are thus not only resilience of what and resilience to what but also **resilience when.**

3.4 Challenges to measure resilience

Key messages: Developing resilience indicators is a difficult task because it must address the typical challenges of assessment (to be feasible, informative, cost-effective etc.) and at the same time deal with the very complex nature of resilience. The literature is so divergent and confusing that the notion of measuring resilience itself has been contested. In practice, different indicators have been proposed to assess proxy properties of resilience. They basically fall into two categories:

[5] To our knowledge, the longest time horizon comes from the REA which uses UK climate projections up to 2100 (RAEng, 2011).

- Persistence, resistance, robustness can be assessed with outcome-based indicators which measure the effectiveness of action and policy.
- Adaptability, responsiveness, ability to recover can be assessed with process-based indicators which monitor progress in implementation.

3.4.1 Generic challenges to define indicators

"An indicator is a quantitative or qualitative measure derived from a series of observed facts that can reveal relative position in a given area and, when measured over time, can point out the direction of change" (Freudenberg 2003, p.7). The principal objective of indicators is to inform decision-making. They must tell whether things are getting better or worse so that adequate responses, now or in the future, can be formulated in a practical manner. However, here again, a simple and clear definition can hide a daunting complexity. The literature on how to define "good indicators" is plethoric, and many different sets of guidelines have been established (e.g. (Boulanger, 2008; Harley et al., 2008; Mainguy, 2012; Moldan and Billharz, 1997). In practice, criteria for defining good indicators vary depending on the definition and attributes of performance.

For instance, in terms of purpose, good indicators can be designed:

- To monitor action;
- To compare places and situations;
- To provide early warning information;
- To anticipate future conditions and trends (Moldan and Billharz, 1997).

In practical terms, good indicators should be robust, precise, objective and transparent, rely on data which are easily accessible and at a reasonable cost (Boulanger, 2008; Harley et al., 2008).

Exploring the different facets of the concept, Boulanger recognized that indicators should be:

- appropriate within the theoretical framework (science issue);
- useful for the governing bodies (political issue);
- legitimate within the territory/the institution (democratic issue);
- easy to monitor (availability, cost, expertise) (practical issue) (Boulanger, 2008).

This list of recommendations is certainly comprehensive, but defining an ideal set of indicators which comply fully with the above may be an impossible task. This is especially true because:

- The more the indicators are detailed or comprehensive, the less practical and the more expensive they become (Mainguy, 2012),
- Indicators for monitoring action are not necessarily efficient at benchmarking and vice versa (Boulanger, 2008; Harley et al., 2008; Mainguy, 2012).

Conclusion: Defining function and performance is absolutely critical to set indicators, and different approaches can appear as apples and oranges because they are based on different conceptions of the issues. In a nutshell, the design of a specific set of indicators depends on the following key questions: What should be monitored? How? and Why? These questions are not necessarily addressed by the same tools.

3.4.2 Specific challenges of indicators of resilience

In addition to these general challenges which must be considered in any attempts to design "good indicators", the nature of resilience introduces new difficulties including:

- the absence of an agreed definition of resilience,
- the absence of an agreed definition of performance and acceptable performance,

- the need for multi-stakeholder agreement on the levels of acceptable risk,
- the multi-sectoral nature of resilience and the large number of responsible organizations,
- the lack of a robust theory of change that includes causal relationships,
- the time horizon posed by climate change,
- the inherent uncertainty associated with climate projections and lack of baseline,
- the limited experience in resilience indicators method and design,
- the limited possibility to test indicators and learn from experience,
- and more!

These shortcomings make it particularly challenging to monitor programs and evaluate actions using classical approaches. The literature is so divergent and confusing that the notion of measuring resilience itself has been contested. Some authors consider it more appropriate to ascertain resilience by proxy properties that represent the processes and properties of the concept (Birkmann et al., 2012a, 2012b; Harley et al., 2008; Prowse and Snilstveit, 2011).

A fragmented/targeted approach seems all the more so necessary that resilience indicators are desirable for very different purposes, e.g.:

- To target and monitor funding and investments;
- To evaluate policy interventions;
- To inform future policy development;
- To compare achievements across regions or countries;
- To anticipate future conditions and trends (adapted from (Harley et al., 2008).

3.4.3 Process- and outcome-based indicators

In practice, two broad categories of indicators can be recognized:

- Outcome-based indicators which measure the effectiveness of the intervention
- Process-based indicators which monitor progress in implementation.

These two different objectives emphasize the two different sides of the resilience concept, persistence and adaptability respectively.

3.4.3.1 Resilience as an outcome

An outcome-based approach seeks to define an explicit outcome, or end point, of the action (Eriksen and Kelly, 2007; Harley et al., 2008).

Outcome resilience is conceived as the ability to resist shocks and remain in the same state (resist, absorb, recover). This conception is compatible with the establishment of assessment methodologies as quantifiable boundaries and thresholds can be defined. In particular, it can be used to determine thresholds of different system states and measure resilience as the distance between different attractor states (Birkmann et al., 2012a). Outcome resilience is based on the system state of interest (see §0) and the perturbations against which this system state has to be resilient (see §3.3) (Carpenter et al., 2001).

This approach corresponds to the question: What can be done to protect the system? It frames adaptive options in terms of solutions, often technological in nature, to minimize the particular impacts that have been projected (Eriksen and Kelly, 2007).

Concrete example: To increase drainage capacity to cope with more intense precipitation events (the outcome is explicit).

3.4.3.2 Resilience as a process

Alternatively, a process-based approach seeks to define the key stages in a process that would lead to the best choice of end points without specifying that point (Harley et al., 2008). It tends to correspond to the question: What can be done to strengthen people's own capacity to respond and adapt? (Eriksen and Kelly, 2007).

Concrete example: To strengthen the risk assessment ability of an organization.

A process-based approach is more flexible, as it can adjust to new information as it becomes available. By focusing on change and transformation, process resilience poses specific challenges in terms of assessment:

- If systems are flexible and constantly re-shaping, how can changes be measured and quantified?
- Are the transformations which affect resilience always observable? (see Birkmann et al., 2012a).

3.4.3.3 Comparison

Process-based indicators are used to build adaptive capacity, where it is needed to monitor the progress in implementing adaptation measures

Outcome-based indicators are needed to measure the effectiveness of adaptation policies and activities in general (Harley et al., 2008).

Being prone to quantification, outcome resilience has been recognized as "one of the most influential attempts to give an empirical identity to resilience" (Birkmann et al., 2012a, p. 13). Resilience as a process is likely to have less tangible results than resilience as an outcome (Harley et al., 2008).

However, uncertainties and long timescales associated with climate change impacts hamper efficient evaluation of adaptation measures and strategies in the short-term (see §3.3). Consequently process-based indicators may be more appropriate for monitoring and evaluating adaptation when the end point is too uncertain or too distant in the future to design suitable outcome-based indicators (Harley et al., 2008).

There is no consensus in the literature on the respective role that these two kinds of indicators should play:

"Perceiving resilience as a process rather than an outcome undermines some of the popular previous attempts to measure resilience" (Birkmann et al., 2012a, p. 13).

"It is expected that a combination of process-based and outcome-based indicators will be needed in order to monitor progress in adaptation across Europe (...) it is likely that process-based indicators will be the focus initially" (Harley et al., 2008, p. 11)

3.4.4 Conclusion

The nature and focus of methodologies developed to assess and measure resilience depend on the adopted definitions, the type of infrastructure of interest —in particular whether soft infrastructures are considered or not —, the perimeter, the sectors and time horizon considered and last but not least, the purpose of the evaluation. The range of potential evaluation needs and the number of specific challenges precludes the elaboration of a one-size-fits-all set of indicators for infrastructure resilience.

Ad impossibilia nemo tenetur[6]. If there is no "perfect" operational framework able to encompass all the dimensions of infrastructure resilience, in practical terms, asset owners, local authorities, regulators and insurers face these issues on a daily basis.

For this reason, significant progress has been made over the last five years and the policy community is now slightly ahead of the research community (Cutter et al., 2010). We will now look into different approaches which have been proposed to assess resilience performance both quantitatively and qualitatively.

[6] No one is held to do the impossible.

4 Approaches to assess resilience

Gaëll Mainguy, with Ludivine Houssin and Georges Valentis

Just as there is no standard definition of resilience, there is no standard measure of resilience (Moteff, 2012).

This chapter provides an overview of selected tools and best practices using the analytical framework introduced in Chapter 3. It presents key results and current research areas:

- Different selected theoretical frameworks to illustrate the diversity of possibilities when it comes to assess infrastructure resilience (§0)
- The means by which resilience is conveyed within business practices (§4.2)
- Several current research areas (§4.3).

4.1 A diversity of frameworks

An impressive number of frameworks have been proposed to assess the resilience of infrastructure in the context of natural hazards, earthquake and terrorism (for reviews see Birkmann et al., 2012a; Cutter et al., 2010; Kahan et al., 2009; Klein et al., 2003; Martin-Breen and Anderies, 2011; Tyler and Moench, 2012).

This diversity will be illustrated here via:

- **Outcome-based approaches**: the framework proposed a decade ago by Bruneau et al. (2003), remains one of the most influential attempts to assess resilience in practice (e.g. Birkmann et al., 2012a; Moteff, 2012). We will introduce this model and describe selected examples to illustrate how it has inspired other quantitative and qualitative approaches.
- **Process-based approaches:** we present two methods which target the "pre-event" phase to enhance and foster resilience.
- **Comprehensive approaches:** we will finally present the approach from the UK Cabinet Office which is, to our knowledge, one of the most pragmatic and business oriented and has been recently adapted by the World Bank.

4.1.1 Outcome-based approaches

4.1.1.1 Bruneau's model

This framework is based on a set of four criteria—robustness, rapidity, resourcefulness and redundancy—to evaluate the technical, organizational, social and economic dimensions of the disaster management process (Bruneau et al., 2003). This matrix is applied to four "critical" infrastructure sectors, namely Water, Energy, Hospitals and Emergency management systems.

The definition of resilience is comprehensive, including persistence and adaptation:

Resilience is the "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 events (Bruneau et al., 2003, p. 735).

A quantitative model has been proposed to measure and compare the level of performance of an infrastructure between 0%, when no service is available, and 100%, when the service is fully operational (Bruneau et al., 2003). The "loss of resilience" is viewed as the magnitude of the degradation of performance following failure over time (Bruneau et al., 2003, p. 737). This operational conception introduces three key generic parameters for resilience:

- Failure probability
- Consequence from failure
- Reduced time to recovery.

These generic parameters correspond to the ability of the system to resist, absorb and recover respectively. Remarkably, these parameters also correspond to the three temporal phases of resilience, namely, before, during and after an event. This triple correspondence is a key asset of the framework (Birkmann et al., 2012a; Lhomme et al., 2010; Moteff, 2012)).

Synopsis of the Bruneau approach:

- **Conception of resilience:** Comprehensive, includes persistence and adaptation
- **Resilience of what:** social units and communities albeit the framework is based on infrastructure sectors which serve as critical lifelines both hard (Water, Energy) and soft (Hospital, Emergency)
- **Resilience to what:** major disruptive events such as natural hazards, terrorism
- **Resilience when:** before the event, during the event, after event
- **Sectors:** Water, Energy, Hospital and Emergency management system
- **Interdependency**: not assessed

In our view, this seminal framework has been particularly useful because it provides:

- a generic model to quantitatively assess the performance of infrastructure
- a tentative list of key indicators, which are either illustrative or generic (see Table 6)

Note however, that the practicality and cost-effectiveness of the approach has not been assessed nor discussed, the method has not been applied directly and its efficiency has not been evaluated.

Table 6 presents a summary of technical performance indicators proposed by Bruneau (2003).

Sectors	**Technical performance indicators**			
	Robustness	Redundancy	Resourcefulness	Rapidity
Global	Damage avoidance and continued service provision	Back up resources	Diagnostic and damage detection methodologies	Optimizing time to return to functional levels
Water	Maximize availability of operational water supply	Replacement inventories	Models to assess network vulnerability and damage	Maximize provision of target water supply
Energy	Maximize availability of operational power supply	Same as above	Same as above	Maximize provision of target power supply

Hospital	Maximize availability of buildings and equipment	Back up resources	Integrated fragility models to assess system vulnerability	Buildings and equipment are fully functional
Emergenc y	Avoid damage and maintain functionality of facilities	Same as above	Damage detection technologies, Decision support system	All technology needed for control, command, coordination is operational
	Organizational performance indicators			
Global	Continued ability to carry out designated functions	Backup resources to sustain operations	Plans and resources to cope with damage and disruption	Minimize time needed to restore services and perform key responses tasks
Water	Emergency organization and infrastructure in place; critical function identified	Alternative water supplies available	Plans for mobilizing supplies and personnel	Maximum restoration of water supply
Energy	Same as above	Replacement inventories for critical equipment	Same as above	Maximum restoration of power supply
Hospital	Same as above	Alternative sites and procedures identified for providing medical care	Plans and procedures for mutual aid emergency	Maximize provision of critical medical and health care
Emergency	Same as above	Division of labour for carrying out emergency response activities		Minimize time needed to initiate and complete critical response tasks

Table 6: Summary of technical performance indicators proposed by Bruneau (2003)

4.1.1.2 Latency limit and minimum performance boundary

The Bruneau approach has been further refined to establish resilience profiles to visualize the performance of systems and their key functions (Kahan et al., 2009). Resilience profiles for each function are determined by performance[7], time and gravity and two parameters which are introduced to describe the system:

- **Latency limit**: It describes the maximum amount of time allowable for a function to remain in a degraded or suboptimal state before it must begin to recover. For a power

[7] Note: performance can be conceived as an aggregate measure of the effectiveness of key inputs, outputs and services which may be important when the infrastructure perform more than one role (Kahan et al., 2009).

plant or IT infrastructures, this might be hours or days; for a household's standard of living, this could be months or years.

- **Minimum performance boundary**: This is the lowest acceptable level of performance for a particular function. For a water plant, this might be quantified in terms of number of m^3 produced daily which are necessary to sustain the vital needs of a community.

Purpose: These parameters can be used to establish stringent or relaxed resilience standards and to identify the acceptable parameters for key infrastructure performance under challenging conditions. They have been proposed to help planners to visualize their desired outcomes though cost-effective assessment (Kahan et al., 2009).

Interest and limit of this approach: This framework is applicable when the performance of the infrastructure is defined, documented, assessed and available "almost in real time" which is the case for issues parameters subjected to business continuity (e.g. number of households deprived of electricity during a black out, number or length of roads closed, volume of water produced by a water plant etc.).

In fact, as we will see that these parameters are strikingly similar to the Recovery Point Objective and Recovery Time Objective, which are used in Business Continuity framework (§0).

4.1.1.3 Quantitative modelling

For quantitative modelling, Bruneau's framework has been subsequently refined to compare the decrease in system performance and time to recovery (Chang and Shinozuka, 2004). Other work has produced resilience metrics for dynamic economic systems (Rose and Liao, 2005).

These models have been developed recently to account for costs and resources expended during recovery efforts following infrastructure disruptions (Vugrin and Camphouse, 2011; Vugrin et al., 2011, 2010). In this approach, resilience is defined as the ability of a system to "efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels after a disruptive event" (Vugrin et al., 2010, p. 83).

Increasing network resilience involves three related capabilities – providing *absorptive capacity* so that the network can withstand disruptions, providing *adaptive capacity* so that flows through the network can be accommodated via alternate paths, and providing *restorative capacity* so that recovery from a disruptive event can be accomplished quickly and at minimum cost (Turnquist and Vugrin, 2013).

The measurement of system resilience costs consists in the quantification of two parameters:

- **Systemic impact** (*SI*) which is the difference between targeted and disrupted system performance,
- **Total recovery effort** (*TRE*) which is the efficiency with which the system recovers from a disruption. The TRE is measured by analysing the amount of resources expended during the recovery process (Vugrin and Camphouse, 2011).

This method has been used in two case studies to assess:

- Recovery strategies for freight rail carriers in a hypothetical flooding scenario (Vugrin et al., 2010) and
- Resilience of supply chains of the US petrochemical sector to different types of hurricanes (Vugrin et al., 2011).

In the latter, the estimation of cost of restoration of services was significantly different—a factor three—between hurricanes types. This method is proposed to be generic and applicable across various infrastructure and economics models (Vugrin et al., 2011).

To our knowledge, this work is currently the most advanced attempt to provide a quantitative basis for resilience.

4.1.2 Process-based approaches: assessing the baseline

The approaches presented above consider resilience as an outcome measure with an end goal of limiting damage to infrastructure (resistance), mitigating the consequences (absorption) and recovery to the pre-event state (restoration). They aim at measuring consequences of hazards and minimizing the deviation of performance (whether technical, financial, social, etc.) and tend to be more focused on the "during event" and "post event" phases.

Other methods have been proposed to specifically assess existing conditions so that priorities can be identified and changes in disaster resilience can be monitored. Here, we present two of these baseline assessment methods which target the "pre-event" phase to enhance and foster resilience.

4.1.2.1 The Disaster Resilience Index

The Disaster Resilience Index (DRI) has been developed by the Community and Regional Resilience Institute (CARRI) to assess the baseline from which the effectiveness of programs, policies and interventions can be measured (Cutter et al., 2010). It is a composite indicator designed to benchmark pre-existing conditions and compare communities.

The DRI recognizes that disaster impacts can be reduced through improved social and organizational factors such as provision of disaster insurance and increased wealth, fostered community engagement and participation and local understanding of risks (Cutter et al., 2010, 2008). It aggregates 36[8] different variables from five different categories: social, economic, institutional, infrastructure, community. The infrastructure categories consist in seven different indicators which mainly assess the response and recovery capacities:

- Housing type: % housing units (excluding mobile homes)
- Shelter capacity: % vacant rental units
- Medical capacity: Number of hospital beds per 10,000 inhabitants
- Evacuation potential: Principle arterial miles per square mile
- Housing age: % housing units not built before 1970 and after 1994
- Sheltering needs: Number of hotels/motels per square mile
- Recovery: Number of public schools per square mile

The aggregation of all the variables results in a colour-coded map displaying a comparative assessment of community resilience. The visualization of the spatial distribution is proposed to be useful to determine underlying driving factors (Cutter et al., 2010).

Note: Ecological resilience is so far excluded from the DRI due to data inconsistency and relevancy for large and diverse study areas (Cutter et al., 2010). This is a limitation to bear in mind in the context of the increasing interest for nature-based solution (see §0).

It is striking to see how the DRI does not assess infrastructures per se[9] which illustrates how complementary the process-based and outcome-based approaches are.

4.1.2.2 The Resilience Index

The resilience index (RI) is an evaluation methodology developed by the Argonne National Laboratory to compare the level of resilience of critical infrastructures and guide prioritization of limited resources for improving resilience. It relies on subjective evaluations by experts of three key attributes of resilience: *robustness, resourcefulness,* and *recovery* (Table 7) where:

[8] See the list p7 in (Cutter et al., 2010).

[9] There is only one indicator targeting the traditional core sectors: water, energy, ICT and transportation.

- **Robustness** is the ability to maintain critical operations and functions in the face of crisis;
- **Resourcefulness** is the ability to skilfully prepare for, respond to, and manage a crisis or disruption as it unfolds;
- **Recovery** is the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible after a disruption (NIAC, 2009).

Each attribute is itself composed of different sub-components which are essentially process-based.

Robustness	**Resourcefulness**
• Redundancy	• Training/Exercises
• Prevention/mitigation	• Awareness
• Maintaining key function	• Protective Measures
	• Stockpiles
Recovery	• Response
• Restoration	• New resources
• Coordination	• Alternative sites

Table 7: The resilience index (RI) relies on subjective evaluations by experts of three key attributes of resilience: robustness, resourcefulness, *and* recovery

A relative weight is assigned to each type of data collected and each component. The value of RI ranges from 0 (“low resilience”) to 100 (“high resilience”).

The RI has been designed to provide valuable information to owners/operators about their facility’s standing relative to those of similar sector assets and how they can increase resilience (Fisher et al., 2010).

These methods refine metrics and assessment schemes and may feed in norms and standards development. Note however, that this methodology is not suitable for analysing dependencies.

4.1.3 Comprehensive and pragmatic approaches

4.1.3.1 The UK Critical Infrastructure Resilience Programme

Following the severe floods which took place during the summer of 2007, the UK Government established a Critical Infrastructure Resilience Programme to reduce the vulnerability of national infrastructure to flooding and other natural hazards. The Cabinet Office’s *Guide to Natural Hazards & Infrastructure* provides advice on building resilience (Cabinet Office, 2011). *Climate Resilient Infrastructure* looks at addressing the challenges and potential opportunities to preparing infrastructure for a changing climate (DEFRA, 2011).

Infrastructure and sectors: The framework adopts a comprehensive conception for infrastructure including hard and soft components. The first report recognizes nine sectors: energy, food, water, transportation, communications, emergency services, health care, financial services and government (Cabinet Office, 2011). The second focuses on the five "hard" sectors: energy, ICT, transport, waste and water (DEFRA, 2011).

Perimeter: National, but many, if not all, infrastructures are urban. In the water sector for instance, sixty-three critical sites were identified as being at risk from flooding (Cabinet Office, 2010).

Impacts: The list of natural hazards which are considered in the report are based on the National Risk Register and include coastal flooding, inland flooding, storms and gales, low temperatures and heavy snow, heat waves and drought. Some impacts which are not related to climate change are also considered (volcanic ash and severe space weather resulting from solar eruptions).

Resilience framework: Resilience is seen as the result of the combination of:

- **Resistance** to provide protection
- **Reliability** to ensure that infrastructure components are designed to mitigate damage or loss from an event
- **Redundancy** to enable operations to be switched or diverted to alternative parts of the network and ensure continuity of services
- **Response and Recovery** to enable a fast and effective response to and recover form disruptive events.

In this model, resilience of infrastructure is provided through:

- **Good design** to ensure that the system has the necessary resistance, reliability and redundancy (spare capacity), and by establishing
- **Good organisation** to provide the ability, capacity and capability to respond and recover from disruptive events.

Indicators: Only one specific indicator is proposed to set an explicit standard against which investments could be planned and appraised: "Essential services provided by Critical National Infrastructure in the UK should not be disrupted by a flood event with an annual likelihood of 1 in 200 (0.5%)" (Cabinet Office, 2011, p. 28). The report mentions ad hoc vulnerability assessments for each sector and recommend using standards (Cabinet Office, 2011).

Comprehensive checklist for self-assessment: A key feature of the report is the focus on providing appropriate support for developing business continuity management standards (See section §0 for a discussion of the role that standards can play). In particular, the report presents a process-based approach consisting of a set of 30 questions to assist infrastructure owners and operators to develop a comprehensive resilience strategy (See Annex §10.15 for the complete checklist).

4.1.3.2 World Bank: Building Urban Resilience: Principles, Tools and Practice (2012)

The World Bank has recently issued a report which follows and extends the approach developed by the UK Cabinet Office.

While the report addresses all components of disaster resilience, the focus rests on critical infrastructure and social aspects. Urban resilience is broken down into four components, *economic, institutional, infrastructural and social*.

Urban infrastructure refers to key systems and services, which are critically important for emergency response and the quick recovery of the community and its economy.

Infrastructural resilience is defined as the vulnerability of built structures including property, buildings and transportation systems. It also refers to sheltering capacity, health care facilities, the vulnerability of buildings to hazards, critical infrastructure, and the availability of roads for evacuations and post-disaster supply lines. Infrastructural resilience also refers to a community's capacity for response and recovery. It is thus a comprehensive definition which covers prevention, protection, resistance, recovery and adaptation.

The report does not provide indicators of resilience. Instead it also proposes a **Checklist for Infrastructure Owners and Operators**, based on the Cabinet Office Checklist. This questionnaire is intended to establish a process to build and assess resilience. The main steps of the process are:

- Identify risks
  - Determine critical infrastructure necessary to continue operations
  - Determine critical infrastructure within the supply chain
- Understand Hazards
  - Identify hazards of greatest concern to the critical infrastructure and supply chains.
- Assess risk and understand vulnerability
  - Determine the capacity of the critical infrastructure to be resilient to hazards of greatest concern through location, structural design and redundancies
  - Determine the organizations level of risk.
- Build resilience
  - Determine the organization's acceptable risk relative to the critical infrastructure.
  - Determine what level of resilience is required and what resilience strategy will be adopted
  - Embed resilience at the core of the strategic decision making processes.
  - Engage with emergency responders in areas where services are operated and delivered
- Evaluate resilience
  - Challenge, test and exercise the organizational resilience strategy.

4.2 Business as usual, a standard approach

From an operational point of view, resilient infrastructures are well designed and well managed. The need for resilient infrastructures is staggering. In the US alone, the investment needed to bring the infrastructure into good condition has been estimated to be $3.6 trillion until 2020 (ASCE, 2013). How to retrofit or maintain built infrastructures and how to build more resilient ones are thus critical issues. Accordingly hundreds[10] of tools have emerged to assess "sustainability" and "resilience".

4.2.1 Infrastructure Sustainability rating tools

New "sustainability rating tools" are becoming available to assess and rate infrastructures in a comprehensive manner. Here we will briefly present three of these tools to illustrate their strengths, weaknesses and potential.

4.2.1.1 The Infrastructure Sustainability Council of Australia (ISCA)

The Australian Green Infrastructure Council (AGIC), now known as the Infrastructure Sustainability Council of Australia (ISCA), developed a comprehensive Infrastructure Sustainability (IS) rating scheme[11] for evaluating sustainability across design, construction and operation of infrastructure in Australia. These guidelines assist industry to address climate change risks and opportunities for new infrastructure projects or existing assets and developing appropriate adaptation measures.

The IS rating scheme is based on a rating tool scorecard which can be used to assess most types of infrastructure including Transport, Water, Energy and Communication sectors. It comprises three rating types which can be applied to different development phases of an infrastructure: design, as built, in operation.

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[10] Envision™ states that they surveyed 900 different tools to prepare their scorecard.

http://www.sustainableinfrastructure.org/rating

[11] http://www.isca.org.au/is/download-is-rating-tool

The scorecard features a category for climate change adaptation which consists in a series of qualitative questions[12] about Climate change risk assessment and Adaptation measures.

4.2.1.2 Envision™

In the US, Envision™ is a comprehensive self-assessment checklist with 60 credits in 5 categories to assess sustainability and resilience of infrastructure. It has been created by the Institute for Sustainable Infrastructure in collaboration with federal agencies, universities, consultants, professional societies, and municipalities.

The scope is very large as the "goal is to improve the sustainable performance of infrastructure projects in terms of not only the technical performance but also from a social, environmental and economic perspective". In terms of resilience, seven questions are dedicated "to ensure that infrastructure projects are resilient to short-term hazards or altered long-term future conditions"[13]:

1. Will the project team develop a Climate Impact Assessment and Adaptation Plan?
2. Will a comprehensive review be conducted to identify the potential risks and vulnerabilities that would be created or made worse by the project?
3. Is there an intent by the owner or the project team to alter the design to reduce or eliminate these risks and vulnerabilities?
4. Will the project be designed to accommodate a changing operating environment throughout the project life cycle?
5. Will a hazard analysis be conducted covering the likely natural and man-made hazards in the project area?
6. Will the project be designed so that it is able to recover quickly and cost-effectively from short-term hazard events?
7. Will the project be designed to reduce heat island effects by reducing the percentage of low solar reflectance index (SRI) surfaces?

The questionnaire is typical of a process-based approach and limited to assess the willingness of the project manager to address the issue. It provides some guidance about the keys steps.

4.2.1.3 CEEQUAL

CEEQUAL[14] is the UK industry scheme for assessing environmental and sustainability performance of civil engineering projects. Promoted by the Institution of Civil Engineers (ICE) and a group of other civil engineering organizations, the scheme uses a 200 questions scorecard applicable to any types of civil engineering or public realm project. The total construction value of all projects assessed or in process of being assessed under CEEQUAL reached the £6 billion mark in 2008. Despite the scope and focus of the toll, it is worth mentioning that the last version released in 2012, is not covering resilience or climate change adaptation issues.

In conclusion, these sorts of tools are extremely diverse, are essentially process-based and their accounting for resilience is limited (when existent at all). The most advanced tools, e.g. the AGIC scorecard, already provide useful templates for practitioners and can contribute to mainstream resilience principles into business practices. They may also be the sources of useful feedback to develop norms and standards.

[12] Infrastructure Sustainability Rating Tool Scorecard. V1.0 released 23/01/2013

[13] http://earthsys.com/cm/News/Newsletter%20Articles/The%20Vision%20of%20Envision%202.0.html

[14] http://www.ceequal.com

4.3 Good Design: Infrastructure codes and standards

Norms of engineering designs, materials, and retrofit strategies have been developed to enhance the ability of infrastructure elements to withstand natural hazards. Many design and engineering standards already contribute to ensuring resistance and reliability of infrastructure.

However, the current status of the term "resilience" (and one of its attributes, "robustness"), in structural design codes has been reviewed recently. Today, most structural design codes only give general guidance and no codes offer a suitable method for verification (Wang and Pham, 2012). The Swiss structural code is a notable exception where robustness is raised as a basic requirement on the same level as economy and durability (Vogel, 2010).

In some cases, current standards may be sufficient to deal with climate change effects as exemplified by the design standard IEC 61936-1 for outdoor components of electricity networks (see §3.1.2). In other cases, revising design standards and building codes for the infrastructures to ensure that they are appropriate for the extreme conditions is a practical way to build resilience.

Concrete example: The New York City Panel on Climate Change (NPCC) is a technical advisory body (climate change and impacts scientists, and legal, insurance, and risk management experts) which advises New York City on climate change science, potential impacts, and adaptation pathways specific to the city's critical infrastructure. A critical component of the NPCC's risk management framework for adaptation planning was to define *Climate Protection Levels* to address the issue of climate change impacts on the effectiveness of current regulations and design standards related to sea level rise and storm surge, heat waves, and inland flooding.

Eurocodes: In the European Union, Eurocodes[15] are developed by the European Committee for Standardization for the structural design of construction works. It is a set of harmonized technical specifications for building product which provide guidelines to achieve increased protection of constructions against earthquakes and fire[16].

Since March 2010 the Eurocodes are mandatory for the specification of European public works and are intended to become the standards for the private sector. They replace the existing national building codes. The Eurocodes system has been acknowledged as an important milestone from "prescriptive" to "performance-based" and "risk-informed" approach for building design and technical regulation (Kirillov, 2008). Eurocodes present significant assets to serve as resilient standards for good design in the future in Europe.

4.3.1 Good Organisation: Risk Management

Design and engineering standards are usually intended to protect the physical integrity of the asset and are not sufficient to confer resilience of the system.

An organizational resilience management system must be based on an effective risk assessment process which consists in:

1. Risk avoidance (eliminate, withdraw from or not become involved),
2. Risk reduction (optimize - mitigate),
3. Risk sharing (transfer - outsource or insure) and
4. Risk retention (accept and budget).
5. Controls can be technical and organizational (involving people and procedures).

[15] EN 1990:2002 E, Eurocode - Basis of Structural Design, CEN, November 29, 2001

[16] Essential requirements "Mechanical resistance and stability" and "Safety in case of fire"

4.3.1.1 ISO 31000

ISO 31000, *Risk management – Principles and guidelines*, provides principles and generic guidelines for managing risk (ISO 31000, 2009). It can be used by any organization regardless of its size, activity or sector. ISO 31000 seeks to provide a universally recognized paradigm for practitioners and companies to replace the myriad of existing standards and methodologies that differ between industries, sectors and regions.

ISO 31000 can help organizations to improve identification of opportunities and threats and effectively allocate and use resources for risk treatment. ISO 31000 provides guidance for internal or external audit programs and encourages organizations to compare their risk management practices with a reference panel.

The risk management process consists of the following steps:

1. Setting objectives and establishing the context of the risk assessment;
2. Identifying the risks;
3. Determining the level of risk, defined as the combination of its consequences and likelihood;
4. Evaluating the risk, to decide if a risk is acceptable, tolerable or not;
5. Treating the risks, focusing on the ones which are intolerable; and
6. Monitoring and review, to continuously refine and improve the assessment and risk treatments.

The risk assessment framework is used extensively in industry and government as it provides a process for determining sensible management outcomes even when there is considerable uncertainty or lack of data. This framework has been advocated for resilient infrastructure.

ISO 31000 is completed by a set of targeted standards such as:

ISO/IEC 31010:2009, which focuses on risk assessment concepts, processes and selection of risk assessment techniques to help decision makers understand the risks they are exposed to as well as the adequacy of controls already in place.

ISO 31000:2009 provides practical guidance for implementing a coordinated, all-hazards approach to infrastructure risk management and has been adapted at the national level (e.g. (PSC, 2010)).

4.3.2 Good Organisation: Business Continuity

Business continuity (BC) "identifies an organization's exposure to internal and external threats and synthesizes hard and soft assets to provide effective prevention and recovery for the organization, while maintaining competitive advantage and value system integrity" (Elliott et al., 1999, p. 48). BC is also called business continuity and resiliency planning (BCRP)[17].

BC planning is based on a Business Impact Analysis (BIA). The threat analysis and impact scenarios identify the business and technical requirements that are necessary for the recovery of each critical function. Critical functions are those whose disruption is regarded as unacceptable, either due to the potential cost of the recovery or because it is dictated by law.

Concrete example: In the IT sector, two values are assigned for each critical function:

- **Recovery Point Objective (RPO)** – the acceptable latency of data that will not be recovered
- **Recovery Time Objective (RTO)** – the acceptable amount of time to restore the function

[17] In the US, governmental entities refer to the process as *continuity of operations planning* (COOP).

A recent survey[18] from the Business Continuity Institute found that most organizations have developed an in-house BC approach, which aligns with one or more Business Continuity Management (BCM) standards. 30% comply or certify with existing standards. Out of the 20 standards surveyed, BS 25999-2 and ISO 27001 were by far the two most popular (BCI, 2012).

4.3.2.1 BS 25999-2

BS 25999 was a British Standard for BCM issued in 2007 and published by the British Standards Institution (BSI). This standard has been widely adopted and applied in many public and private organizations across all sectors. Officially recognized in the UK only, half of the certifications concern organization in other countries.

BS 25999-2 consists of four phases: planning, implementing, reviewing and monitoring, and finally improving, and as such follows the typical management PDCA process (Plan, Do, Check, Act). It provides a set of guidelines on how to define the scope, objectives and responsibilities, how to conduct Business Impact Analysis (BIA) and risk assessment, and how to define BC strategy and maintenance of plans and systems.

The BIA defines the maximum tolerated period of disruption (MTPD), interdependence of individual actions, determines which activities are critical, explores existing arrangements with suppliers and outsourcing partners, and finally sets the recovery time objective[19].

Risk assessment is carried out to establish which disasters and other disruptions in business operations may occur, what their consequences are, but also which vulnerabilities and threats can lead to business disruptions. Based on such assessment, the organization determines how to reduce the probability of risk, and how it will be mitigated if it should occur.

The standard also stipulates how to:

- Exercise and test plans regularly to make staff more familiar with the plans and check their up-to-datedness
- Conduct internal audits at regular intervals
- Manage reviews to ensure that the Business Continuity Management is functioning and to make appropriate improvements
- Take preventive and corrective actions to improve not only plans but also other elements of the system.

4.3.2.2 ISO 22301

Since May 2012, BS 25999-2 has been withdrawn and replaced by International Standard ISO 22301, which is basically an upgrade of BS 25999 (ISO 22301, 2012). ISO 22301: Societal Security -- Business Continuity Management Systems -- Requirements is one standard that is part of a series of standards developed with the intention to, "… work towards international standardization that provides protection from and response to risks of unintentionally, intentionally, and naturally-caused crises and disasters that disrupt and have consequences on societal functions." This series of standards address the "public planning & response" as well as "private sector planning & response."[20] Notable differences with BS 25999 include the introduction of three generic indicators:

- **Maximum acceptable outage (MAO):** The time it would take for adverse impacts to become unacceptable. Adverse impacts may arise as a result of not providing a product/service or not performing an activity.

[18] 613 responses from 60+ countries and 15 industry sectors.

[19] http://www.iso27001standard.com/en/what-is-bs-25999-2

[20] ISO 22312: Technical Specifications

- **Minimum Business Continuity objective (MBCO):** The minimum level of services and/or products that is acceptable to the organization to achieve its business objectives during a disruption.
- **Maximum data loss (MDL):** The point to which information used by an activity must be restored to enable the activity to operate upon resumption –also referred to as Recovery Point Objective.

ISO 22301 has been received favourably in particular in Europe where 70% of the organizations are planning to align with the standards within three years (BCI, 2012). ISO 22301 is accepted by national standards institutes in 163 countries[21] and is expected to become the leading business continuity framework worldwide[22].

Note: ISO 22301 and ISO 31000 overlap significantly both in terms of goals and process, ISO 22301 specifically recognizing ISO 31000 as a reference in terms of Risk Management. The key differences between the two standards are thus unclear.

4.3.3 Current limits of standardisation

- Due to the lack of appropriate metrics for characterization of resilience and its main attributes, standards are not accounting for other threats associated with climate change such as floods, extreme weather event, drought and high temperature. There is clearly a need for research on the potential impacts of climate change on infrastructure design.
- Standards do not reflect on cascading effects and systemic failures. There is a need for a broader systems perspective to account for network interdependencies (Meyer, 2008).
- Updating standards is a long process (e.g. 14 years in the example presented by Meyer) (Meyer, 2008; Neumann and Price, 2009). Developing justification for change, institutional procedures -- involving many different stakeholders from government, private and non-governmental organizations—and use of design guidance as evidence in litigation lead to conservative approach and long time frame (Meyer, 2008).
- Risk management and Business Continuity Management standards are generic and comprehensive approaches. They provide frameworks, guidelines and process-based indicators to continually update and improve the abilities of an organization to overcome a disruptive event.
- Generic standards do not include implementation details. For example, risk assessment standards indicate that threats should be identified by the risk assessor, but do not specify how this can be done in practice. Current research aims at improving the quality of the risk management and business continuity processes using methods with a higher degree of accuracy while staying within budget (Zambon et al., 2010).

4.4 Research perspectives

4.4.1 Modelling of dependencies

Most approaches today address the impacts of climate change effects focusing on loss or damage to infrastructure by sectors; lessons learned from historical disruptive events however have dramatically shown the paramount importance of cascading effects. Modelling of infrastructure dependency provides a promising avenue for approaching complexity of the

[21] http://blog.iso27001standard.com/2012/05/22/iso-22301-vs-bs-25999-2-an-infographic/
[22] A number of other standards have been developed by the technical committee on societal security (ISO/TC 223) in the wake of ISO 22301 (ISO22313 / 15 / 22 / 23 / 25).

system and ensuring that vulnerabilities in one sector do not compromise others (see §4.3.1). Modelling interdependent infrastructures is a complex, multifaceted, multidisciplinary problem and capacities for analysing potential impacts from an interdependent or systems approach have developed only recently (Wilbanks et al., 2012).

4.4.1.1 NISAC

In the US the National Infrastructure Simulation and Analysis Center (NISAC) has developed capacities for modelling infrastructure interdependencies to help anticipate and deal with cascading infrastructure effects. Individual infrastructures are each defined by a number of components and their interdependencies are modelled as a complex system of systems. The developed tools include process-based systems dynamic models, mathematical network optimization models, physics-based models of existing infrastructure, and high-fidelity agent-based simulations of systems[23]. By projecting impacts and threats, the tools can provide decision support in the face of threats emerging in real time such as major hurricanes. The tools can also compare their predicted impacts with actual effects and learn from the discrepancies to improve analytical capacities through time. This has led to significant improvement in the accuracy of model depictions of interdependencies (Wilbanks et al., 2012).

Concrete example: The National Transportation Fuels Model estimates the capability of the fuel system to respond dynamically to disruptions. The system consists of locations and capacities of tank farms, refineries pipelines and terminals; algorithms are used to estimate the locations, timing, and severity of the impacts[24].

4.4.1.2 CaSoS

In the wake of NISAC programs, the Sandia Laboratory runs a research program on Complex adaptive Systems of systems (CaSoS), which are complex, large and irreducible.

One of the key issues is the lack of systemic view of the representational complexities of CaSoS, which makes it difficult to fully understand and corroborate the resulting analysis (Glass et al., 2008). Another challenging feature of these systems is their ability to adapt which prevents building understanding through testing because repeatable initial conditions are generally not achievable and simultaneous tests are not independent (Glass et al., 2011). Their dynamics have a wide range of time scales so that interpretation, modification and quantification of impacts of modifications are difficult. An essential component of the CaSoS research agenda is to set a unifying body of theory to counter the "butterfly collecting approach that dominates many current efforts” (Glass et al., 2008, p12).

4.4.1.3 Hazus

In the US, Hazus is a standardized methodology developed by the US Federal Emergency Management Agency (FEMA) models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic, and social impacts of disasters:

- **Physical damage** to residential and commercial buildings, schools, critical facilities, and infrastructure
- **Economic loss**, including lost jobs, business interruptions, repair and reconstruction costs
- **Social impacts**, including estimates of shelter requirements, displaced households, and population exposed to hazards.

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[23] http://www.sandia.gov/nisac/

[24] http://www.sandia.gov/nisac/capabilities/national-transportation-fuels-model/

Hazus is an assessment method used for mitigation and recovery as well as preparedness and response by government planners, GIS specialists, and emergency managers. Hazus can be used to determine potential losses and the most beneficial mitigation approaches to reduce these disaster losses[25].

4.4.2 Ecosystem-based adaptation: Green and blue infrastructures

Cities are not closed systems or self-contained. They are open systems, in constant interaction with their hinterlands. Surrounding ecosystems supply energy, food, and water, they also provide shelter and protection, which help adaptation to climate change and increase resilience of urban areas. Ecosystem-based adaptation (EbA) is increasingly recognized as an important player to prevent, protect from, resist to and mitigate natural hazards consequences (Munang et al., 2013).

Concrete example: In tropical countries, restoring or conserving mangrove forest and coastal marshes has been shown to buffer storm surges and help protect coastal communities (Alongi, 2008). One case study has shown that EbA could be more cost-effective than hard interventions. In the Maldives facing powerful tropical storms, building sea walls would cost about US$1.6-2.7 billion (Moberg and Rönnbäck, 2003). In contrast, preservation of natural reefs, would have an initial set up cost of US$34 million and maintenance costs of US$47 million per year. Investment into natural infrastructure restoration and protection would maintain critical protection services and could generate up to US$10 billion per year in co-benefits (Emerton et al., 2009).

In Europe, the Green and Blue Space Adaptation for Urban Areas and Eco Towns project (GRaBS) aims at integrating climate change adaptation into regional planning and development. GRaBS has compiled a database of 33 cases studies mostly from Europe and the US (Kazmierczak and Carter, 2010) and several examples illustrate the breadth of interest of this approach (see also Chapter **Error! Reference source not found.**):

The cooling influence of green spaces and roofs is used to reduce the *urban heat island effect* in many cities, for example:

- In Seattle, maintenance and restoration of vegetation is used to limit the hazards of landslides
- Conservation and restoration of wetlands as a buffer zone between the coast and the city of New Orleans
- Creation of sustainable urban drainage systems, including ditches, retention ponds, green roofs and green spaces in Malmö (see Kazmierczak and Carter, 2010).

There is now good evidence for the effectiveness of these "natural approaches" which have proved to provide flexible, cost effective and broadly applicable alternatives for reducing impacts of climate change (Munang et al., 2013). They also achieve multiple policy objectives by providing options for climate change mitigation, environmental protection and biodiversity conservation.

This role is currently not sufficiently recognized and lacks integration in mainstream planning (Kazmierczak and Carter, 2010). Accordingly, these options have rarely been integrated in the design of frameworks and indicators, in particular due to perimeter issues. There is a wide gap between the potential and interest on one hand, and the ability to measure and monitor in practice on the other hand (Cutter et al., 2010). This is thus an important area of research that is likely to influence the way resilience is conceived, measured and managed in the near future.

[25] http://www.fema.gov/hazus

4.4.3 Assessing costs and benefits of adaptation: the need for evaluation

4.4.3.1 Evaluation of the indicators: an intractable issue

Selection and design of effective resilience strategies should be based on evidence of what works and what does not, under what circumstances and at what cost. There is a strong case for wider application of rigorous impact evaluation as advocated elsewhere (Prowse and Snilstveit, 2011). If this statement is largely consensual, in practice things can become awfully complex as evidence on the impact of policies and metrics may not be tested, evaluated and improved (see §0 and §0).

In fact, most frameworks and indicators proposed in literature have not been used on the ground. The feasibility and practicality of these approaches is thus yet to be studied. Furthermore, even where indicators have been used (e.g. the DRI, §0), the nature of resilience challenges implies that the efficiency of the metrics can not been evaluated. In other words, there is no method to test if a set of indicators A (or framework A) is better than a set of indicators B, nor if a modified "set A2" gives better "results" than a "set A1", where results could mean:

- Monitored adaptation strategy better,
- Identified critical gaps better,
- Concur to reduce the loss due to the impact of natural hazard H,
- Etc.

How to design effective and practical ways to assess costs and benefits is thus an intense area of research.

4.4.3.2 Cost-Benefit analysis

Countless studies have demonstrated the impacts that natural hazards can have on infrastructures. Recognizing the full costs of climate impacts is critical to weight reasonable adaptation costs and disruptive impacts (Wilbanks et al., 2012). However, if identifying the costs of the direct impacts is a crucial research need, the full scope of costs goes far beyond the actual damage to infrastructure due to logical dependencies (see §0). On the other hand natural hazards are not necessarily related to climate change adding to the complexity of establishing the economics of the climate related impacts.

Concrete example: Since 1936, the U.S. Army Corps of Engineers has invested more than $120 Billion in flood control projects, which have estimated benefit to the economy in those areas of $706 billion. This example indicates that direct costs of infrastructure damage represent only a fraction of the total economic impact of infrastructure service disruptions (see (Wilbanks et al., 2012) and references therein for other examples).

Adaptation measures are available to make societies more resilient to the impacts of climate change. But decision makers need information and indicators to select the most cost-effective investments.

4.4.3.3 The Economics of Climate Adaptation

The Economics of Climate Adaptation (ECA) methodology has been developed by the Economics of Climate Adaptation Working Group[26]. ECA wishes to provide decision makers with a factual base to understand the impacts of climate change on their economies and

[26] The ECAWG is a partnership between the Global Environment Facility, McKinsey & Company, Swiss Re, the Rockefeller Foundation, ClimateWorks Foundation, the European Commission and Standard Chartered Bank.

identify appropriate actions to minimize these impacts at a reasonable cost (ideally the lowest) to society.

ECA uses probabilistic modelling to estimate expected economic loss today, incremental increase from economic growth and incremental increase of risk due to climate change[27]. This latter parameter is predicted using scenario analysis under moderate and high climate change projections in 2030.

The benefit of each adaptation measure (the loss aversion potential) is assessed by modelling the effect of this specific measure and calculating capital and operating expenditures. The assessment of all measures results in a balanced portfolio of adaptation measures.

This method has been applied in 17 cases studies and the preliminary analysis has produced some remarkable and counterintuitive results[28]:

- Prioritization of adaptation measures is not strongly dependent on the chosen climate change scenario,
- Cost effectiveness is still valid even without climate change for a substantial subset of proposed measures.

In other words, present situation is already a strong case for action, and in most cases it is cheaper to start adapting now.

[27] http://media.swissre.com/documents/Economics_of_Climate_Adaption_UK_Factsheet.pdf
[28] Ibid.

5 Resilient architecture and infrastructure indicators

James Kallaos and Annemie Wyckmans, with Gaëll Mainguy and Floriana Ferrara

While there may be no universal, standardized definition or assessment methodology for resilience in the built environment, research in the field is accelerating, and seems to be converging around a few key themes.

Chapter 2 clarified the distinction between vulnerability and resilience, which is embedded in corresponding definitions and assessment frameworks. Literature studies and workshops have however shown that vulnerability assessment methodologies also can provide useful questions, data and approaches for further development towards resilience indicators,

Chapter 5 provides an overview of different methodologies, research approaches and projects in the realm of resilience assessment in the built environment. It presents recent research and indicator sets covering:

- Different approaches for assessment of vulnerability, adaptive capacity, and other system characteristics
- Approaches to quantitative physical and social resilience assessment.

5.1 Indicators in the context of climate change research

As far back as 1998, it has been clear that mitigation goals alone, even if properly followed and attained, were not enough to limit climate change to safe levels (Parry et al., 1998). Recent research is consistent with Parry's predictions. A mix of approaches will be necessary, involving mitigation and adaptation, as well as coping and accepted damage (Agrawala et al., 2010; Bosello et al., 2010; Parry, 2009; Parry et al., 2009).

However, the majority of existing indicator sets and frameworks addressing sustainability or sustainable development in the built environment have focused on mitigation. Here we refer to mitigation as representing attempts to reduce the ever-increasing GHG emissions to avert or lessen future climate change, to lessen the impact of humans and their activities on both the natural and built environments. Often the goal does not even reach as far as actual reductions in emissions or impacts. Efficiency based goals such as decoupling only promote the reduction in rate of increase of emissions, or even a relative reduction compared to an otherwise expected rate of increase.

Most frameworks in use for indicator development and presentation are based on the Pressure – State – Response (PSR) framework (Figure 2) (OECD, 1993; Segnestam, 2002), which has been expanded in an attempt to better exemplify the web of causes and effects inherent to complex systems. Expanded PSR frameworks include

- Pressure – State – Impact – Response (PSIR)
- Driving Force – Pressure – State – Impact – Response (DPSIR)
- Driving Force – Pressures – State – Exposure – Effects – Actions (DPSEEA)

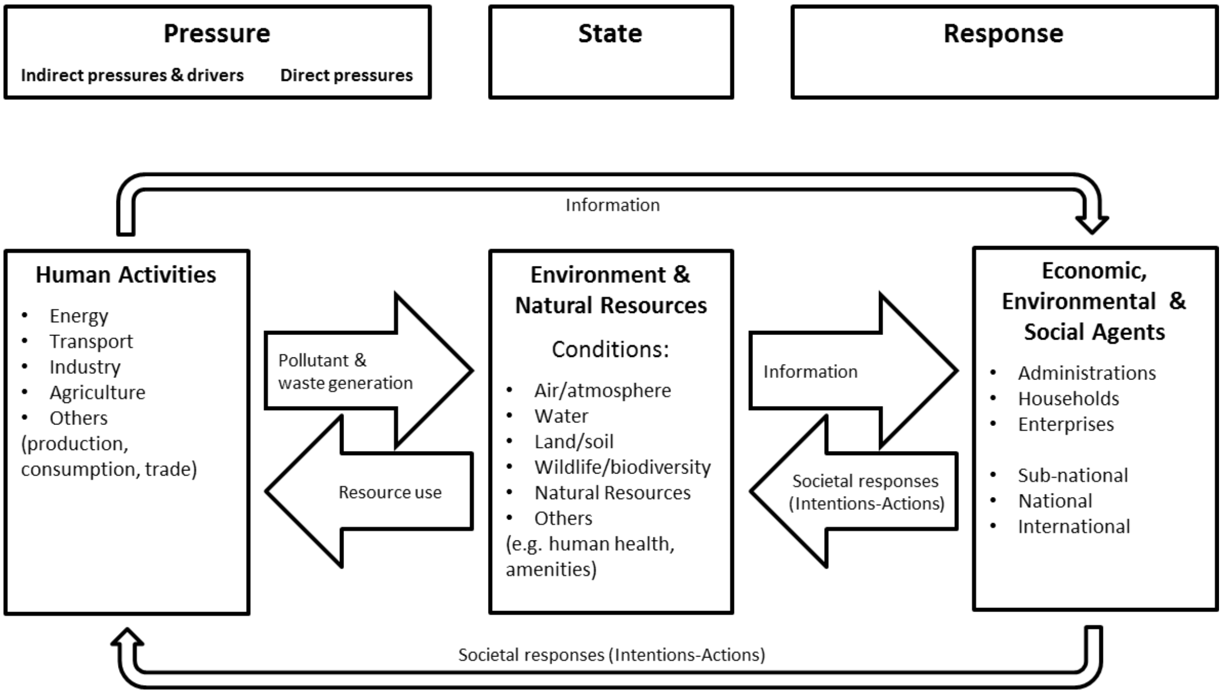


Figure 2: The Pressure-State-Response (PSR) Framework (Adapted from OECD, 2003)

Core indicators include economic, social, and environmental factors, from which relevant indicators for a project can be chosen and reported. Standards, and the indicators contained within them, have been relatively slow in assimilating climate change concerns. The original 2006 ISO standard regarding sustainability in building construction did not consider climate change, except for reporting emissions, while the 2011 update specifically includes a basic indicator for adaptability related to climate change (ISO 21929-1, 2011, 2006).

As noted earlier (§2.1), most assessment methods, as well as country level indicators and indices, utilize a comparative or relative approach, with no set limits or boundaries. Terms such as "resilient," "vulnerable" or "sustainable" are used to represent systems that may be only slightly closer to these goals than the status quo. Effort is rarely made to define the boundary conditions for these terms and assess whether the system meets these criteria.

With this in mind, a large group of authors collaborated to develop a more absolute and limit-based approach to visualizing human impacts on the environment, utilizing nine indicators based on biophysical thresholds (Rockström et al., 2009). The nine "planetary boundaries" representing "preconditions for human development" are:

1. Climate change
2. Biodiversity loss
3. Biogeochemical flows (nitrogen and phosphorus)
4. Ozone depletion
5. Ocean acidification
6. Freshwater use
7. Land use
8. Atmospheric aerosols
9. Chemical pollution (2009, p. 472).

Quantitative boundaries (critical values) have been developed for seven of the nine indicators, and three of these (climate change, biodiversity, and biogeochemical) have already been surpassed (Rockström et al., 2009).

5.2 Feedbacks and relationships

Until recently, the system characteristics related to climate change existed as purely theoretical concepts with which stakeholders might better understand the issues. Attempts to further define and specifically relate the different system characteristics to climate change impacts have resulted in conceptual frameworks that attempt to elucidate connectivity and feedbacks. Füssel and Klein (2006), in their presentation of such a conceptual framework for vulnerability research, document the development of terminology related to vulnerability as well as the evolution of approaches to vulnerability assessment. The framework itself provides a valuable service: a visual linkage map between many of the terms and concepts surrounding climate change. The framework has been utilized and expanded by other research groups (e.g. (EEA, 2012b; ESPON Climate, 2011; Lung et al., 2011). and now presents a compelling image (Figure 3) to describe the system in ways that help lead to quantifiable definitions and explanatory equations.

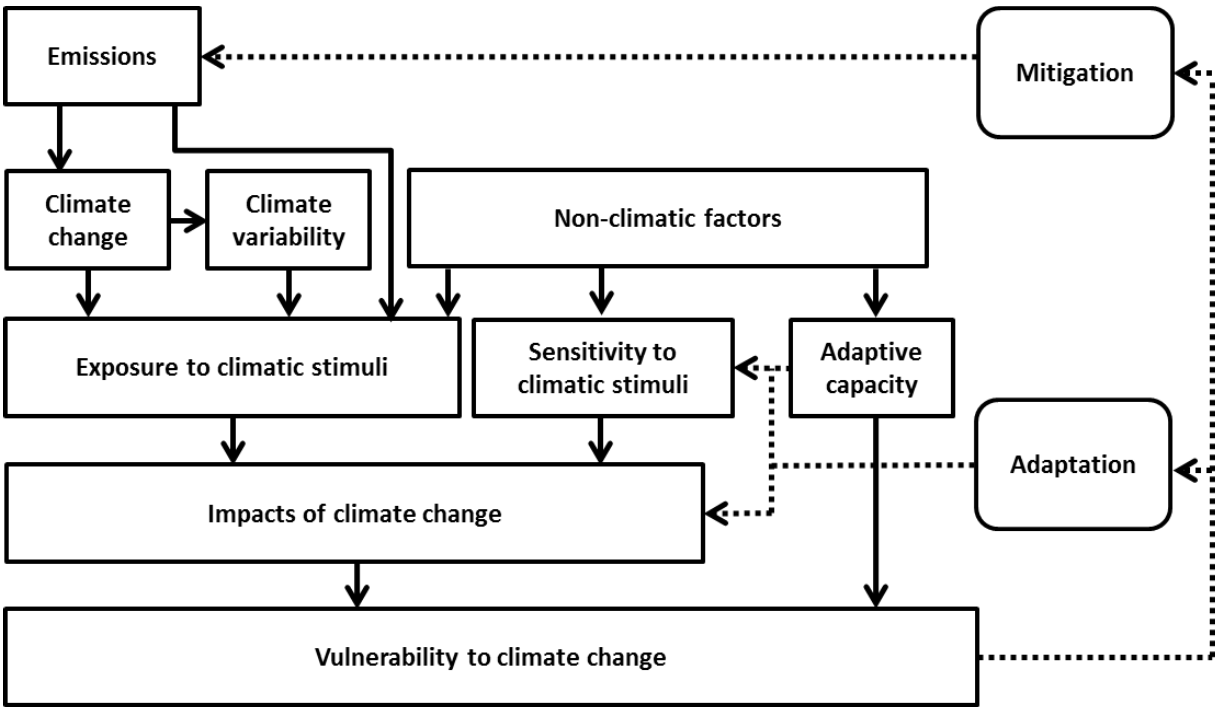


Figure 3: Vulnerability assessment framework (ESPON Climate, 2011); adapted from (Füssel and Klein, 2006)

A recent study (Eisenack and Stecker, 2012) challenges the emergent status quo with regard to the conceptualization of adaptation to climate change. The authors introduce a framework that perceives climate change adaptations as actions, in order to analyse stimuli and barriers to adaptation in human systems. Adaptation actions are defined as intentional acts undertaken by actors. The stimulus is the biophysical variable affected by climate change. The exposure unit refers to social, technical, or non-human systems that are exposed to the climatic stimulus. The receptor is the target of the adaptation action, which may be different than the exposure unit. The term direct adaptation is used to refer to situations where the receptor and the exposure unit are the same and indirect adaptation where they are not. The authors introduce a case-study specific to energy generation, which exposes an often overlooked fact that every adaptation is made up of a complex, hierarchical (or iterative) web of adaptations, sub-adaptations, and actions. The authors do not include a concept or method for integration of the action framework into the existing climate change discourse.

5.3 Impacts and vulnerability assessment

Vulnerability has been defined as a function of exposure, sensitivity, and adaptive capacity, or potential impacts and adaptive capacity, with potential impacts defined as a function of exposure and sensitivity (EC and EEA, 2013; Hinkel, 2011; IPCC, 2001a; Metzger et al., 2008). Hinkel argues that this vague definition is similar to defining a car as "a function of tires, engine, and coachwork" - that vulnerability is not a simple decomposition of the three functions but instead more details are necessary in order to progress from functions to components to an assembly (2011, p. 200). Hinkel identifies two sources of confusion regarding indicators and vulnerability: confusion about the purpose of indicators, especially considering the vagueness and lack of clarity surrounding the main terms in climate change discourse, and confusion about the purpose of vulnerability assessment in general (Hinkel, 2011). Vulnerability is scenario specific, to a defined sector, service, location, and time (Metzger and Schröter, 2006; Metzger et al., 2008), and requires specific, operational definitions of the function terms (exposure, sensitivity, and adaptive capacity) as well as the terms that define the functions, which remain absent or undefined in many cases (adverse, rare, etc.). (Hinkel, 2011).

Adger et al. provide an overview of the steps necessary to assess vulnerability and adaptive capacity with indicators:

1. Develop a coherent conceptual framework
2. Identify factors constituting vulnerability and adaptive capacity
3. Choose appropriate proxies and proxy variables
4. Construct indicators to represent variables (Adger et al., 2004, p. 6).

Indicators can:

1. Attempt to assess some absolute measure of vulnerability or adaptive capacity specific to a system or area
2. Be relative/comparative between systems, groups, regions or nations, in order to facilitate choice and "allocate priorities" for intervention areas (Adger et al., 2004, p. 14)
3. Act as a knowledge enhancement tool.

5.3.1 New indicators of vulnerability and adaptive capacity

Vulnerability represents a "state of potential adversity" (Adger et al., 2004, p. 24), but remains a complicated concept with no consensus – the two definitions in the IPCC TAR (IPCC, 2001b) are "contradictory" (Adger et al., 2004, p. 31). The breakdown in understanding can be assigned to the approaches taken by different sciences: social scientists view vulnerability through the lens of socioeconomic factors and people's coping ability, while climate scientists take a more probabilistic approach based on the likelihood of hazards of impacts (Adger et al., 2004). Assessment should maintain the distinction between current, potential, or actual vulnerability, and accept that to be meaningful, vulnerability needs to refer to a specific "system or exposure unit" and a specific "hazard or range of hazards" at a certain time (Adger et al., 2004, p. 28). The scale or "range of scales" of the assessment needs to be defined (Adger et al., 2004, p. 7) in both time and space. The time frame of the assessment should be consistent: this can include "present day or future patterns of vulnerability" but many studies impose expected or projected future environmental stressors on "present-day society" (Adger et al., 2004, p. 16). Adger defines a hazard as a purely physical event consisting of a "physical manifestation of climatic variability or change" which should remain conceptually separate from the outcome of the event (2004, p. 28). Adaptation refers to "adjustments in a system's behaviour and characteristics that enhance its ability to cope with external stresses" (Adger et al., 2004, p. 34). Adaptive capacity of a society depends on both the limits of potential adaptation as well the capacity for collective action (Adger et al., 2004).

5.3.1.1 ESPON Climate

The ESPON Climate project (2011) adapted and operationalized the climate change research framework from Füssel & Klein (2006), integrating projections of climate change with exposure, sensitivity, vulnerability, and adaptive capacity indicators. The results were geocoded and mapped at the regional level (NUTS-3) with color-coded legends quantifying the indicators (Eurostat, 2012). Projections of climate change were assessed by comparing differences in modelled climate data (using the CCLM model) between two 30-year time periods (1961-1990 & 2071-2100). An exposure analysis was then conducted using 10 exposure indicators, consisting of direct and indirect climate events and effects. Climate sensitivity was assessed for five different dimensions (physical, environmental, social, economic, and cultural), each of which is comprised of 4-10 specific indicators. All 10 of the indicators for the physical dimension of sensitivity consist of different forms of settlements and infrastructure, while most of the indicators related to social and cultural sensitivity relate to the placement of buildings, settlements, and infrastructure. Three of the seven indicators for the economic dimensions of climate sensitivity relate to energy supply and demand. Exposure and sensitivity indicators were combined to determine potential impacts for the five dimensions. Adaptive capacity was determined through a hierarchy of 3 dimensions (awareness, ability, & action), having 1 or 2 determinants each for a total of five determinants, each of which are made up of 3 indicators. The hierarchical combination of 15 adaptive capacity indicators utilized a modified version of the framework developed in the ATEAM project (Schröter et al, 2005; p. 118). Indicators for potential impacts were aggregated into a single measure of overall impact for each region. Likewise, indicators for adaptive capacity were aggregated into a single overall measure for each region. Vulnerability to climate change was mapped for Europe by combining the aggregate measures for potential impacts and adaptive capacity. All indicator combination and aggregation utilized Delphi-based surveys to determine weighting values. The vulnerability framework is applied to seven case studies in different climate change regions. Mitigative capacity is also estimated and mapped, with regional capacity for mitigation determined using a mitigation indicator hierarchy that mirrors adaptive capacity, but includes the GHG emissions of the region. Mitigative capacity and adaptive capacity are compared, with the results presented as response capacity.

5.3.1.2 RESPONSES

Another project based on the vulnerability framework developed by Füssel and Klein (2006) is the European RESPONSES project, which included a deliverable focusing on regional development and infrastructure (Lung et al., 2011). The deliverable disregarded the mitigation aspect, focusing solely on exposure, sensitivity, and adaptive capacity. Parameters for exposure (climatic variations in the system) and sensitivity (non-climatic factors such as land use patterns and population structure) were combined to form indicators of potential impacts. Climatic variations were modelled under the IPCC SRES A1B scenario over three 30-year periods (1961-1990, 2011-2040, 2041-2070), using averaged simulation results from five regional climate models. Sub-indicators for financial, human, and technological capital were integrated into a single indicator for adaptive capacity. The study considered four hazard parameters (heat, floods, droughts, and forest fires) mapped at the NUTS-2 (basic regions) level (Eurostat, 2012). The result of the study was hotspot identification mapped to European regions. Section §10.3 in the Appendix summarises the indicators of the RESPONSES project.

While "physical infrastructure" is mentioned as one of the risk categories under the heat parameter, none of the heat parameters made any direct specific reference to physical infrastructure, buildings, or settlements. Population density forms a core issue in urban planning, and physical design of the built environment that harbours this population will be a better-qualified resilience indicator than the actual density of the population in itself. The same population density can be harboured in compact or sprawled neighbourhoods, high- or low-rise buildings, bioclimatically designed or largely depending on technical systems for heating, cooling and lighting, exhibit large or small spatial and functional diversity and so on. The drought parameter mentions 2 qualifications that can be related to resilience in terms of dependence on local ecosystems:

- Percentage of agricultural area (CLC classes 211, 221, 222, 223, 241, 242 and 244) (DS_AGRI)
- Topsoil available water capacity (DS_SOIL)

In addition to population density the flood sensitivity parameter includes location of settlements, industrial and commercial areas in flood zones with a recurrence interval of a 100-year event flood. This could to a certain degree be linked to a resilience characteristic of “learning, memory”, to learn from past experiences and failures and avoid repeating past mistakes; a traditional 100-year interval might however not provide the necessary incentive to create novel adaptations. Core resilience characteristics such as connectivity, feedbacks and redundancy are not addressed.

5.3.1.3 VATÍ

Owing to the diversity of impacts that may result from climate change induced hazards and perturbations in the EU "no unified model or standard solution" has been developed to "make urban settlements climate friendly" (VÁTI, 2011, pp. 14, 15). A report by Hungarian non-profit organisation for Regional Development and Town Planning VÁTI, issued within the framework of the Hungarian presidency of the Council of the European Union, claims to provide a city management toolkit to alleviate this deficiency, but mainly delivers a comprehensive collection of the state of the art of knowledge about climate change and cities, and existing vulnerability assessment methods. The report is a large compilation of issues and options, well organized but loosely defined as a toolkit.

Four chapters can be related to soft infrastructures as defined and discussed in this RAMSES deliverable:

- Climate-friendly urban governance for forming economic and other urban policies
- Integrated strategic planning for climate-friendly cities
- Creation of climate-conscious attitude and lifestyle
- Supporting deprived groups in adapting to climate change
- Economic effects and the enhancement of urban economy

While the main weight of these chapters and the indicators discussed therein is not explicitly related to resilience, there are a number of indicators that can provide a relevant foundation for core resilience characteristics. The VÁTI report for example includes the following indicators (units) for climate-friendly urban governance for forming economic and other urban policies:

- Memberships in climate-aware networks and organisations (piece)
- Number of climate-aware legislation and policy initiations (piece/annum)
- Rate of green (climate-aware) public procurement actions (%)
- Rate of public companies run by the city having climate-aware business policy (%)
- Rate of divisions at the municipality having climate protection and adaptation tasks officially (%)

- The total number of partners (individuals and organisations) in climate partnership initiations (piece)
- Rate of local enterprises and firms taking part in climate partnership initiations (%)

In terms of integrated strategic planning for climate-friendly cities, the following indicators (units) are discussed:

- Aims towards climate protection or climate adaptation at high decision making levels / policy level (yes/no)
- Rate of city plans and programmes incorporating principles on climate protection and adaptation to climate change (%)
- Rate of strategic environmental assessments of the city's planning processes integrating the issue of climate change (%)
- Number of involved partners (individuals and organisations) into climate planning actions (piece)

These indicators can be related to core resilience characteristics such as the institutional ability to respond to changing conditions; accumulate, store and share experience; and the ability to establish priorities and mobilise resources.

The VÁTI report further lists and discusses indicators for a range of hard infrastructures, architecture and urban structures. The definitions of these concepts vary slightly from the ones chosen in this RAMSES report, but combined cover the same main elements of green, blue and grey infrastructures, architecture and public space, and urban morphology and typology:

- Climate friendly urban structure
- Climate friendly urban transport
- Low carbon energy management of the settlement
- Climate friendly architectural solution
- Adaptable water management and urban communal infrastructure
- Preparing for disaster management and health care

A large number of these indicators are related to green and blue infrastructures, with a clear potential link to core resilience characteristics. Apart from the contribution of biologically active areas (not covered / built in) to local ecosystems services, flood control, pollutant filtration and local food production, the VÁTI indicator table also includes links to spatial and functional diversity (leisure, tourism, roofs etc.). However the performance of green infrastructure in terms of resilience (functional capacity, system quality) and its distribution, feedback loops and connectivity potentially leading to cascading effects is not explicitly addressed.

Architecture and infrastructure are mainly addressed in relation to consumption and/or production of energy, waste and water without any clear connection to the morphologies and typologies that cause these resource flows or their potential contribution to resilient urban systems in terms of flexibility, modularity and connectivity.

Economic effects and the enhancement of urban economy is also discussed, with a number of costs directly and indirectly related to climate change adaptation. While no explicit link is made to resilience indicators and design, the report does provide a range of cost indicators that suggest calculation methodologies that can be further explored in the context of the RAMSES project (see also Section §0):

- Flood control costs (and extent of flooded area)
- Irrigation costs of the public parks, urban green areas
- Changes in the average heating costs
- Changes in the real estate prices

- Cost of road construction
- The city's environmental tax revenues
- Public money spent on environmental protection
- Changes in tourism tax revenues

A complete list of indicators presented and discussed by the VÁTI report, arranged by the referring chapter, is presented in the Appendix (§10.4). While the purpose of the indicators, recommendations on their utility and methodology for implementation are absent, the indicators listed above can provide useful links to core resilience characteristics and will be taken into account in the development of resilience indicators for architecture and infrastructure in the RAMSES project.

5.3.2 European Environment Agency (EEA)

The EEA report on climate change, impacts and vulnerability in Europe describes the diversity of approaches to defining vulnerability and risk (EEA, 2012b). The report moves from a generic, universal understanding of vulnerability to a definition specific to climate change by adapting definitions from different assessment communities - qualified with specific factors. The indicators presented in the report are summarised in the Appendix, see Section §10.5.

They comprise a mix of observed and projected climate changes, impacts, and vulnerabilities, without an explicit cohesive framework. It is unclear how the indicators were chosen or how they should be implemented. Though the report notes that energy is responsible for the majority of anthropogenic GHG emissions, only 1 of the 45 indicators relates specifically to energy – heating degree days (HDD). Another indicator covers the costs of impacts to transport infrastructure.

5.3.2.1 EVDAB and Urban Audit

The European Database of Vulnerabilities to Natural Hazards (EVDAB) uses a mix of databases and models to present an online visualization of vulnerabilities in EU urban areas - the database is still under development, however, with currently only "illustrative" maps displayed (JRC, 2013). Datasets include those from other units of the European Commission's Joint Research Centre (JRC), statistical data from Urban Audit, digital land use maps (from a variety of sources), and information on changes in weather and climate extremes from the European Climate Assessment & Dataset (ECA&D) project.

EVDAB utilizes the urban structure hierarchy outlined in Urban Audit (EC, 2013b), consisting of three geographic/spatial levels: the sub-city district (SCD), the city, and the larger urban zone (LUZ). The SCD consists of districts with between 5,000 and 40,000 inhabitants, within a city. The city is defined by political boundaries and the LUZ by administrative boundaries. Urban Audit data is currently only accessible online through an interactive website (EC, 2013b). The underlying metadata and methodologies are now buried within a Eurostat database within the UK Data Service (UK Data Service 2013) with access only to researchers at UK institutions. Urban Audit contains data for 258 cities, with over 250 indicators (Eurostat, 2004) covering:

- Demography: population, nationality and household structure
- Social aspects: housing, health and crime
- Economic aspects: labour market, economic activity and income disparities and poverty
- Civic involvement: civic involvement, local administration
- Training and education: education and training provision, education qualifications
- Environment: climate / geography, air quality and noise, water, waste management, land use and energy use

- Travel and transport: travel patterns
- Information society: users and infrastructure, local e-Government, ICT sector
- Culture and recreation: culture and recreation, tourism

The complete table of Urban Audit indicators (Eurostat, 2004) is presented in the Appendix (§10.8). Urban Audit utilizes a set of variables that can function independently as indicators, or combine with other variables (numerator/denominator) to form compound indicators. These indicators are for the time being however not explicitly linked to core resilience characteristics such as connectivity, diversity and adaptability. Furthermore the Urban Audit Spatial Units (A,L,S) correspond with the Administrative city (A), Larger urban zone (L), and Sub-city district (S). With Sub-city district being the lowest level of detail in the gathered data, the opportunity to identify local interventions for application in cities and urban models is restricted.

5.3.3 Climate Resilience Toolkit

The green paper "Guidelines for Project Managers: Making vulnerable investments climate resilient" (EC, 2013a) presents guidelines for project managers to include adaptation assessment into projects. The paper provides an outline for integration of a "Climate Resilience Toolkit" into a generic project development process (2013a, p. 4) and a summary of indicators is presented in the Appendix (§10.6).
The toolkit consists of seven modules:

1. "Sensitivity analysis (SA)
2. Evaluation of exposure (EE)
3. Vulnerability analysis (incorporating the outputs of modules 1 and 2) (VA)
4. Risk assessment (RA)
5. Identification of adaptation options (IAO)
6. Appraisal of adaptation options (AAO)
7. Integration of adaptation action plan into the project (IAAP)" (2013a, p. 17).

The first module (SA) involves the identification of important and relevant variables, consisting of primary climate drivers and secondary climate related hazards. Primary drivers to be considered include average and extreme values for air temperature, rainfall and wind speed, as well as humidity and solar radiation. Secondary considerations include 15 effects/hazards ranging from sea level rise to wildfire. Four aspects of the project are considered with respect to sensitivity: "on-site assets and processes, inputs (water, energy, others), outputs (products, markets, customer demand), and transport links" (2013a, p. 28), and then rated on a 3-level scale (high, medium, or no sensitivity).

Based on the results of module 1, a focused exposure evaluation (EE) is made on those variables that received a sensitivity score of medium or high. The EE consists of first gathering relevant spatial data, and then assessing current and future exposure, with the result presented using a 3-level scale (high, medium, or no exposure). The third module assesses vulnerability by comparing the results of the prior modules, sensitivity and exposure. The results of those assessments populate a simple matrix – but it is unclear how the levels (high, medium, no) interact with each other. It seems the higher of the two values prevails, though a "no" value for either exposure or sensitivity should logically propagate. Risk identification utilizes the results of module 3 in a qualitative cause-effect assessment.

Risk is defined as a combination of probability and consequences, but the recommended quantification methods are qualitative and sometimes arbitrary scales (1-5). Adaptation options are identified in module 5 through stakeholder workshops. These options are appraised in module 6 utilizing an 8-step cost-benefit analysis (CBA) with the goal of "maximising net benefits" to the country, not the project (2013a, p. 48). The final module consists of integrating the adaptation plan into the project.

5.3.4 Examples of national approaches

5.3.4.1 Norway – Climate change adaptation policies

Three concerns can be distinguished regarding climate change and the built environment: the effect of buildings and infrastructure on the environment at local, regional and global scales, the effect of the environment on the utility and service lives of buildings and infrastructure, and adaptation to potential impacts from climate change (Holm, 2003; Lisø et al., 2003). Successful adaptation will need to include the development of strategies, adjustments at the societal and sectoral levels, and improved understanding of interactions between sectors and processes. The existing stock needs to be the starting point for sustainable strategies involving adaptation and enhanced adaptive capacity, as the inertia of the existing stock renders progress through design and construction of new buildings and infrastructure incremental at best (Holm, 2003; Lisø et al., 2003).

In addressing the threat of climate change on the built environment, Lisø et al. (2003) distinguish between vulnerability, sensitivity, exposure, coping, and adaptation. Vulnerability has both social and physical components, including an external risk exposure and an internal lack of coping ability. Exposure also contains a social element, described as sensitivity, related to the degree of societal reliance on a structure at risk. Coping refers to the ability to ameliorate damages and consequences in order to maintain societal goals. Adaptations are the adjustments needed to manage changing conditions, in order to reduce vulnerability. Decreasing vulnerability can include measures to reduce sensitivity and exposure, as well as increasing coping capacity.

Anticipated climate change is expected to lead to "warmer, wetter and wilder" Norwegian weather in the future (Almås et al., 2011, p. 228). Researchers expect harsher weather events and increased impacts on the built environment. Almås et al. consider the climate change impacts related to changing precipitation, wind, temperature and solar radiation on rot-decay risk in timber buildings in Norway. The Norwegian building stock has a long lifetime, with 80% of the current stock still existing in 2050. Their results show a dramatic increase in rot decay risk with changing climate. Their recommendations include designing buildings not just for present climate, but for the anticipated climate over the service life of the building.

Serre et al. consider flooding to be "the major natural hazard in the EU in terms of risk to people and assets" (Serre et al., 2011, p. 746). "Flood risk is likely to increase significantly" from increased "severe storm and rainfall events" river discharge, and sea level rise from climate change (Serre et al., 2011, p. 746). Many flood variables assessed at different scales contribute to the assessment of flood impacts on buildings, assets and infrastructure. Assessing risk or vulnerability requires trade-offs between complexity and accuracy. Existing methods are well developed to assess flood risk to buildings, but not the complex web of interactions that comprise an urban system. Modification of the existing Norwegian risk and vulnerability analysis (RVA) tool Infrarisk to study climate-change induced risks showed interdependencies between sectors and the need to analyse "infrastructures collectively" (Serre et al., 2011, p. 750).

Seljom et al. consider the anticipated effects of climate change on the energy system in Norway (2011). Current electricity production is primarily hydropower based, with increased production in recent years possibly from increased precipitation due to climate change. Electricity has traditionally been relatively inexpensive, leading to its high penetration in space heating in buildings. With changing precipitation and temperatures expected in Norway, climate change will likely influence both supply and demand of electricity. The authors use an array of climate models, several energy models, and a schedule of future energy demands to examine possible or expected changes in the Norwegian energy system from climate change. The main impacts of climate change on the energy sector are increased hydropower production and decreased demand from space heating.

Häkkinen presents a state of the art report for sustainability indicators for buildings, cities, and the built environment, within the CRISP (Construction and City-related Sustainability Indicators) project (2001). The report considers the three main functions of indicators as quantification, simplification, and communication. Indicators should also be able to show trends, and be comparable internationally. The report compares and contrasts some existing indicator sets, eco-efficiency approaches, and life cycle assessment (LCA), but provides little guidance as to improving on existing approaches. The Norwegian national report to the CRISP thematic network proposes indicators for five areas: resources, emissions to air and water, waste, indoor environment, and dangerous substances (SINTEF Byggforsk, 2001). The indicators should represent "simplified expressions" of more complex phenomena, and follow the indicator categories laid out in ISO 14050 (2009, p. 2).

Rambøll (2012) presents a review of climate change adaptation policies in Norwegian municipalities, reviewing the 13 cities participating in the Norwegian “Cities of the future” programme. This review is based on interviews with municipality representatives as well as systematic analysis of relevant municipal policy documents. Rambøll not only reviews policies specifically related to climate change impact assessment and resiliency strategies, but also assesses whether this topic is taken into account in general urban planning and development policies, regulations, and generic checklists for project development used by city officials (2012). For each document, it is evaluated whether:

- Climate change is mentioned and taken into account in the executive summary, introduction or conclusion (a sign of its significance)
- Climate change is mentioned and taken into account in the goals and strategies described in the document (a sign of operationalisation)
- Specific impacts and urban areas are described in detail
- The proposed measures related to climate change are legally binding
- The methodology for assessing and monitoring the vulnerability and impact of specific measures is clear
- The measures described above are integrated in checklists for project development used by city officials (urban, neighbourhood and building scale) (Rambøll 2012).

In general all municipalities have included climate change adaptation in their planning documents and the most recent changes are the most ambitious ones. All municipalities have included climate change adaptation in checklists for urban and master planning used by city officials, while 9 out of 13 included the issue in checklists for building scale. All municipalities in the study are also developing specific policy documents related to vulnerability assessment. Participation in the national Cities of the Future programme, which features climate change adaptation as one of four main pillars, is indicated to have spurred this positive development (Rambøll 2012).

5.3.4.2 Italy – The ITACA Protocol

As the building sector – i.e. residential and commercial buildings - is the largest energy consumer and CO_2 emitter in the EU with about 40% of the EU's total final energy consumption and CO_2 emissions, the Energy Performance of Buildings Directive (EC-EPBD, 2003) has been approved in 2002 and then replaced by the EPBD2 (EC-EPBD, 2010), aiming to make the Climate and Energy Package objectives, set in 2007 by the European Commission[29], more binding. The EPBD establishes a methodological framework for calculating energy performance of buildings, taking into account the functional typology of buildings (residential houses, offices, hospital, restaurant and so on), the thermal characteristics of buildings, including its internal partition, the presence of heating and hot water systems, conditioning and ventilation systems, etc. Furthermore it takes into account local and climate conditions and even prescriptions of internal environments both from an efficiency and costs perspective.

[29] http://ec.europa.eu/clima/policies/package/

To measure energy efficiency progress by country, by sector, and for all final consumers, the European Environment Agency (EEA) refers to ODEX index, developed within ODYSSEE-MURE Project by the 27EU national energy agencies and by Norway and Croatia. ODEX by sector (overall economy, industry, households, transports, services) combines unit consumption indices by sub-sector (or end-use or mode of transport), into one index for the sector by weighing each sub-sector index by its share in the sector's energy consumption. In detail, unit consumption index by sub sector can use different physical measures and units so as to fit better with the specific energy efficiency evaluation: toe/ m2, kWh/appliance, toe/ton, litre/100km. ODEX is presently calculated on the basis of 26 subsectors (7 modes in transport, 9 end-uses/equipment for households, 10 branches in industry). As reported by ENEA (2011), ODEX indicators represent a better proxy for assessing energy efficiency trends at an aggregate level than the traditional energy intensities, as they are cleaned from structural changes and from other factors not related to energy efficiency (more appliances, more cars, etc.). ODEX can also be expressed in terms of volume of energy savings.

Based on the 2003 EPB Directive, the ITACA Protocol has been developed, promoted by Italian ITACA Institution, and composed by Italian Region and other national bodies. ITACA Protocol is an evaluation system of buildings environmental quality, officially approved by the Regions Presidents and the Autonomous Province Conference. Many Regions have transformed in law the commitment of Environmental Sustainability Certification for new public buildings. Such certification is optional for private buildings. Many of these certifications are based on ITACA Protocol. In Table 8, a list of indicators related to residential building sustainable performance is shown (Umbria Region, 2013). These indicators have been identified to evaluate criteria established by ITACA Protocol. In the table, a further column, detailing the first one, has been added in order to correlate such criteria with the specific need to pursuing sustainability according to the 20-20-20 objectives set by the Climate and Energy Package.

Need/Objective	Protocol Criteria	Performance indicator
Reduction of private vehicle use	Access to public transport	Index to measure distance to public transport
Reduction of primary energy needs for winter heating	Thermal transmittance of building envelope	Percentage (%) of heat loss from building envelope compared with theoretical efficiency
Reduction of primary energy consumption	Primary energy for heating	Percentage (%) of annual primary energy compared with maximum primary energy according to law
Reduction of solar radiation in the summer period	Solar radiation control	Index based on the total minimum solar transmittance of the package window/screen
Reduction of building energy demand by optimizing building envelope.	Net Energy for fresh air systems	Index of thermal performance index as established by Italian law (L. 192/05) stemming from 2002/91/CE Directive.
Reduction of primary energy for Sanitary Hot Water (SHW) production	Primary energy for SHW production	Energy Performance Index for the production of SHW.
Promotion of electric energy produced by renewable sources	Electric energy produced by Renewable sources	Percentage (%) of electric energy demand as satisfied by renewable sources or cogeneration
GHG emissions reduction - Stimulation of sustainable materials use	Presence of sustainable materials for buildings	Sustainability index established according Life Cycle Assessment (LCA) criteria or literature data
GHG emission reduction related to transport of material / To favour local production	Use of locally produced materials	Percentage (%) of locally produced materials with respect to total materials
Reduction of annual GHG emissions from non-renewable primary energy used in the building	Emissions associated to the functioning of the building	Percentage (%) of annual GHG emissions from non-renewable primary energy compared to a standard building with the same final use
Maintain thermal comfort and limit energy consumption	Air temperature	Typology of thermal exchange with regards to heating and fresh air distribution systems and thermal terminals (radiators, fan coil, etc.).
Guarantee adequate ventilation for air quality and limit energy consumption needed for air conditioning	Ventilation	Existence of design strategy for guaranteeing adequate air exchange rates
Guarantee adequate levels of natural light in all building spaces/rooms	Natural Lighting	Index established according to average daily light (%)
Provide building with integrated intelligent technologic systems and ensure the collection of data	Systems integration	Presence of Intelligent Technology systems devices.

Table 8: Performance indicator for measuring sustainability of buildings (Umbria Region, 2013)

An interesting exercise can be represented by matching measures implemented for enhancing the values of these indicators for sustainability, by a climate change perspective, with resilience properties to check to what extent these measures can be resilient-oriented.

By this perspective, an attempt has been recently led by Galderisi and Ferrara (2012) with a contribution that is mainly addressed, on one hand, to provide, by integrating different disciplinary perspectives, a conceptual model of the set of adaptive capacities and properties that characterize a resilient system and, on the other hand, to verify, starting from a snapshot of current strategies and actions for urban adaptation currently implemented at European level, the consistency between those strategies and the identified set of resilience capacities and properties.

5.3.4.3 Australia – CSIRO

The approach taken in an Australian regional risk assessment of climate change impacts to infrastructure (CSIRO, 2007) does not follow the IPPC vulnerability assessment framework, yet references are made to the potential impacts occurring due to a convergence of exposure and sensitivity. While the study was a qualitative risk assessment only, it utilized outputs from 2 versions of the CCAM global atmospheric model, "scaled to include the full range of IPCC SRES scenarios of greenhouse gas and aerosol emissions, and the full range of IPCC uncertainty in climate sensitivity to these emissions" (CSIRO, 2007, p. 8). The study is of particular interest owing to its focus on all major infrastructure types. The result is a matrix-style qualitative risk assessment (low, medium, high) based on the climatic variation expected in Victoria, Australia.

5.3.4.4 New Zealand – Climate Change Toolbox

Guided by the risk management framework outlined in ISO 31000 (2009), the New Zealand Ministry of Science and Innovation supported the development of an Urban Impacts Toolbox: "Impacts of Climate Change on Urban Infrastructure and the Built Environment" (NIWA et al. 2012a). The toolbox definition of risk refers to the severity and probability of occurrence of impacts, and depends both on hazard frequency and severity, as well as characteristics of the impacted systems (built environment and activities). The toolbox is designed to help planners and other stakeholders in urban councils evaluate the potential impacts of climate change on their communities, and reduce risk through climate change adaptation. Adaptation measures can include both pro-active and reactive approaches to reducing risk in structural (hard, physical) and non-structural (community, governance) systems. The goal is to "mainstream" adaptation through incremental changes – the integration and anchoring of climate change adaptation policies into existing policy mechanisms (Tait 2012, p. 4).

The toolbox is divided into five sections, called trays (following the toolbox metaphor):

1. Understand the Issues
2. Assess the likely hazard
3. Identify the risks
4. Evaluate the options and their costs/benefits
5. Using the tools and improving practice (NIWA et al. 2012a).

The toolbox is not intended to be followed in a rigorously linear manner, but more as a collection of progressively specific linked tools, categorized as either guidance tools or decision tools.

Guidance tools include:

1. Reference and general information – background knowledge and existing guidance
2. Models, methods and examples to assess climate change hazards and impacts – outlining data needs, assumptions, and limitations.
3. Guidance messages – information on integrating assessments into planning and operations (NIWA et al. 2012a).

Decision tools should be utilized within a decision-making framework, with the assessment following three stages:

1. Scoping – identification of relevant hazards and vulnerable assets
2. Prioritization – mapping of geographical locations based on risks and needs
3. Optimization
   a. Screening and prioritization of adaptation options
   b. Evaluation of options, and execution of preferred solution (NIWA et al. 2012a).

The toolbox is an open-access, online service, yet each tool is also presented as a downloadable and printable file. Case studies are integrated throughout the project, and used as examples (NIWA et al. 2012b).

This type of approach is highly useful as a guideline for developing a taxonomy of resilience indicators for architecture and infrastructure in RAMSES. The toolbox takes a unique approach to attempt to reduce a dauntingly complex task down to manageable elements. Instead of one long report full of tables of possible indicators, which stakeholders may find overwhelming, the process is divided into stand-alone tools that can be accessed when relevant and needed. Instead of considering all possible hazards and all segments of infrastructure, the purpose is to successively refine the relevance of both, in order to prioritize adaptation resources (including research) where they are most needed and most effective.

5.4 Indicators for resilient architecture and infrastructure

The many disparate approaches to the consideration and assessment of resilience have merged around some common themes. Many of these different approaches are from fields other than climate science, and are being developed for different threats. While the specifics may be different, especially in those focus on immediate vs. long-term hazards, the goals and results are comparable and often interchangeable. In fact, attempts to increase the resilience of cities should be interchangeable, or at least complementary. A community that is resilient to a terrorist attack but not an earthquake (or vice-versa) is not a resilient community after all.

The conceptual vagueness surrounding resilience and resilience thinking may be an asset (Strunz, 2012), allowing a diverse mix of researchers to approach the topic with their own distinct talent sets, to develop creative solutions to multifaceted problems. The problem lies less with the definition of resilience, and more with the expectation of results, consisting of an implicit yet confusing "mix of description and evaluation" (Strunz, 2012, p. 118). There remains a need to clarify concepts otherwise researchers and practitioners run the risk of talking "past one another" (Manyena, 2006, p. 437). These aspects need to be disentangled and distinguished from each other in order to be practical.

5.4.1 The Bruneau/Chang model

The main approach around which quantitative resilience assessment has seemed to unite is the framework developed by Bruneau et al. (2003) and Chang & Shinozuka (2004), see also Section §4.1.1.1. Hereafter this framework will be referred to as the Bruneau/Chang model. The original focus of the Bruneau/Chang model was disaster resilience of communities – specifically to earthquakes, but their results have proven generalizable to other hazards. Resilience in this context refers to reducing failure probability, consequences, and recovery time. The concept can be reduced in complexity to be represented visually with a simple graph of functionality over time, describing the time for a system to return to original performance levels. (Figure 4)

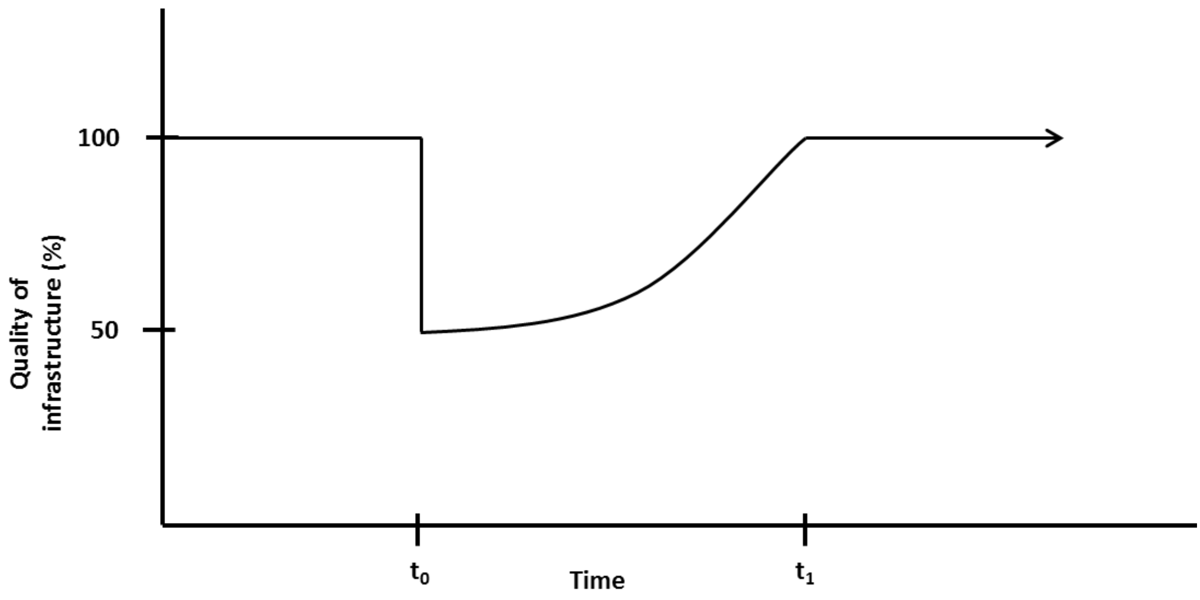


Figure 4: Graph of functionality over time, describing the time for a system to return to original performance levels (adapted from Bruneau et al., 2003, p. 737)

Resilience is simultaneously a physical and social phenomenon (with four dimensions: Technical, Organizational, Social, and Economic), but in all contexts can be described as dependent on four measures (4R):

1. Resourcefulness – problem solving and flexibility to thwart a disruption
2. Redundancy – substitutable elements that are capable of maintaining function during a disruption
3. Robustness – strength, the ability to withstand a hazard with no loss of function (aligned more with reducing sensitivity to a hazard, and therefore vulnerability – considered differently by other authors)
4. Rapidity – restoring lost functionality rapidly (Bruneau et al., 2003).

Resourcefulness and redundancy represent the ex-ante "means" of achieving a resilient system, while robustness and rapidity are "ends" measured ex-post.

5.4.2 Quantitative resilience concepts in water systems

Adapting the Bruneau/Chang model and conceptual underpinnings of resilience assessment in their review of quantitative resilience concepts in water systems, Wang & Blackmore (2009) focus on a systems view consisting of two discrete types of resilience: crossing a threshold, and response and recovery, both of which are modified by flexibility and management. The authors introduce a variation on the Bruneau/Chang system model (Figure 5), where alternate paths are shown besides a simple return to normal (Case B). The post recovery system quality may exceed the original system (Case A) through better design that takes advantage of lessons learned, or it may suffer permanent losses, and never return to its initial state. In this sense we see the emergence of degrees of resilience, instead of a binary concept. Wang & Blackmore (2009) recognize the interdependencies of urban ecosystems and infrastructure – and the need to consider both hard (physical) and soft (socioeconomic) assets.

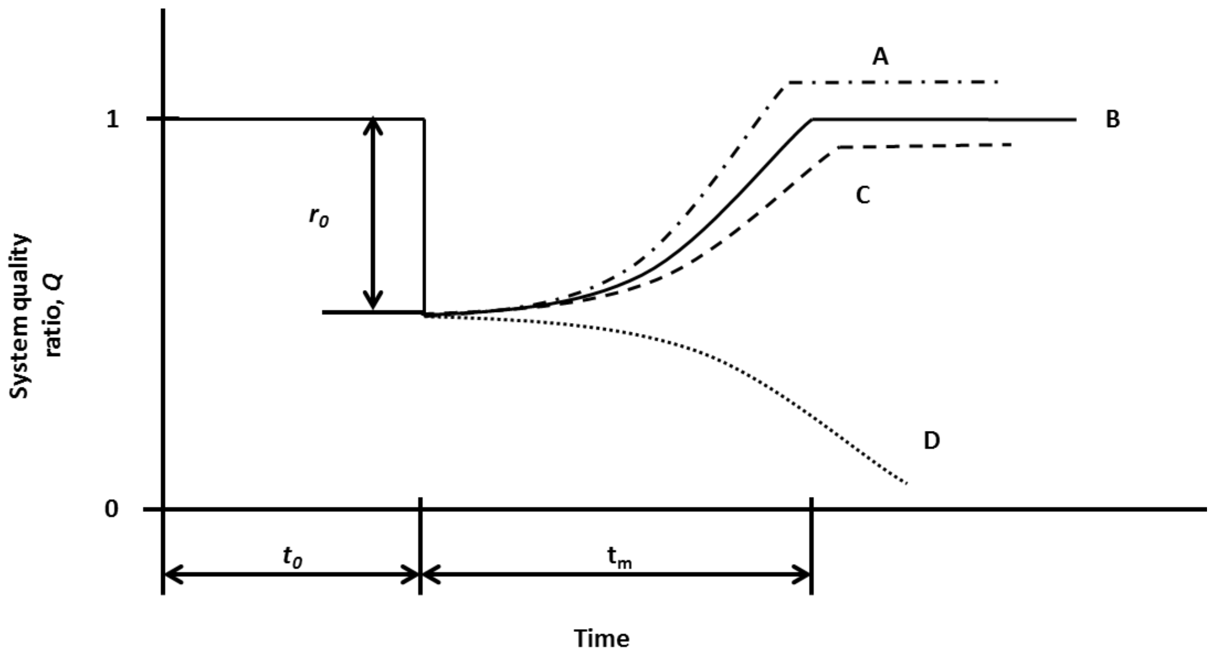


Figure 5: Wang & Blackmore (2009) focus on a systems view consisting of two discrete types of resilience: crossing a threshold, and response and recovery, both of which are modified by flexibility and management. Alternate paths are shown besides a simple return to normal (Case B). The post recovery system quality may exceed the original system (Case A) through better design that takes advantage of lessons learned, or it may suffer permanent losses, and never return to its initial state. (Adapted from Wang and Blackmore, 2009)

5.4.3 Quantification of Disaster Resilience

Analyses of social and technical aspects of resilience tend to occur separately, while they actually are intimately connected and interdependent (Cimellaro et al., 2010). Refining the Bruneau/Chang model further, (Cimellaro et al., 2010) define T_{LC} as a predetermined control time (Figure 6), which can represent expected life cycle or service life, and represents the time over which the assessment is conducted.

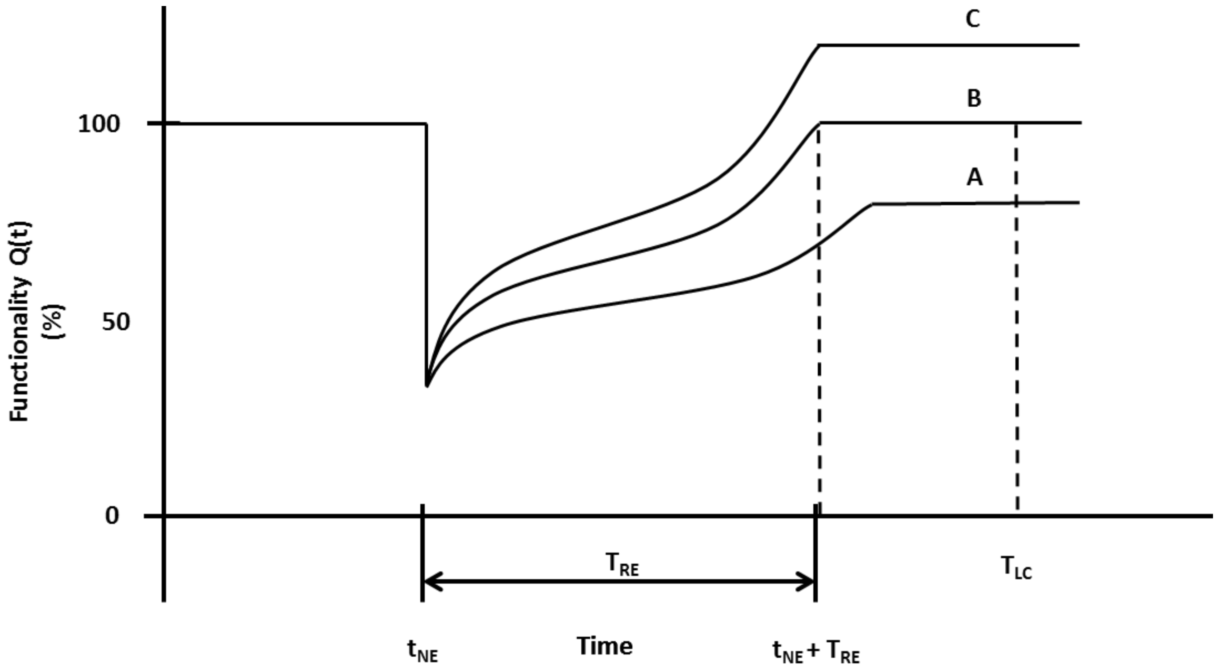


Figure 6: Refining the Bruneau/Chang model further, (Cimellaro et al., 2010) define T_{LC} as a predetermined control time, which can represent expected life cycle or service life, and represents the time over which the assessment is conducted. (Adapted from Cimellaro et al., 2010, p. 3642)

5.4.4 Resilience of infrastructure and economic systems

Vugrin et al. (2010) approach resilience through the lens of homeland security, but resilience has proven to be a concept that transfers easily between disciplines, as long as collective definitions and framework are utilized. The authors differentiate between protection and resilience (and assessment of both) as complementary but discrete concepts. Resilience assessment consists of an immediate consequence analysis after an event, as well as assessment of restoration and recovery. System resilience depends on "inherent properties of the system" - tolerance, flexibility, and restorability capacities (Vugrin et al., 2010, p. 83).

Building on the Bruneau/Chang model, where a quantifiable measure for resilience assessment the time required to restore functionality, Vugrin et al. (2010) explicitly include more than just time as a factor from which ex-post resilience can be assessed (Figure 7). The area under the system performance target level, from which the system has deviated, is referred to as systemic impact (SI), and represents the total loss of system performance (SP) over a prescribed time interval, (defined as T_{LC} by Cimellaro et al 2010). The total recovery effort (TRE) includes not only the duration of recovery, but the effort required to restore functionality. While the Bruneau/Chang model would consider two systems equally resilient if they recover in the same timeframe, effort (cost) is factored into this model approach, allowing optimization based on trade-offs.

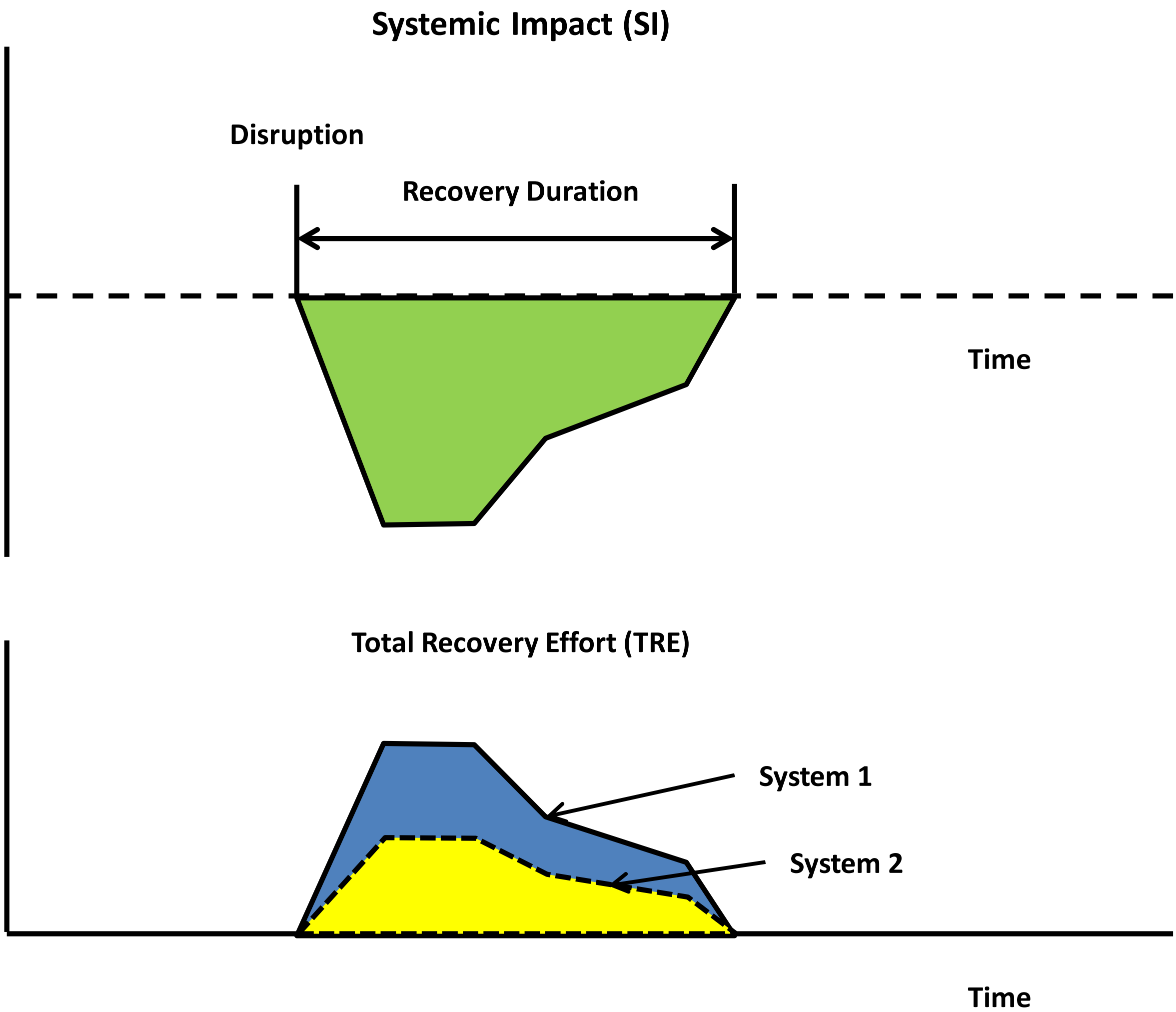


Figure 7: Vugrin et al. (2010) explicitly include more than just time as a factor from which to assess ex-post resilience. The total recovery effort (TRE) includes not only the duration of recovery, but the effort required to restore functionality. While system performance is identical for systems 1 and 2 (upper figure), system 2 requires a smaller recovery effort than system 1 (figure below) and is thus more resilient (Adapted from Vugrin et al., 2010, p. 95)

5.4.5 MCEER, the PEOPLES Resilience Framework, and ResilUS

Another approach building on the Bruneau/Chang framework is the PEOPLES Resilience Framework (Renschler et al., 2010) developed at the Multidisciplinary Center for Earthquake Engineering Research (MCEER). Several authors have taken the initial framework, which includes dimensions of Population and demographics, Environmental/ecosystem, Organized governmental services, Physical infrastructure, Lifestyle and community competence, Economic development, and Social-cultural capital. The dimensions are organized with a list of elements and sub-elements for each category. The framework focuses on the community scale, which range from neighbourhoods and villages, up to regions and states. The framework has been operationalized into several models.

Miles and Chang developed the ResilUS model simulating the recovery dynamics of socio-economic agents (households and businesses), neighbourhoods, and communities following a disaster (Miles and Chang, 2011, 2008). ResilUS assesses hazards and resulting damage to "community capital" including the built environment, economics, and health factors (Table 9). Two indicators of recovery are utilized: the ability to perform and the opportunity to perform (which are loosely correlated with supply and demand for services) (Miles and Chang, 2011, 2008).

A different a GIS-based model, measuring performance and functionality with geo-spatial and temporal distributions, focuses on comparing pre- and post-event GIS data from communities in order to assess resilience and elucidate the factors that contribute to recovery (Arcidiacono et al., 2011).

Capital Type	Variable	Description
Physical Capital	BYR	Year building or lifeline component built.
	BL	Ratio of resources (materials, labor etc.) expended in reconstruction to building replacement value. Alternatively, percent to which reconstruction is complete. 0 to 1, with 1 being reconstructed.
	CRIT	Probability that critical facilities network component service is fully restored.
	CYR	year seismic (or other building) code effective
	DMG	Damage of building or lifeline component expressed as ratio of building replacement value.
	ELEC	Probability that electrical network component service is fully restored.
	FACILITY	Service level of a business's facility. 0 to 1, with 1 indicating operation at pre-event service level.
	MAINT	Probability that component has been well-maintained.
	MIT	Pre-event structural mitigation of building or lifeline component. Currently 1 (maximum) indicates a 25% increase is fragility curve median.
	SHEL	Probability that household has adequate shelter and associated services.
	STH	Probability that short-term housing is available, Y/N.
	TRNS	Probability transportation network component service is fully restored.
	TYPE	Type of building or lifeline component—a proxy for size and/or complexity for reconstruction. 0 to 1, with 1 indicating largest or most complex.
	WAT	Probability that water network component service is fully restored.
	WAT_ALT	Provision for alternate water sources (water trucks) for neighborhood. 0 to 1, with 1 being equivalent to maximum total water service in neighborhood (WATn=1)

Capital Type	Variable	Description
Economic Capital	AID	Normalized post-event grant amount.
	DEBT	Normalized level of debt. The inverse of LOAN.
	DEMAND	Post-event demand for product. 0 to 1, with 1 indicating pre-event demand level.
	EMPL	Probability that employment is available.
	FAIL	Occurrence of business failure (Y(1)/N(0))
	INC	Normalized annual income.
	INS	Whether or not an agent has insurance.
	LOAN	Normalized amount of reconstruction loan taken out. Implicitly related with DMG (ratio of building replacement value).
	LOAN_MAX	Limit on post-event loan amount.
	MARG	Pre-event financial marginality.
	OUTLAY	Whether or not an agent has received an insurance payment. 1 is implicitly defined as the replacement value of their building.
	PROD	Probability that business is at pre-event production level.
	SAVINGS	Normalized savings or assets.
	SECT	Type of business sector (0:local or 1:export).
	SIZE	Normalized number of employees.
Socio-Cultural Capital	CAP	Recovery capacity of community (proxy for integration and consensus). 0 to 1, with 1 being highest capacity.
	CONSTR	Probability that necessary construction resources available for restoration.
	INSP	Time in weeks after event that safety inspections are completed.
	MUT	Provision for mutual aid in lifeline restoration. 0 to 1, with 1 equal to maximum construction resources without mutual aid (i.e., MUT can at most double construction resources)
	PLAN	Probability of an effective restoration plan.
	PRTY	An absolute score given at the neighborhood level, indicating priority. The score can range from NBRHD (number of neighborhoods) to 1, with higher numbers indicating higher priority.
Personal Capital	HEALTH	Probability that household is healthy
	INJURY	Probability that household health or business demand has been injured.
	LEAVE	Whether or not household has left region.
Ecological Capital	HAZ	Severity of earthquake’s (or hazard event) physical effects. 0 to 10, Conceptually equivalent to ShakeMap intensity/MMI

Table 9: The ResilUS Resilience Framework: Types of capital and variables from Miles and Chang (2008)

Frazier et al. (2013) integrate ecosystem resilience into existing approaches to assessing community scale resilience. Pre-disaster satellite imagery was used to assess ecosystem function in comparison with post disaster, at discrete time-intervals, allowing the construction of recovery charts. Spatially explicit resilience indices were calculated for each type of land use and land cover (LULC). Ecosystem resilience (ERI) was then incorporated into the existing resilUS computer model of community recovery dynamics to assess the relationships and interdependencies between businesses and ecosystem function. ERI was found to influence overall community resilience, with the largest effect on businesses with heavy reliance on ecosystem services.

While these approaches provide valuable input for robustness and restorative capacity, various core resilience characteristics still appear to be missing – in particular related to adaptability, diversity and cascading effects. The capacity and ability to change while maintaining functionality adopt alternative strategies and respond to changing conditions is not addressed explicitly, neither are spatial and functional diversity and modularity to enable substitution of system elements in case of damage. The stability of green and blue infrastructures and their role in maintaining control over local ecosystem services is not addressed explicitly either.

5.4.6 Quantifying coastal system resilience

In a further adaptation and extension of the Bruneau/Chang model, Schultz et al. (2012) provide a breakdown of the different stages of the resilience process. Shown in Figure 8, Q_∞ represents the performance objective. If a disturbance of magnitude *m* causes system performance to drop to *q*, the result is a performance impairment of *d*. The (predefined) critical performance impairment level d^*_m is surpassed, and r_s represents the time between the event and the return to the critical performance level q^*_m.

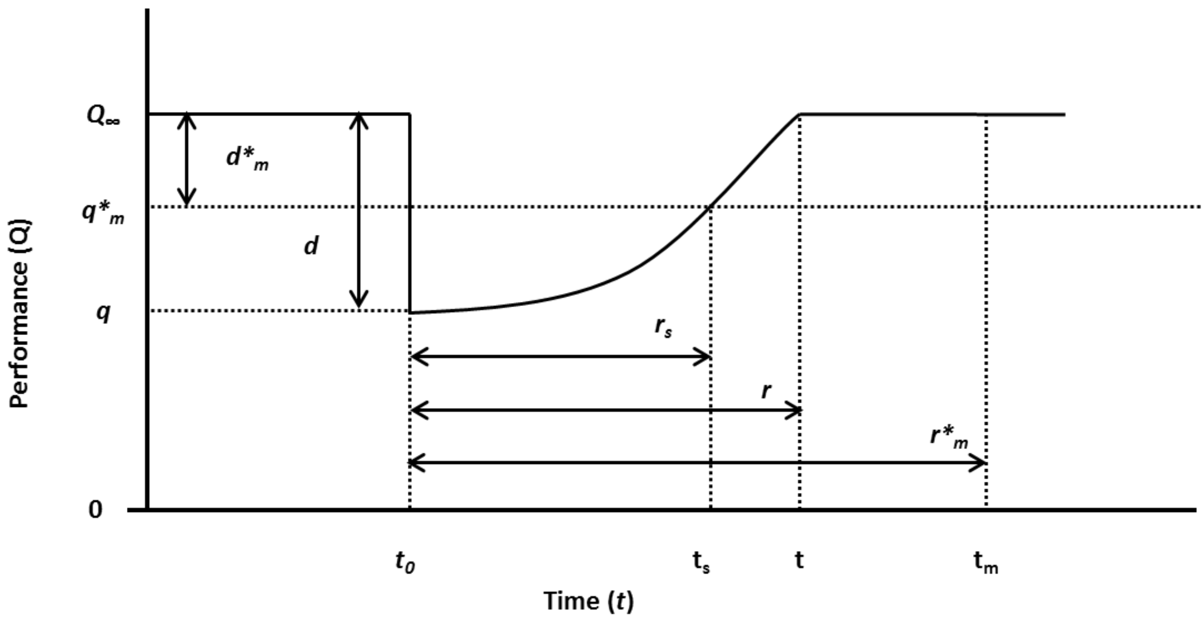


Figure 8: In a further adaptation and extension of the Bruneau/Chang model, Schultz et al. (2012) provide a breakdown of the different stages of the resilience process. Q_∞ *represents the performance objective. If a disturbance of magnitude* m *causes system performance to drop to* q*, the result is a performance impairment of* d*. The (predefined) critical performance impairment level* d^*_m *is surpassed, and* r_s *represents the time between the event and the return to the critical performance level* q^*_m*. (Adapted from Schultz et al., 2012)*

Based on the theory of reliability analysis, Schultz et al. (2012) provide a step-by-step procedure outlining a probabilistic approach to evaluating resilience in coastal systems:

1. Identify functional performance objectives for each subsystem.
2. Decompose each subsystem - identify the components and processes that support each functional performance objective.
3. Establish performance measures for the function of each component and process.
4. Establish performance objectives for each component and process function in terms of selected performance metrics considering each possible level of event severity.
5. Develop a fragility curve for each component and process function, describing the conditional probability of failure to meet performance objectives.
6. Transform the fragility curve to characterize uncertainty in functional performance given the level of environmental force acting on the component or process.
7. Develop an inter-operability matrix, and update the probabilities of functional performance.
8. Establish recovery objectives for each component or process.

9. Characterize uncertainty in the time that would be required to restore the pre-disturbance performance level of that component or process given the severity of the disturbance event.
10. Using a suitable performance function, simulate performance for each level of event severity, accounting for uncertainty in the response and rapidity of the component or process function.
11. Calculate the probability of maintaining an acceptable level of functional performance for each component or process.
12. Calculate a measure of resilience for the subsystem as a whole and aggregate subsystem resilience measures to obtain a measure of resilience for the system (Schultz et al. 2012).

Though a probabilistic approach may provide the most information, it also requires the most detailed information - much of which may be unknown or unattainable for any but the simplest processes and systems (Schultz et al., 2012). While powerful, probabilistic measures may not be the best communication tools, as "decision makers may not have sufficient training to interpret this information correctly or be able to understand its limitations" (Schultz et al., 2012, p.60).

Given the data intensity, uncertainties, and complexity of implementing a probabilistic approach to resilience assessment, Schultz et al. (2012) examine different approaches to resilience assessment. The authors compare probabilistic measures to direct and indirect indicators, noting the advantages and disadvantages of each (Table 10). Probabilistic measures necessitate models of components, process functions, and interdependencies, direct indicators are based on models or observations, and indirect indicators are based on information about system characteristics with an expectation of correlation.

Resilience Measure	Advantages	Disadvantages
Probabilistic measure	Provides information about resilience to disturbances that have not yet been observed.	Requires detailed information about the system to implement.
	Incorporates explicit information about robustness and recovery objectives.	Requires models to simulate component, process and system response to disturbance effectively.
	Provides a single characterization of resilience accounting for both robustness and rapidity.	Requires information on interdependencies among components and processes.
	Provides a single measure of resilience over the full set of potential disturbance events.	Requires a high level of training and skill to estimate and interpret.
	Provides direct comparisons of different systems exposed to different types of disturbances are possible.	Relatively costly and time-consuming to estimate.
	Probabilistic measures provide direct inputs to risk management decisions.	
Direct indicator	Direct indicators are unambiguously linked to system performance.	Evaluation of direct indicators requires empirical data on or models of system response and recovery.
	Based on empirical data on system response or models of system response.	Provides information about resilience to a single event rather than the full set of potential disturbance events.
	Does not require a high level of training or skill to implement or interpret.	May be difficult to interpret the indicator in a way that is useful for decision-making.
	Incorporates explicit information about management objectives.	Indicator is non-probabilistic and, therefore, cannot be used as a direct input to risk-based decisions.
	Easy to communicate to decision makers and stakeholders.	
Indirect indicator	Based on apparent characteristics of the system that can be measured and monitored over time.	Provides information about resilience to a single event rather than the full set of potential disturbance events.
	Does not require observations of system	May be difficult to interpret the indicator in a

Resilience Measure	Advantages	Disadvantages
	performance during and following a disturbance.	way that is useful for decision-making.
	Easy to communicate to decision makers and stakeholders.	Indicator is non-probabilistic and, therefore, cannot be used as a direct input to risk-based decisions.
		The association between an indirect indicator and robustness and rapidity may be unclear.
		Weak link to management objectives for system performance, robustness, and rapidity.

Table 10: Approaches to developing resilience indicators, from (Schultz et al., 2012)

Combining the work of Bruneau et al. (2003) and Walker and Salt (2006), Schultz et al. (2012) collected a list of properties of resilient systems (Table 11). These properties and descriptions "may be useful in identifying indicators of robustness and rapidity". (Schultz et al. 2012, p. 53) The authors consider indicators of robustness and rapidity to be "direct indicators of resilience" (Schultz et al. 2012, p. 53). Indicators of "adaptability, diversity, modularity, redundancy, resourcefulness, and tightness of feedbacks" are indicators only of robustness and rapidity (Schultz et al. 2012, p. 53), or indirect indicators of resilience, with uncertain correlation.

System Property	Description
Adaptability	Capacity to change as the surrounding environment changes while still maintaining functionality (Walker and Salt, 2006).
Diversity	Variety in the number of species, people, and institutions that exist in a social-ecological system (Walker and Salt, 2006).
Modularity	The extent to which the components and processes that make up a system are dependent upon each other to maintain function (Walker and Salt, 2006).
Rapidity	The time required to restore system performance to a pre-disturbance level. The capacity of a system to meet priorities and achieve goals in a timely manner to contain losses and avoid future disruption (Bruneau et al., 2003)
Redundancy	Extent to which elements, systems, or other units of analysis exist that are substitutable (i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality (Bruneau et al., 2003; Walker and Salt, 2006).
Resourcefulness	The capacity to identify problems and priorities, and mobilize resources when the function of some element, system, or other unit of analysis is disrupted. Resourcefulness may also be conceptualized as the ability to apply material (i.e., money, physical, technological, and informational) and human resources to meet goals (Bruneau et al., 2003).
Robustness	The ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau et al., 2003).
Feedbacks	How quickly and strongly the consequences of a change in one part of the system are felt and responded to in other parts of the system (Walker and Salt, 2006).

Table 11: Properties and characteristics of resilient systems, from (Schultz et al., 2012)

5.4.7 Modelling resilient design

As opposed to the myriad of approaches that only frame the concept of resilience, or explain possible methods of how to qualitatively or quantitatively asset it, Turnquist and Vugrin (2013) promote the concept of designing systems with resilient qualities. The authors advocate designing absorptive (tolerant), adaptive (flexibility, redundancy), and restorative capacities into systems and networks. Increasing network resilience involves three related capacities: increasing tolerance to withstand disruptions, adaptive capacity (redundancy) to accommodate flows via alternate paths, and restorative capacity to quickly recover from disruptions. Their approach involves a network model involving "22,500 variables and 23,000 constraints" focusing on optimization based on minimum cost (Turnquist and Vugrin, 2013, p. 112). Their results highlight the interdependencies of the three resilience capacities, and the need to therefore consider design investments with a systems perspective.

Lhomme develops a framework for GIS-based urban network resiliency assessment, based on the Bruneau/Chang model, and three capacities related to resilience: resistance, absorption, and recovery (Lhomme et al., 2013). Resilience is considered to be a function of absorption capacity (measured through redundancy assessment) and recovery capacity (considers distance between damaged network components and service centres) directly, while resistance capacity is expected to mediate absorption and recovery. The authors develop two indicators of network redundancy to analyse absorption capacity, and apply them to a case study road network. The two indicators of redundancy are based on graph theory, and consider the number or average proportions of independent paths linking a point to sets of other points.

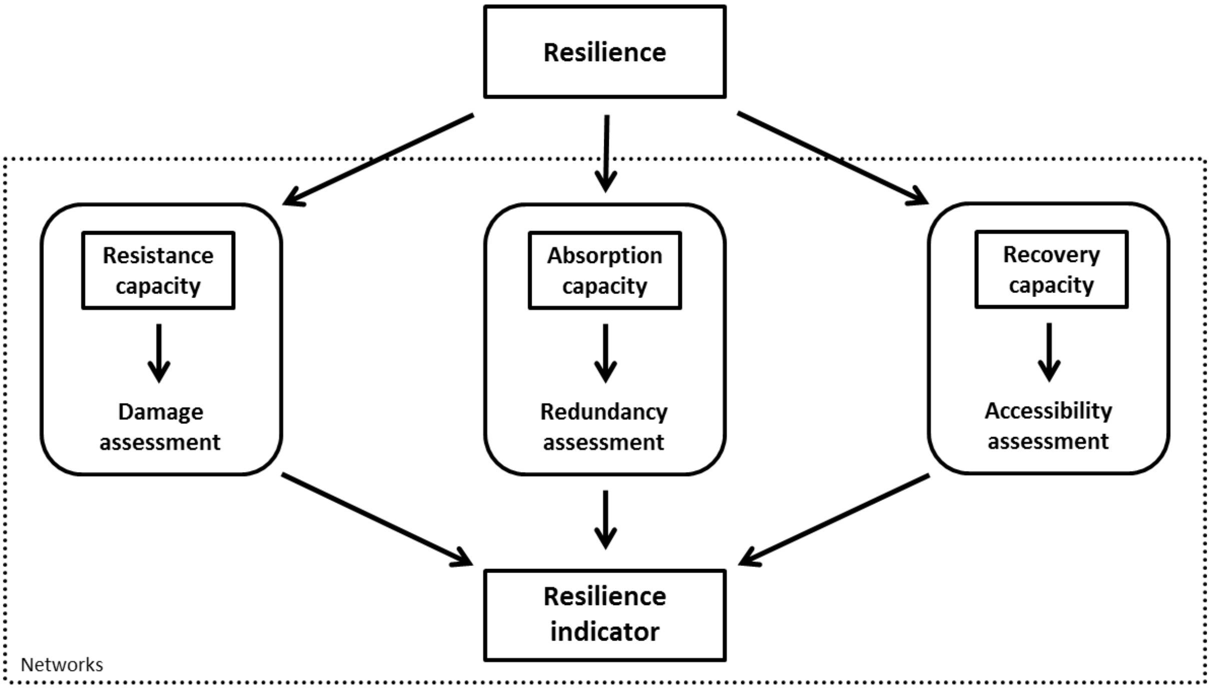


Figure 9: Resilience as the capacity to absorb and recover (Adapted from Lhomme et al., 2013, p. 224)

5.4.8 European Topic Centres on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) and Spatial Information and Analysis (ETC/SIA)

Some of the indicators from Urban Audit are utilized in a recent joint report on Urban Vulnerability Indicators by the European Topic Centres on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) and Spatial Information and Analysis (ETC/SIA) (Swart et al., 2012). Similar to other approaches, the report considers urban vulnerability to be composed of three factors: exposure, sensitivity, and "response capacity" (Swart et al., 2012). Response capacity is a variation of the "adaptive capacity" in the IPCC/Füssel framework, but contains a more explicit temporal differentiation - between anticipatory (planning and preparation), and reactive (during and effort a perturbation) dimensions. The three dimensions of response capacity considered are awareness, ability, and action (Swart et al., 2012). In addition to the generic indicators of response capacity (Table 24), the report includes specific indicators (and data sources) for exposure, sensitivity, and response capacity to heat, floods, droughts, and forest fires (Swart et al., 2012).

Two aspects of response capacity as identified by Svart et al. (2012) are promising to include and further develop into resilience of soft infrastructure:

- Perception of the city population that the authorities are committed to fight against climate change (Human: awareness of climate change)
- Risk perceptions of European citizens (Human: Risk perception)

In terms of actions and actual response, two relevant aspects are identified that might be included in further development of a taxonomy of resilience indicators for architecture and infrastructure:

- Urban adaptation strategies and measures (actual adaptation at the city level)
- National adaptation strategy (national measures)

However these are too generic in terms of scope, spatial and temporal scale to identify concrete opportunities for intervention within the RAMSES project.

5.4.9 Tyndall Centre for Climate Change Research (London)

A comprehensive study from the Tyndall Centre for Climate Change Research uses a systems-based approach to model climate change impacts in London (Hall et al., 2009). The study integrated several different scenario based models for London: a scenario based climate model, a multi-sectoral regional economic model with demographic projections, and simulations of four different land use scenarios (Hall et al., 2009). Results include modelled carbon dioxide emissions from personal transport, freight transport, and energy use, as well as climate change impacts on urban temperatures, water availability, and flood risk in London (Hall et al., 2009).

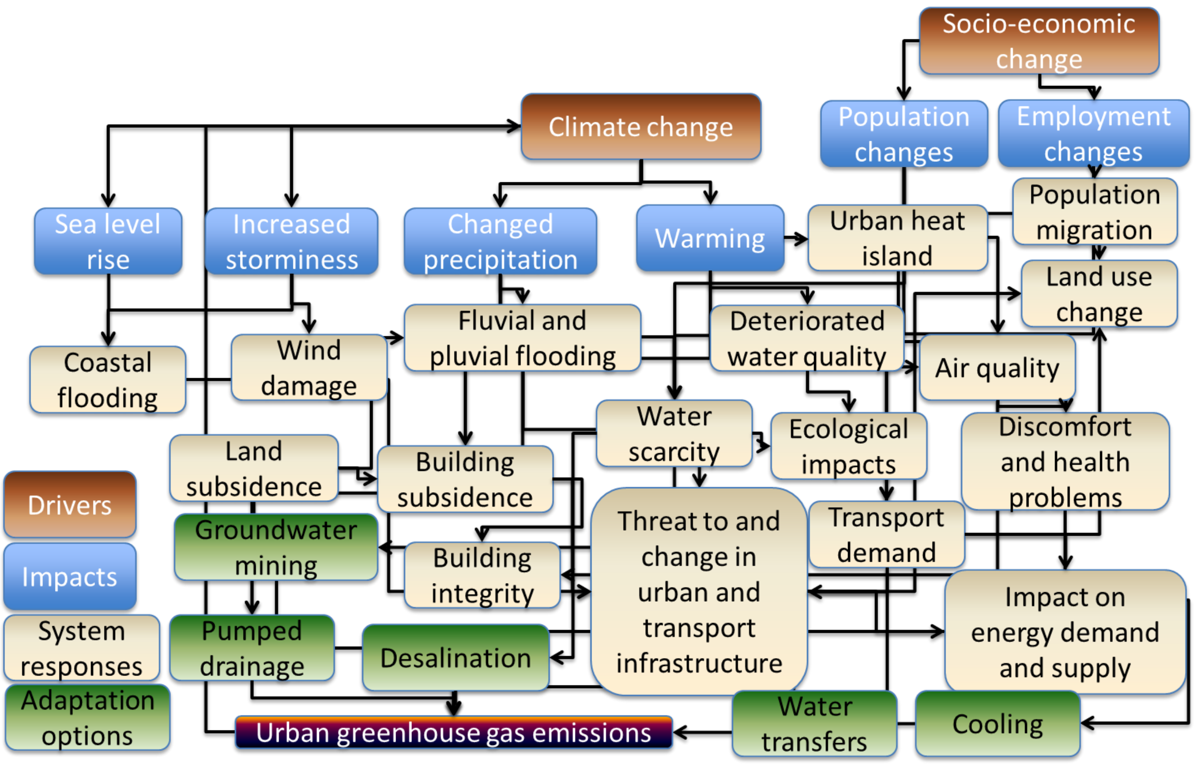


Figure 10: Schematic representation of the complex relationships, feedbacks, and interdependencies between drivers and impacts of climate change, and responses and adaptation options in cities. Adapted from (Hall et al., 2009).

The results from this complex integration do not provide any specific indicators, but do highlight some potential conflicts between mitigation and adaptation (Hall et al. 2009). The model also stresses connectivity, feedbacks and potential cumulative effects between diverse urban sectors and impacts – a feature that was mainly missing in the approaches discussed in the previous sections.

5.4.10 Cross-Scale Spatial Indicators

Bourdic et al. (2012) present a list of quantitative indicators for "urban sustainability" with a focus on urban morphology and spatial form. The authors lament the "lack of robustness" found in existing urban assessment tools, and the mixing and aggregation of qualitative and quantitative parameters (Bourdic et al., 2012, p. 593). While climate change is not explicitly considered, the plethora of indicators, classified under nine cross-scale themes (land-use, mobility, etc.), may provide interesting starting points for the development of city-based climate change indicator sets.

This indicator system is different from those discussed in previous sections as it specifically deals with spatial indicators and thus forms a good basis for design and management of resilient urban morphology. The authors develop quantitative indicators of intensity, spatial distribution, proximity, connectivity, diversity, and form, which are presented as a sort of menu from which planners could presumably choose the indicators that are useful under the circumstances. The indicator system is shown in its entirety in the Appendix (§10.10). Below the most relevant indicators for resilient architecture and infrastructure in the RAMSES project are shown and discussed.

Land use and urban form are linked through two main types of indicators at district (D) and neighbourhood (N) scales:

- Intensity – covering various kinds of density: human density, building density, housing density, job density, density of legal entities, coefficient of land occupancy and subdivision intensity
- Diversity – covering diversity of subdivisions size, diversity of land use (road network, built environment, courtyards, green spaces), and diversity of subdivision use (housing, offices, shops, public facilities etc.)

Theme	Concept	Type	Name	Scale	Equation
Land Use	Urban form	Intensity	Human density	D/N	$\frac{\text{population}}{\text{area of the selection } (m^2)}$
			Building density	D/N	$\frac{\text{floor area } (m^2)}{\text{area of the selection } (m^2)}$
			Housing density	D/N	$\frac{\text{number of housing units}}{\text{area of the selection } (m^2)}$
			Density of legal entities	D/N	$\frac{\text{number of legal entities}}{\text{area of the selection } (m^2)}$
			Job density	D/N	$\frac{\text{number of jobs}}{\text{area of the selection } (m^2)}$
			Coefficient of land occupancy	D/N	$\frac{\text{land occupancy } (m^2)}{\text{area of the selection } (m^2)}$
			Subdivision intensity	D/N	$\frac{\text{number of parcels}}{\text{area of the selection } (m^2)}$
		Diversity	Diversity of subdivisions size	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_{tot\,i}S_i^m}{A}\right]^2$
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$

Table 12: Excerpt of system of spatial indicators, using land use and urban form as example, by Bourdic et al. 2012

Both of these indicator types can be linked to core resilience dimension “Diversity” in Table 1. Spatial diversity relates to the physical distribution – or clustering – of assets and functions to avoid all of them from being affected by a given event at any time. High density increases the risk of considerable damage levels due to disruptive events, but may also increase response capacity, particularly when combined with high functional diversity.

In terms of mobility and urban form Bourdic et al. (2012) list 5 main indicator types:

- Intensity – covering surface occupied by pedestrians and bicycle paths, surface occupied by road networks, and proportion of the road network dedicated to public transport
- Connectivity – covering connectivity and cyclomatic complexity of the pedestrian / bike grid, connectivity and cyclomatic complexity of the car grid, and average distance between intersections in bike/pedestrian grid and car grid, respectively
- Proximity – covering the proportion of the population more than 300 meters away from a public transport stop
- Diversity – number of public transport modes accessible within 300 metres
- Complexity – scale hierarchy of the street network

Theme	Concept	Type	Name	Scale	Equation
Mobility	Urban form	Intensity	Surface occupied by pedestrian and bicycle paths	D/N	$\frac{\text{area occupied by ped and bike paths}}{\text{area of the selection (m}^2\text{)}} \times 100$
			Surface occupied by the road network	C/D	$\frac{\text{area of the road network (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}} \times 100$
			Proportion of the road network dedicated to public transport	D	$\frac{\text{area dedicated to public transport (m}^2\text{)}}{\text{total area dedicated to transport (m}^2\text{)}} \times 100$
		Connectivity	Connectivity of the pedestrian/bike grid	D/N	$\frac{\text{number of intersections of the ped/bike grid}}{\text{area of the selection (m}^2\text{)}} \times 100$
			Connectivity of the car grid	D	$\frac{\text{number of intersections of the car grid}}{\text{area of the selection (m}^2\text{)}} \times 100$
			Cyclomatic complexity of the car grid	D	$\mu = \text{L} - \text{N} + 1$ L = number of links; N = number of nodes
			Cyclomatic complexity of the pedestrian/bike grid	N	$\mu = \text{L} - \text{N} + 1$ L = number of links; N = number of nodes
			Average distance between intersections (bike/ped grid)	D/N	
			Average distance between intersections (car grid)	D	
		Proximity	Proportion of the population more than 300 meters away from a public transport stop	C/D	$\frac{\text{pop. more than 300 m away from p.t.}}{\text{population}} \times 100$
		Diversity	Number of public transport modes accessible within of 300 meters	D	
		Complexity	Scale hierarchy of the street network	C/D	$S = \frac{1}{\text{Cat}} \sum_{i=1}^{Cat} \left[1 - \frac{n_i x_i^m}{A} \right]^2$ n_i the number of streets of width x_i (per category)

Table 13: Excerpt of system of spatial indicators, using mobility and urban form as example, by Bourdic et al. 2012

These indicators are not explicitly related to climate resilience but could be extended to do so, answering to multiple core resilience characteristics at neighbourhood, district and city scale. This is one of few approaches for example that explicitly covers connectivity – though not yet in sufficient detail to be able to deal with cascading effects. It is also promising in terms of indicators for redundancy and modularity, enabling replacement of urban elements with parallel parts.

Dependency on local ecosystems is a core resilience characteristic embedded in two indicator types in Bourdic et al. (2012): water and biodiversity.

- Water – covering hydrological intensity, impermeability of land, efficiency of water use, accessibility of drinking water, and intensity of water treatment (rate of wastewater collection and treatment)
- Biodiversity – covering proportion of agricultural surfaces and of green fabric, connectivity of green habitats, and distribution of green spaces (distance from an even distribution)

Theme	Concept	Type	Name	Scale	Equation
Water	Environmental	Intensity	Hydrological intensity	D	% of natural hydro. functions preserved or restored
			Impermeability of land	D	$\frac{\text{imperm. area (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}}$
			Intensity of water treatment: Rate of wastewater collection and treatment	C/D	$\frac{\text{volume of collected and treated water (m}^3\text{)}}{\text{volume of water consumed (m}^3\text{)}}$
			Efficiency of water use	C	$\frac{\text{water needs (m}^3\text{)}}{\text{water cons. (m}^3\text{)}}$
			Accessibility of drinking water	C/D	% of the population with access to drinking water
Biodiversity	Environmental/ Urban form	Intensity	Proportion of agricultural surfaces	C/D	$\frac{\text{agri. land area (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
			Proportion of green fabric	D	$\frac{\text{green fabric area (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
		Connectivity	Connectivity of green habitats	D	$\frac{\text{area of connected green habitats (m}^2\text{)}}{\text{total area of green habitats (m}^2\text{)}} \text{ x } 100$
		Distribution	Distribution of green spaces (distance from an even distribution)	C/D	$\frac{Q}{Q-1}\left[1-\sum_{district=1}^{Q}\left(\frac{S_{green\ area_{district\ i}}}{S_{district\ i}}\right)^2\right]$

Table 14: Excerpt of system of spatial indicators, using biodiversity and water as example, by Bourdic et al. 2012

As in the case of mobility and land use these indicators are not explicitly related to resilient architecture and infrastructure but can be further developed for this purpose, in particular in terms of functional interdependence of system components and processes and corresponding control over services provided by local and surrounding ecosystems.

In addition to their ability to link resilience and design, these spatial indicators can easily be connected to GIS-data for block, neighbourhood, district and urban scales, which are in most cases readily available. This type of system should thus be fairly compatible with creating and monitoring action plans, development project check lists and other tools used by municipalities in their daily management of urban function and form, as discussed in Section §5.3.4.1.

5.4.11 Quantifying social resilience

While much of the work on developing quantitative measures of resilience has focused on specific segments of physical infrastructure, some researchers have been attempting to find quantitative indicators to represent social resilience. Social resilience indicators are generally based on assumed connections between indicators of social or economic capacity and resulting resilience (Foster, 2012). When these connections are tested using historical data (of recovery from economic shocks) to compare predicted and actual resilience, the assumed indicators of social resilience capacity have not correlated well with measured resilience (Augustine et al., 2013; Hill et al., 2012). While this work is emergent and still developing, the risk remains of creating proxy indicators with weak or non-existent correlations to the processes they are attempting to expose or quantify (Schultz et al., 2012).

Foster's (2012) development of social resilience indicators has been expanded and refined into the Resilience Capacity Index (RCI) (BRR, 2013). The RCI is a reported as a single number, representing the relative score of a community as a deviation from the mean (z-score) (BRR, 2013). The RCI is comprised of 12 equally weighted variables, encompassing three capacity dimensions (regional economic, socio-demographic, and community connectivity) with four indicators each (BRR, 2013). Using data from various sources for different variables (Appendix, §), the RCI was calculated for 361 metropolitan areas in the US, with the results presented online in tables and maps (BRR, 2013). The results of the RCI show a clear geographic disparity, as the index tends to reward the attributes typical of slow-growth regions, such as "metropolitan stability, regional affordability, homeownership and income equality" (BRR, 2013).

There remains much room for debate in whether the variables chosen to represent social resilience, and the resulting index, actually succeed in measuring (or predicting) resilience capacity. However in the previous sections examples of soft infrastructures have been included in various approaches to measure resilience. Further work in RAMSES WP2 will work on developing resilience indicators for hard infrastructure, architecture and urban form based on core characteristics summarised in Table 1. These include to some degree also social and institutional resilience, for example related to:

- Learning and memory. Individual and institutional capacity to learn from past experiences and failures, use information and experience to create novel adaptations, avoid repeating past mistakes, and accumulate, store, and share experience
- Resourcefulness. The capacity or ability to identify (and anticipate) problems, establish priorities, mobilise resources, and visualise, plan, collaborate and act

5.5 Properties and characteristics of resilient systems: a summary

Table 15 presents a core dimensions of resilient systems based on the contributions of the various authors discussed in Chapters 4 and 5. The RAMSES project is aiming to distil a taxonomy of resilience indicators that include all of the characteristics above, in particular core resilience characteristics such as connectivity, adaptability and diversity that are generally still missing in existing approaches.

Characteristic	Description
Adaptability, flexibility	Capacity or ability to: • change while maintaining functionality • evolve • adopt alternative strategies • respond to changing conditions
Connectivity, feedbacks, safe-failure	Functional interdependence of system components and processes (Effect of change in one part of the system on other parts of the system). Capacity or ability to: • absorb shocks • absorb cumulative effects of slow-onset challenges • avoid catastrophic failure if thresholds are exceeded • fail progressively rather than suddenly • fail without cascading impacts (domino effect)
Dependence on local ecosystems	Local control over services provided by local and surrounding ecosystems. Maintaining health and stability of green and blue infrastructure, providing: • flood control • temperature regulation

Characteristic	**Description**
	• pollutant filtration • local food production etc.
Diversity	Spatial diversity - Key assets and functions physically distributed to not all be affected by a given event at any time • Functional diversity - Multiple ways of meeting a given need
Learning, memory, *foresight*	Individual and institutional. Capacity or ability to: • learn from past experiences and failures • use information and experience to create novel adaptations • avoid repeating past mistakes • accumulate, store, and share experience
Performance	How well does the system perform in its role? • Functional capacity • System quality
Rapidity, responsiveness	Following a disruptive event, the capacity or ability to: • contain losses, including mortality and illness • reorganise • maintain and re-establish function • reinstate structure • restore basic order • avoid future disruption
Redundancy, modularity	The capacity or ability to: • substitute systems, or elements of systems • buffer from external shocks or demand changes • replace components with modular parts
Resourcefulness	The capacity or ability to: • identify (and anticipate) problems • establish priorities • mobilise resources • visualise, plan, collaborate and act
Robustness	The capacity or ability to: • withstand a given level of stress or demand • without degradation or loss of function
Co-benefits	• Added value assessment of resilience • No/low regret measures

Table 15: Core dimensions of resilient systems, from (Adger et al., 2005; Briguglio et al., 2008; Bruneau et al., 2003; Chang and Shinozuka, 2004; Chuvarayan et al., 2006; da Silva et al. 2012; Davis, 2005; Fiksel, 2003; Galderisi et al., 2010; Godschalk, 2003; ICSU, 2002; Longstaff et al. 2010a, 2010b; Maguire and Hagan, 2007; McDaniels et al., 2008; Reghezza-Zitt et al., 2012; Schultz et al., 2012 ; Tierney and Bruneau, 2007; Tyler and Moench, 2012; Van Der Veen and Logtmeijer, 2005; UN-ESCAP, 2008; Wilson, 2012)

6 Identifying opportunities for intervention

Annemie Wyckmans and James Kallaos, with Bernd Hezel and Ephraim Broschkowski

Highlights from literature reviews of chapters 3, 4 and 5 were presented and discussed during two workshops:

- A RAMSES stakeholder workshop with city representatives in Brussels 11 October 2013 organised by ICLEI
- A researchers' workshop with climate change mitigation and adaptation experts in Helsinki 23 October 2013 organised within the framework of COST Action TU0902 Integrated Assessment of Cities

During these workshops three aspects of WP2 were emphasised: core dimensions of resilient systems, identification of resilience indicators for architecture and infrastructure, and approaches in which these indicators can be applied to identify opportunities for intervention. The purpose of this series of exercises was to highlight the positive impact of resilience, its potential for regeneration and its co-benefits for urban quality.

6.1 Identifying core resilience dimensions

Workshop participants were first asked to list core dimensions of resilience according to their own experience and knowledge, after which this input was matched with Table 15 derived from literature reviews. The results are shown in Table 1; words in italic indicate participant input that was not explicitly present in the original table.

The importance of thresholds was emphasised by the workshop participants, in particular the difference between life and death – which measures are needed to prevent loss of life?

Linking resilience to co-benefits, no and low regret measures, was mentioned often and stressed as a core manner in which to operationalize visions of resilience in cities' daily routines. At the request of the participants an additional row was added to the table to indicate the importance of this dimension.

Characteristic	**Description**
Adaptability, flexibility	Capacity or ability to: • change while maintaining *or improving* functionality • evolve • adopt alternative strategies *quickly* • respond to changing conditions *in time* • *design open and flexible structures (in general)*
Connectivity, feedbacks, safe-failure	Functional interdependence of system components and processes (Effect of change in one part of the system on other parts of the system). Capacity or ability to: • absorb shocks • absorb cumulative effects of slow-onset challenges • avoid catastrophic failure if thresholds are exceeded • fail progressively rather than suddenly • fail without cascading impacts (domino effect) • *analyse and implement across spatial scales (city to site)* • *analyse as human-technology coupled system* • *identify lock-in effects and potential conflicts with mitigation* • *identify synergies with other city policies, added value assessment*

	• *balance clear distribution of responsibility with concerted action*
Dependence on local ecosystems	Local control over services provided by local and surrounding ecosystems. Maintaining health and stability of green and blue infrastructure, providing: • flood control • temperature regulation • pollutant filtration • local food production etc. • *bioclimatic design and management (adjusted to local conditions)*
Diversity	Spatial diversity - Key assets and functions physically distributed to not all be affected by a given event at any time • Functional diversity - Multiple ways of meeting a given need • *balance diversity with potential cascading effects*
Learning, memory, *foresight*	Individual and institutional. Capacity or ability to: • learn from past experiences and failures • use information and experience to create novel adaptations • avoid repeating past mistakes • accumulate, store, and share experience • *build on long-term cultural value and history of the city* • *integrate resilience in long-term development scenarios*
Performance	How well does the system perform in its role? • Functional capacity • System quality • *in an appropriate and efficient way* • *self-sustaining, reducing external dependencies* • *compared to others – "I want a bigger dike than my neighbours"*
Rapidity, responsiveness	Following a disruptive event, the capacity or ability to: • contain losses, including mortality and illness • reorganise • maintain and re-establish function • reinstate structure • restore basic order • avoid future disruption
Redundancy, modularity	The capacity or ability to: • substitute systems, or elements of systems • buffer from external shocks or demand changes • replace components with modular parts • *balance redundancy with potential cascading effects*
Resourcefulness	The capacity, ability, *resources and infrastructures* to: • identify (and anticipate) problems • establish priorities • mobilise resources • visualise, plan, collaborate and act • *re-evaluate* • *integrate resilience in governance and working processes* • *involve and co-create with citizens (e.g., crowd-sourcing and funding)*
Robustness	The capacity or ability to: • withstand a given level of stress or demand • without degradation or loss of function

	• *capacities that ensure sufficient margins*
Co-benefits	• Added value assessment of resilience • No/low regret measures

Table 1: Core dimensions of resilient systems, from RAMSES workshop participants and (Adger et al., 2005; Briguglio et al., 2008; Bruneau et al., 2003; Chang and Shinozuka, 2004; Chuvarayan et al., 2006; da Silva et al. 2012; Davis, 2005; Fiksel, 2003; Galderisi et al., 2010; Godschalk, 2003; ICSU, 2002; Longstaff et al. 2010a, 2010b; Maguire and Hagan, 2007; McDaniels et al., 2008; Reghezza-Zitt et al., 2012; Schultz et al., 2012; Tierney and Bruneau, 2007; Tyler and Moench, 2012; Van Der Veen and Logtmeijer, 2005; UN-ESCAP, 2008; Wilson, 2012)

This exercise indicates that the table contains four main priorities for further action in development of resilience indicators for architecture and infrastructure:

- Main weight on prevention through design and awareness
- Need for concerted action by city and citizens
- Connecting to local opportunities and resourcefulness (climate, site, culture, resources)
- Knowing how to prioritise within limited time and budget

6.1.1 Towards indicators for resilient architecture and infrastructure

The core dimensions of resilient systems (§6.1) were matched to main indicators and measures for resilient architecture and infrastructure as found in literature and identified by participants of the RAMSES stakeholder and researcher workshops. These results are summarised in tables xx below, categorised according to four main topics:

- Grey infrastructures (ICT, water, waste, energy etc.)
- Green and blue infrastructures
- Land use, mobility, urban-rural interface
- Architecture, public space, urban regeneration

First this section gives a short introduction of the main concerns related to resilient architecture and infrastructure found in literature: lifetime performance, various spatial and temporal scales, and the importance of co-benefits also mentioned in §6.1.

6.1.2 Literature review

Buildings and infrastructure, including roads and transport systems, energy, water, waste, vegetation and water bodies, and even public space, are designed to last for decades and are expensive to renovate or replace. Vulnerability risks and costs can be considerably reduced when designing the built environment with inherent flexibility for adaptation to climate change, prioritising passive and local solutions, and providing redundancy of solutions (diverse supply options).

In addition, it is recommended to prioritise low-regret options providing a range of co-benefits for climate change mitigation as well as quality of life; for example, green areas and water bodies can provide storm water management, delay the urban heat island effect, and create local leisure facilities for the urban population, accessibly by non-motorised or public transport. Costs can further be reduced when adaptation measures are timed according to upcoming windows of opportunity such as building retrofits, urban renewal, densification or development (EEA, 2012a).

A number of publications provide design recommendations for a climate change adapted built environment (amongst others Brophy and Lewis, 2011; EEA, 2012a; Lechner, 2009; Olgyay, 1963; Shaw et al., 2007; VÁTI, 2011; Walton et al., 2007). The European

Environmental Agency (EEA) recently published a comprehensive report on "Urban Adaptation to Climate Change in Europe" (EEA, 2012a), including a wide range of case studies and measures for grey and green infrastructure, categorised according to climate change impacts. Grey infrastructures are defined as “construction measures using engineering services”, while green infrastructures are “vegetated areas and elements such as parks, gardens, wetlands, natural areas, green roofs and walls, trees etc. contributing to the increase of ecosystems resilience and delivery of ecosystem services” (EEA, 2012a, p. 7).

Shaw et al (2007) propose a classification in terms of "scale", between the *building scale* that looks at individual buildings and building blocks, the *neighbourhood scale* that includes developments of discrete groups of buildings, including a mix of uses and the public realm, and the *conurbation or catchment scale* that can involve services for the entire city. Adaptation and mitigation measures can be in fact different according to the adopted scale. At the building scale physical design and engineering solutions are preeminent, at neighbourhood scale master planning and urban form gain importance. Spatial planning and urban design have to be conceived in order to find the best way to satisfy the requirements of these different scales, trying to harmonize and balance their integration, their overlaps and potential conflicts.

6.1.3 Identifying resilience indicators for grey, green and blue infrastructures, architecture and public space, land use and mobility

For each topic the workshop participants were asked to propose indicators and topics freely related to these four main themes. Afterwards their input has been clustered around core resilience dimensions to identify gaps and opportunities. The main feedback from this exercise, as also remarked by the participants themselves, is that the proposed indicators essentially are related to “good” urban planning, mitigation and adaptation, but often do not specifically take into account resilience.

Added value assessment and identification of no-regret and low-regret measures that improve urban quality beyond climate change adaptation are stressed by participants in this exercise as well as in §6.1 and §6.3, and should be taken into account in further RAMSES work. An extra row has been added to the tables in order to be able to incorporate feedback on this particular dimension.

In each category there are two dimensions that received few or no input: “learning, memory” and “redundancy, modularity”. Potentially this is related to the apparent conflict between resource efficiency needed for climate change mitigation, with which most cities have much more experience, and the redundancy needed to provide alternative pathways in case of hazards, which traditionally has been much less emphasised. Learning and memory was mentioned on a similar level as the other dimensions in the previous exercise (Section §6.1), but is little emphasised when detailed input regarding resilience performance of particular infrastructure and architecture is requested.

6.1.4 Grey infrastructures

Table 16 shows input from workshop participants related to resilience of grey infrastructures, clustered ex-post according to core resilience characteristics from literature.

Grey infrastructures	Literature / *Stakeholder and researcher workshops*
Adaptability,	• *How robust are infrastructures to last 80 years? How adaptable*

flexibility	*is the infrastructure in the future?*
Connectivity, feedbacks, safe failure	• *Look at the whole system not just parts of it – interrelations* • *Decentralised systems* • *Infrastructure connectivity in case of extreme events*
Dependence on local ecosystems	
Diversity	• *Location of critical parts of infrastructure* • *Location of networks*
Learning, memory	• *Historical data saving*
Rapidity, responsiveness	• *Recovery of vital infrastructure* • *Security of energy supply*
Redundancy, modularity	• Ensure diverse and redundant energy supply and distribution, including local, decentralised systems
Resourcefulness	• *Building code* • *User-based approaches (the very first)*
Robustness	• Make infrastructures able to withstand excessive weather conditions using appropriate location, design, materials and detailing, and regular maintenance, e.g., *spare storage capacity in sewage system before overflow into surface water; number and capacity of drains; ground permeability* • Prioritise vital infrastructures, *e.g., railtrack materials (buckling etc.)*, *metro vulnerability to floods*, *temperature level ICT datacentres can cope with* • Reconstruction of vulnerable structures
Co-benefits, no/low regret measures	• *Coordination of mitigation and adaptation* • *Level of ITS (Intelligent Transport Systems)* • *Waste reduction as preventive measure for extreme events; recycling facilities; Pollution and consumption; Reuse and recycle – less dependency* • *Annual energy imports, energy consumption and conservation; self-sufficiency; insulation density; renewables* • *Demand side management, smart grids* • *Greenhouse gas emissions*

Table 16: Summary of literature and input from workshop participants on indicators for resilient grey infrastructures (Brophy and Lewis, 2011; EEA, 2012a; Lechner, 2009; Olgyay, 1963; Shaw et al., 2007; VÁTI, 2011; Walton et al., 2007)

The results correspond generally to the outcome of the previous exercise (§6.1), with main weight on connectivity of systems and policies, long timelines including historical data and foresight, and robust design able to tolerate impact without degradation of function. A large number of responses were related to co-benefits of mitigation, resource efficiency and adaptation.

6.1.5 Green and blue infrastructures

Table 17 shows input from workshop participants related to resilience of green and blue infrastructures, clustered ex-post according to core resilience characteristics from literature.

Green and blue infrastructures	**Literature / *Stakeholder and researchers workshop***

Adaptability, flexibility	
Connectivity, feedbacks, safe failure	• Safety of water supply from more remote areas (pipelines), desalination plants • *Integrated green infrastructure mix* • *Connecting city green spaces with the surrounding landscape* • *Connectivity of green areas; landscape fragmentation, number of unfragmented areas* • *Green infrastructure measures implemented at all levels (region/city, city/district, district/sites)*
Dependence on local ecosystems	• Green-blue infrastructures provide water retention, storage and stormwater management, passive cooling and shading, and protection from noise and air pollution, *capacity of green structures to mitigate effects of storm surge in tidal rivers, trees (most effective green infrastructure under heatwaves)* • *Water storage capacity in relation to amount of paved urban area* • *Urban agriculture as food security issue* • *Restore natural functions of ecosystems to optimise benefits of green infrastructure, ecosystems services*
Diversity	• Maintain and increase the number, accessibility, functionality and distribution of green urban areas, facades and roofs, trees, parks, gardens and other vegetation; *multifunctionality* • *Different types of green infrastructure (public, private, trees, grass etc.) can serve different purposes in different ways. E.g., private green is still important for climate, less for recreation* • *Sewage systems: split grey water and rainfall*
Learning, memory	
Rapidity, responsiveness	
Redundancy, modularity	
Resourcefulness	• *Indicators for new development* • *Knowledge of what you have, state it is in, to ensure resilience* • *Green intervention measures for private and public spaces* • *Integrate biodiversity in construction standards*
Robustness	• Select vegetation that tolerates variable and sometimes excessive weather conditions, and does not require excessive watering or regular maintenance • Reducing on-site demand by means of efficient equipment, grey water recycling systems, ground water recharge systems, and rain water harvesting systems • Design water bodies for natural gravity-flow drainage, improved ground drainage, *proportion of city area that is built-up, area per capita* • Ensuring sewage systems can cope with heavier precipitation; separate treatment of rainwater, disconnected from sewage
Co-benefits, no/low regret measures	• Green-blue areas provide an attractive visual environment and valuable ecological habitats*; no-regret measures, social and environmental co-benefits, quality of life, health benefits,* • *Ensuring good green spaces; green infrastructure well-adjusted*

	to environmental and social conditions of a city (expert and public assessment); distance to green space average for citizens, accessibility of green spaces for inhabitants; green roofs, bicycle lanes • *Traditional compact cities increase heat island effect, but a greened compact city should reduce the effect* • *Ocean acidification, biodiversity loss, invasives, number of species*

Table 17: Summary of literature and input from workshop participants on indicators for resilient green and blue infrastructures (Brophy and Lewis, 2011; EEA, 2012a; Lechner, 2009; Olgyay, 1963; Shaw et al., 2007; VÁTI, 2011; Walton et al., 2007)

The results correspond generally to the outcome of the previous exercise (§6.1), with main weight on connectivity and ecosystems services. Added value provided by green and blue infrastructures for inhabitants is stressed considerably, as no-regret or low-regret measures that can increase urban quality beyond climate change adaptation.

6.1.6 Land use, mobility, urban-rural interface

Table 18 shows input from workshop participants related to resilience of land use, mobility and urban-rural interface, clustered ex-post according to core resilience characteristics from literature.

Land use, mobility, urban-rural interface	**Literature / *Stakeholder and researchers workshop***
Adaptability, flexibility	• If public spaces are necessary in risk-prone areas, design them for variable use and accessibility according to weather conditions (e.g., a park with pond can tolerate occasional flooding and help during stormwater management)
Connectivity, feedbacks, safe failure	• *Settlement hierarchy* • *Connectivity*
Dependence on local ecosystems	• *Ensure connectivity of rural and urban ecosystems for services provided to cities* • *Being able to cycle to green areas in a heatwave* • *Accessibility of rural products*
Diversity	• Create street and footpath networks that allow for different choices, with clear and multiple connections (avoid dead ends) and sufficient capacity • Design urban form and density to allow for integration of decentralised renewable energy systems, for energy security during excessive weather events • *Polycentric development vs. centralised concentration (existing settlements)* • *Number of mixed-use zones* • *Number of functions for land parcel* • *Land use diversity*
Learning, memory	• *Avoid building in risk-prone areas*
Rapidity, responsiveness	• *Vulnerability of electricity units in public space for functioning of rail transport (train, tram…) + restore capacity* • *Ability to bring food and services into the city* • *Guarantee accessibility (e.g., work-home)*

Redundancy, modularity	• Design a coherent structure of public spaces, forms and functions with accessibility to all user groups; provide connections and overlaps between different areas, streets and squares, of a human scale; recognisably distinct and with a positive relationship between public and private spaces • *Redundancy of infrastructure to cope with extreme events (e.g., transport)* • Provide sufficient density for accessible services, but avoid competition for scarce resources among neighbouring functions and sectors (housing, tourism, industry etc.); *multiple services – redundancy of uses*
Resourcefulness	• Use spatial planning as a tool to stop urban development in current and future risk-prone areas, *risk factor per area for flooding* • *Resource and information flow from rural to urban for new governance system*
Robustness	• Design mobility systems in a manner that is accessible and attractive for pedestrians and cyclists, reducing dependability on motorised transport; e.g., street and footpath networks adapted to local topography and orientation • Provide a sufficient amount and distribution of permeable and green surfaces to avoid contributing to the urban heat island effect and allow for water storage and draining • *Resistance of gas or heat networks for amount of water on ground level due to flooding (pressure)*
Co-benefits, no/low regret measures	• *Link to identity* • *Quality indicators too (e.g., not only km of bike lanes, but actual quality of lanes, safety and awareness of cyclists and pedestrians* • *Connectivity in the aim of sustainable transport (e.g., bike facilities), daily travel distance, time required for regular trips, to get out of the city* • *Looking for opportunities to reduce urban sprawl and encourage densification without increasing impervious surfaces, with good width-height ratio of streets, reducing loss of forests and semi-natural areas* • *Local economy*

Table 18: Summary of literature and input from workshop participants on indicators for resilient land use, mobility and urban-rural interface (Brophy and Lewis, 2011; EEA, 2012a; Lechner, 2009; Olgyay, 1963; Shaw et al., 2007; VÁTI, 2011; Walton et al., 2007)

Design and management of spatial structure is the field in which dimensions such as redundancy, diversity and connectivity are emphasised most by the workshop participants. Urban quality as an added value of resilience was also mentioned frequently.

6.1.7 Architecture, public space, urban regeneration

Table 19 shows input from workshop participants related to resilience of architecture and public space, clustered ex-post according to core resilience characteristics from literature.

Architecture, public space, urban regeneration	**Literature / *Stakeholder and researcher workshops***

Adaptability, flexibility	• *Embedding measures in the existing city (design + management)* • *Flexible structures, multiple uses*
Connectivity, feedbacks, safe failure	• *Maximise use of industrial ecology*
Dependence on local ecosystems	• *The compact city in the ecological net (mitigation + adaptation)* • *Maximise use of local resources* • *Integration with nature (bioclimatic)*
Diversity	• *Accessibility of the open spaces and services* • *Accessibility index for buildings of various functions* • *Economic diversity* • *Fiscal gap indicator*
Learning, memory	
Rapidity, responsiveness	• *Rate of provision of housing (having people accommodated quickly)* • *Capacity of restoring functionality of buildings after flooding in unembanked areas, making damaged buildings usable again and restore to previous level of quality (economic impact)* • *Capacity of public space (e.g., roads, plazas) to store water incidentally (how are roads, pavements etc. designed?)*
Redundancy, modularity	
Resourcefulness	• *Preparedness for extreme events* • *Building standards for climate extremes* • *Indicators dealing with uncertainty, thresholds* • *Indicators for management* • *Upgrade of indicators for urban planning, e.g. using good urban planning/design to reduce the urban heat island effect* • *Helping politicians deal with it* • *Insurance ratio – finance* • *How to measure the resilience of people?* • *Public acceptance as an indicator of resilience* • *Society's demands and expectations* • *Competitiveness*
Robustness	• Appropriate selection of geographical location and topography, taking into account for example soil instability and other exposure • Make buildings flood proof by appropriate design and material use, such as elevated entrances, building on poles, floating houses, temporary water storage, green roofs etc. • Design public spaces for protection from excessive weather events. Excessive heat, storm, flooding, drought and humidity will reduce the use of public spaces, and thus constrain life. • Prioritise bioclimatic design of buildings and open space: adaptation to local climate and topography to provide a comfortable microclimate with natural ventilation, solar access and shading, *and green surfaces in open space*. Design of buildings with sufficient insulation, wind and rain resistance, solar access and shading, natural ventilation, and green roofs and walls rather than relying solely on mechanical systems such as air conditioning. • Design for changes in temperature and relative humidity to avoid

	pests (fungus, bacteria and insects) that threaten the integrity of built structures and health • Avoid large building mass with extensive impervious surfaces, as these will act as thermal mass for heat and will prevent water drainage. Use surfaces with high albedo or reflectance where possible. • Reduce on-site energy demand by means of energy-efficient buildings and infrastructures, use energy and resource efficient devices, and promote on-site integration of renewable energy generation to increase self-sufficiency and depend less on external supply • Regular maintenance, reconstruction of vulnerable buildings
Co-benefits, no/low regret measures	• Bioclimatic design also saves energy and can make cities more visually attractive, *protection against air pollution etc., opportunity for a healthier livelier city* • *Synergies with resilient concepts to other changes (e.g., demographic, financial, crisis…) – use it!* • *Expanding greenery while reducing urban sprawl*

Table 19: Summary of input from literature and workshops on indicators for resilient architecture, public space and urban regeneration (Brophy and Lewis, 2011; EEA, 2012a; Lechner, 2009; Olgyay, 1963; Shaw et al., 2007; VÁTI, 2011; Walton et al., 2007)

This category received a lot of input on resilience of soft infrastructures such as “resourcefulness” of city and citizens, when compared to the exercises involving “grey infrastructure” and “green and blue infrastructure”. It includes a fair amount of socio-economic suggestions, such as a fiscal gap indicator and insurance ratio, indicators for urban planning, and societal demands and expectations.

6.1.8 Development of indicators

The measures identified in Sections §6.2.3-6 indicate how morphological factors and socio-economic activity can alter exposure and impact at local scale in cities, and how appropriate building and infrastructure design can mitigate these effects, so-called "climate proofing" (EEA, 2012a, p. 89). The impact of such measures, however, needs to be assessed and compared to various competing scenarios for best impact (for example, combining green roofs with integration of photovoltaic panels) and avoidance of lock-in effects. Prioritising amongst design measures therefore requires knowledge-based scenarios, benchmarking, and operational indicators.

This approach can be used as a stepping-stone towards the development and design of resilient systems, as advocated by Turnquist and Vugrin (2013) (see §5.4.7), if the absorptive, adaptive and restorative capacities of urban architecture and infrastructure systems are mapped and assessed.

The workshop resulted in few specific indicators, but did include many proposals for measures that in fact are already embedded in modelling, urban spatial structure planning, insurance assessment and other practical applications by means of quantitative and qualitative indicators. It was also emphasised that resilience indicators ideally should be embedded in already existing initiatives and frameworks in order to be successful and operationalized quickly. The next step of the research is therefore to analyse these sources within the RAMSES case cities in order to identify solution spaces for further development.

6.2 Identifying opportunities for intervention

Chapters 4 and 5 have described a spectre of methodologies to identify opportunities, related to modelling and simulation, impact assessment diagrams, databases and simplified design guidelines, all based on each other but valid for distinct purposes, detail and target groups. During the third workshop exercise these approaches and methodologies were discussed for their capacity to identify opportunities for intervention and assess the correct type and extent of action:

- Simplified design guidelines
- Simulation, modelling and mapping
- Quantitative indicators
- Impact and connectivity diagrams

A first approach “Simplified design guidelines” was represented by an illustration of a generic urban built environment surrounded by guidelines for improving its resilience (Figure 11)

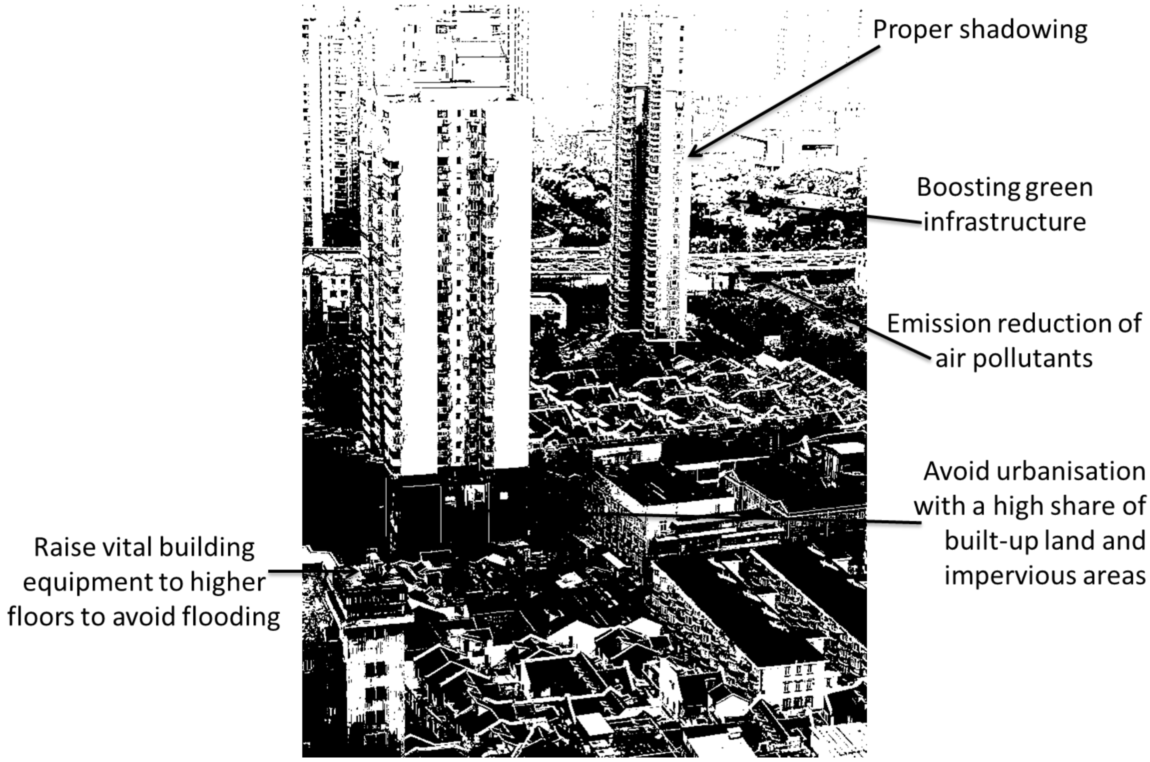


Figure 11: An example of simplified design guidelines for resilient architecture and infrastructure

The second approach “Simulation, modelling and mapping” was represented by an ESPON map of potential climate change on settlements (ESPON Climate 2011), as shown in Figure 12 (see also §10.2).

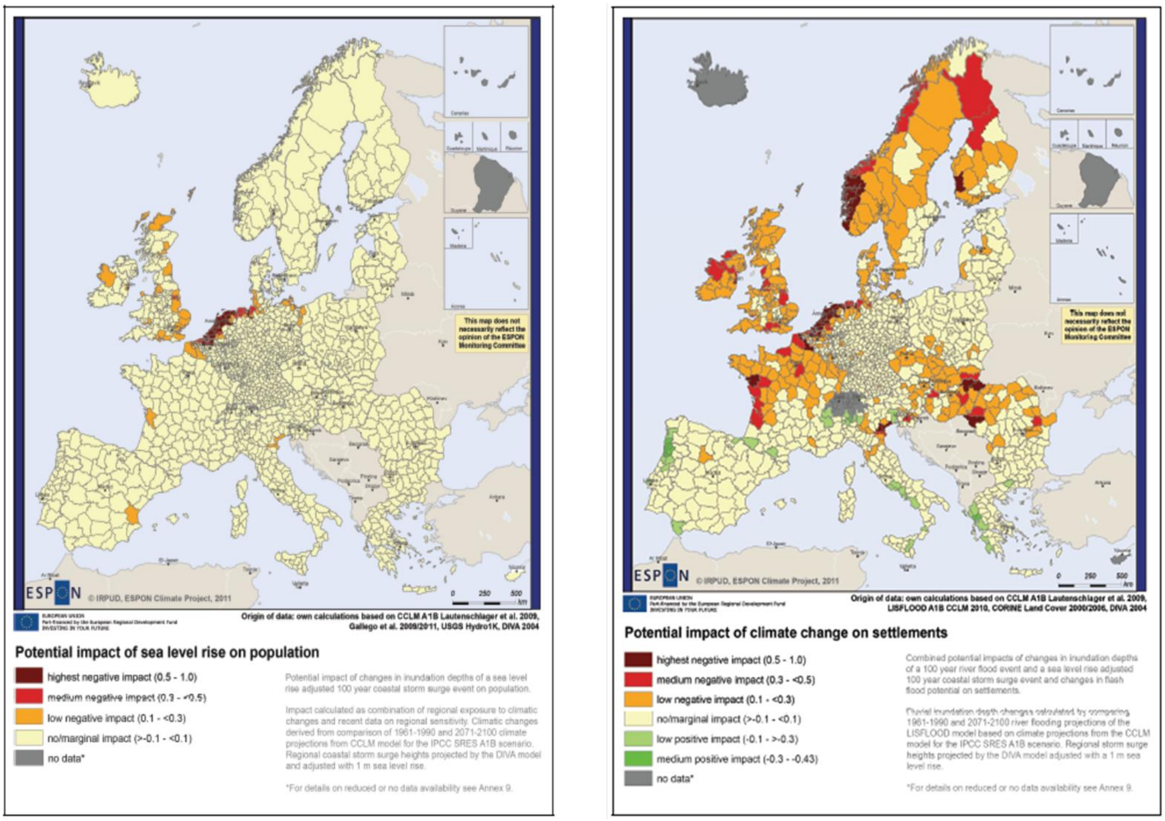


Figure 12: ESPON Climate, 2011. ESPON Climate - Climate Change and Territorial Effects on Regions and Local Economies. Scientific Report (Final Report No. Version 31/5/2011), Applied Research 2013/1/4. ESPON 2013 Programme: European observation network on territorial development and cohesion, Luxembourg.

As an example of a third type of approach “Quantitative indicators” a spatial indicator system by Bourdic et al (2012) was shown (see Table 12 for partial representation, and §10.10 for the entire table).

Theme	Concept	Type	Name	Scale	Equation
Land Use	Urban form	Intensity	Human density	D/N	$\frac{\text{population}}{\text{area of the selection (m}^2)}$
			Building density	D/N	$\frac{\text{floor area (m}^2)}{\text{area of the selection (m}^2)}$
			Housing density	D/N	$\frac{\text{number of housing units}}{\text{area of the selection (m}^2)}$
			Density of legal entities	D/N	$\frac{\text{number of legal entities}}{\text{area of the selection (m}^2)}$
			Job density	D/N	$\frac{\text{number of jobs}}{\text{area of the selection (m}^2)}$
			Coefficient of land occupancy	D/N	$\frac{\text{land occupancy (m}^2)}{\text{area of the selection (m}^2)}$
			Subdivision intensity	D/N	$\frac{\text{number of parcels}}{\text{area of the selection (m}^2)}$
		Diversity	Diversity of subdivisions size	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_{tot\,i}S_i^{\,m}}{A}\right]^2$
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{\,obj}}\right]^2$

Theme	Concept	Type	Name	Scale	Equation
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N	$\frac{1}{\mathrm{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$

The fourth approach "Impact diagrams – relationships, feedbacks, and interdependencies" was represented by a schematic representation of the complex relationships, feedbacks, and interdependencies between drivers and impacts of climate change, and responses and adaptation options in the city of London, created by Hall et al. (2009) (Figure 10, see also §5,4,9).

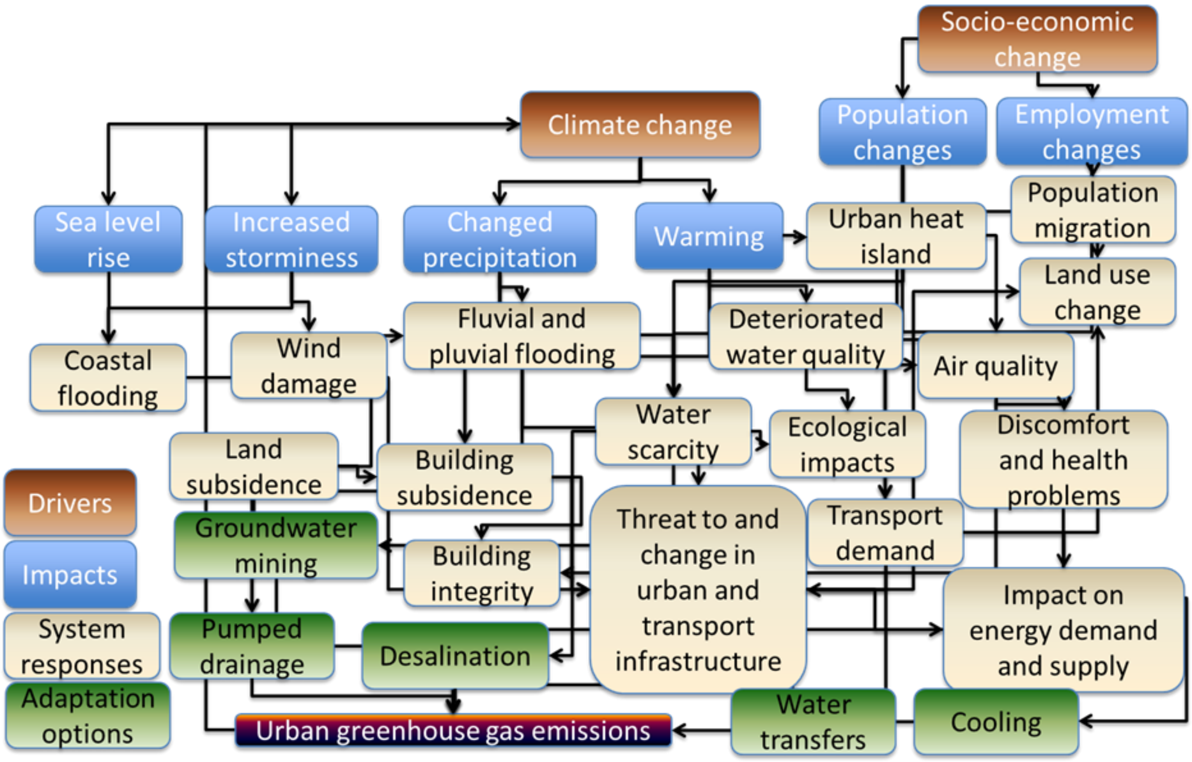
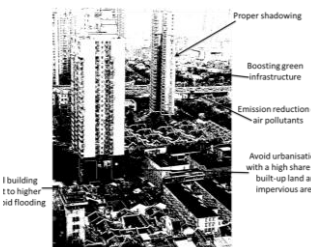
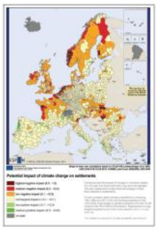


Figure 10: Schematic representation of the complex relationships, feedbacks, and interdependencies between drivers and impacts of climate change, and responses and adaptation options in cities. Adapted from (Hall et al., 2009).

For each approach the workshop participants were asked to discuss strengths and weaknesses. A summary of this discussion is provided in Table 20.

Simplified design guidelines	Strengths	Weaknesses
	• Immediate reassurance; fast • Clear, understandable instructions for action; linked to action • Local scale • Stakeholders learn: visual, no expertise needed; easier to grasp, for designers, public • Illustrative, but you need a sort of (quick) pre-analysis based on the risks in your city; useful solutions if	• Design of architecture and infrastructure is too reactive, should be more proactive; avoid attempting to mitigate prior failures • How to communicate system changes vs. changing components; no connectivity, no spatial analysis • Missing cost-benefit analysis and strategic analysis • Missing spatial analysis

	implementation is going to be checked	• Encouraging poor behaviour?

Simulation, modelling and mapping	Strengths	Weaknesses
 	• Global vision • Great for strategic purposes • Benchmarking • Prediction, reducing uncertainty • Useful for cities • Can be used across different scales • Uncertainty visualisation • Visualisation aids understanding, easy to understand • Timescale of the scenario • Global awareness for people • Climate change maps useful • Often used	• Uncertainties? Sensitivity analysis? • Static (resilience is about learning) • Doesn't explain why • Unnecessary comparison • Not a learning tool if dynamics are not integrated • Need to link analytical (global) scale with options at local level – need for feedback • Irrelevant for local level (sometimes wrong) • Models cannot predict unexpected events / hazards • Half of the story due to aggregation – what is behind? (indicators, feedback)

Quantitative indicators	Strengths	Weaknesses
(see table below)	• Lot of detailed information , good overview possible • Gives numbers that are relatively easy to understand • This helps a city at the start to choose and prioritise further actions • Easily turned into measures with specific departmental responsibilities • Use of performance measures • Enable for comparison between different cities • Linked to perception of residents • Open to new indicators • Basis for building guidelines or norms	• Identify problem before • Data availability • Interactions missing • Problem with defining uniform benchmarks; no benchmarks or objectives, defining goals • Too many indicators, not operational • Has to be designed ad-hoc for each city • Too complex; needs to be simple / accessible to be useful; need an expert for understanding • Subjective • Weighting procedure? • Needs interpretation, graphic representation • How to accommodate cities in developing countries that may lack resources for such assessment?

Theme	Concept	Type	Name	Scale	Equation
Land Use	Urban form	Intensity	Human density	D/N	$\frac{\text{population}}{\text{area of the selection (m}^2\text{)}}$
			Building density	D/N	$\frac{\text{floor area (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}}$
			Housing density	D/N	$\frac{\text{number of housing units}}{\text{area of the selection (m}^2\text{)}}$
			Density of legal entities	D/N	$\frac{\text{number of legal entities}}{\text{area of the selection (m}^2\text{)}}$
			Job density	D/N	$\frac{\text{number of jobs}}{\text{area of the selection (m}^2\text{)}}$
			Coefficient of land occupancy	D/N	$\frac{\text{land occupancy (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}}$
			Subdivision intensity	D/N	$\frac{\text{number of parcels}}{\text{area of the selection (m}^2\text{)}}$
		Diversity	Diversity of subdivisions size	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_{tot\ i}S_i^{m}}{A}\right]^2$
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$

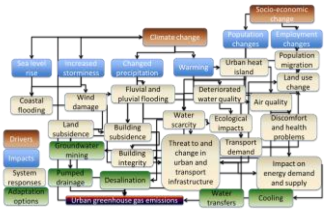
Impact diagram	Strengths	Weaknesses
	• Great starting point • All included, convincing • Addresses problems in an integrated way • Useful for planners • Learning tool • Enables understanding of complexity • Dynamic simulation – forecasting • Enables understanding of potential events • Better system understanding • Highlights synergies / conflicts between measures • Shows causality • Important to know relationships – it helps to talk together with the right stakeholders • Prioritise some measures according to connectedness	• Useful only at initial phase • Need to quantify interdependencies • Need qualified researchers to imagine scenarios of hazards / events, and appropriate tools • Complicated (depends) • Requires stakeholders to learn a new way of thinking, difficult • Needs to integrate stakeholders in the model building • Very sensitive

Table 21: Summary of strengths and weaknesses of various approaches as discussed by RAMSES workshop participants

It was remarked that these approaches represent four stages of an urban resilience analysis, each feeding in to the other, targeting distinct audiences and stages. Participants also commented that implementation of the results is always difficult than the analysis itself, and needs to be embedded thoroughly in the city's daily urban planning routines. In addition to implementation it is also challenging to obtain public understanding and adoption of the measures, which requires concerted action and communication.

6.3 Concerted action for resilience

As pointed out repeatedly in this report, indicators are special reductions of complexity with the purpose to serve as quantitative measures allowing for comparability. In literature and workshops the need for concerted action across municipality sectors, and with citizens was emphasised consistently. Indicators should therefore also be assessed by their fitness for creating awareness, for science communication and comparability. The translation of scientific results into non-technical terms, and the communication of these results with the policymakers, stakeholders, media, and the public are key ingredients for both mitigation and adaptation efforts to succeed.

Within the RAMSES project, therefore, we propose that indicators also be evaluated in terms of their potential to enhance the public debate about appropriate targets and pathways, and in terms of their appeal to be taken up by mass media, which plays an important role in teaching about climate change (adaptation) and the social construction of risks (Boykoff and Boykoff, 2004; Rhomberg, 2009; Zhao, 2009). Evaluating the dimensions of indicators that characterize their communicability, including simplicity, appeal, and relevance in the context of stakeholders and connection to everyday life (O'Neill and Nicholson-Cole, 2009; Schwender et al., 2007), their degree of association with (positive) emotions (Schwender et al., 2007), or whether they allow for a local narration (Shaw et al. 2009 p.460), would be scientifically valuable as such.

From a communications perspective, also comparability is essential. It allows for the scaling and the diffusion of results since learning processes in cities can be effectively initiated by benchmarking against peer models, thus by the example of other cities.

7 Conclusion

James Kallaos, Gaëll Mainguy and Annemie Wyckmans

Resilience of architecture and infrastructure has been approached in theory and in practice by many different disciplines, stakeholders and schools of thought. This extreme diversity is reflected in the nature and focus of methodologies developed to assess and measure resilience.

7.1 Lack of quantitative indicator-based assessments specific to settlements, cities, buildings, and infrastructure

Much of the current research on climate change impacts, adaptation, and vulnerability (IAV) follows the conceptual framework outlined in Füssel and Klein (2006), and is rapidly progressing in specificity as well as quality. There remains a definite lack of quantitative indicator-based assessments specific to settlements, cities, buildings, and infrastructure. While many studies reference cities or infrastructure, they are often referring solely to the inhabitants, and not to the physical structures and networks themselves. The two aspects of settlements need to be considered simultaneously, and the complexity of interactions between humans and the built environment disentangled, in order to assess potential impacts (sensitivity, adaptive capacity, etc.) from climate change. A promising approach is to integrate the action model from Eisenack & Stecker (2012) into the existing conceptual framework. While this is likely not the intention of the action framework, it is possible to envision an updated framework integrating the two methodologies. When designing a framework specific to cities, settlements, infrastructure, and buildings, the vagueness of many of the terms in the current discourse could be replaced with specific references to the object or system under evaluation.

The inclusion of climate change IAV consideration and assessment into the broader sustainability discourse has yet to fully develop. The discussion and assessment of sustainability remains focused on mitigation. Assessments of IAV are undertaken separately, as a subject external to broader sustainability concerns. There is a clear overlap between sustainability and IAV assessment, and the integration of the two may provide better insights for planning or policy than either applied in isolation. Evidence of climate change has transformed the concept of sustainability from that of a far-off future state to one that is upon us. Attempts at mitigation have not succeeded in reducing or stabilizing either GHG emissions or global temperature increases. Current and future considerations of sustainability will need to consider trade-offs and balances between mitigation and adaptation, and likely include aspects of coping as well.

7.2 A dual concept

In this complex multitude of overlapping frameworks, a dual pattern seems to emerge around two opposite poles. To caricature, on the one hand engineers tend to develop outcome-based approaches to increase the resistance of hard infrastructure so that they do not fail. On the other hand, social scientists and policy makers are keen to develop process-based approaches to strengthen the adaptive capacities of communities and institutions to respond to and recover from failure.

This dual nature of resilience seems to run through all the topics in this work as illustrated by key differences and attributes listed in Table 2 below.

Hard infrastructure	Soft infrastructure
Resist	**Adapt**
Built	Social, economic, political
Focused	Comprehensive
Engineering/technical	Organizational
Industrial, operators	Institution, local authority
Quantifiable	Not (easily) quantifiable
Technological fix	Organizational fix
Structural measures	Non-structural measures
Outcome-based	Process-based
Sectoral	Non-sectoral

Table 2: Resilience characteristics for hard and soft infrastructures

This table does not represent an attempt to propose a consistent model for resilience (which would be a first…), but to recognize the inner contradictions at the heart of the concept and the legitimacy of the different conceptions. As shown by the practice, the different approaches should not be seen as mutually exclusive, but rather as complementary.

7.3 A pragmatic approach

Our efforts to identify "indicators" for architecture and infrastructure resilience have not revealed many existing indicators of value. Instead, it is clear that best practice guidelines are increasingly perceived as efficient tools to encourage and promote resilience and deliver a level of reassurance not otherwise available through specific indicators.

There are no standards for resilience of architecture and infrastructure per se and establishing standards for all hazards and all sectors would be disproportionate and unachievable. An "all-risks" approach to resilience through upgrading current norms and standards has been proposed to be more appropriate (Cabinet Office, 2011).

This pragmatic and flexible approach builds upon existing industry standards for Government, regulators and infrastructure owners and operators to develop cost-effective resilience (Cabinet Office, 2011; Neumann and Price, 2009; RAEng, 2011; The World Bank, 2013). Adaptive capacity could be enhanced by developing explicit standards against which investments could be planned and appraised.

Indeed, in principle, incorporating resilience principles and metrics into standards and codes could provide:

- A monitoring framework for improvement of practices
- A consistent approach across sectors and countries.

7.4 Indicators and models

What can be learned from existing indicator-based studies is that the interpretation of what is or not an indicator varies widely. Indicators may be useful as indirect or proxy metrics for variables/parameters that are difficult or impossible to measure directly. Whether the use of the term indicator is the proper one to be used with scenario-based climate change models can be debated (Hinkel, 2011) but the parameters, variables, metrics, or indicators chosen for cities will depend on the specific impacts which can be expected for each individual architectural, sectoral, or societal element for each individual region. Any set of indicators will need to be organized along with a flow chart defining which indicators should be implemented and at what stage in the assessment/development cycle. Alternatively, all indicators could be applied, since it would likely take some expert assessment to compare simulation/model results to geospatial data to determine the risk of climate change induced hazards in specific situations.

Resilience exists as an inherent characteristic of a system, yet one that cannot be fully exposed ex-ante. Resilience is only observable after an event. But if we learn from past examples of resilience what characteristics in a system may help it exhibit resilience in the face of adversity, these characteristics can be cultivated in new developments and existing communities.

Indicators based on determining factors are useful for phenomena that have yet to be observed, or are not directly measurable, but for which a conceptual understanding of determining factors is available. Imagine we wanted to know the height of a person. Height is a function of genetic, epigenetic, nutritional, and other variables (G,E,N,O). But even if these variables were somehow measurable, height does not equal (GxExNxO). Height is directly measurable in units of meters. But without access to the individual for measurement, it could be argued that with enough previous experience and data regarding the influence of (G,E,N,O) on the heights of other individuals, an equation could be formulated which would provide a fair prediction of expected height.

The problem with applying an indirect approach to resilience assessment is determining which characteristics of systems influence or determine their capacity for resilience, and clarifying and simplifying these complex concepts into indicators. Resilience may be directly measurable as the time and effort required to restore or improve functionality after a disruptive event, but indicator development requires working backward from ex-post assessment to ex-ante indicators of system characteristics.

8 Acknowledgements

The authors are grateful to resilience experts and infrastructure practitioners who have contributed to our understanding of the complexity of the issues: Bruno Barroca, David Bresch, Denis Chanteur, Frederic Dhers, Richard Lalande, Dominique Olivier and Damien Serre.

For their valuable comments, enthusiasm and insights we would also like to thank the participants and organisers of the 1st RAMSES Stakeholder Dialogue, organised by ICLEI 11 October 2013 in Brussels, and the researchers' workshop organised 23 October 2013 in Helsinki as part of a COST Action TU0902 meeting.

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10 Appendix

The indicator lists are gleaned from texts, tables, and appendices in the referenced reports. They intend to be extensive but are not exhaustive. Some aspects may have been omitted. The lists are useful for identifying the range of approaches in current use, the differences in inclusiveness and specificity of different approaches, as well as the integration of qualitative and quantitative aspects. Most of the indicator sets involve components that have been modeled or simulated, and are therefore difficult to reduce to simple equations, metrics or units.

10.1 New indicators of vulnerability and adaptive capacity (Adger et al., 2004)

Indicator	Variable	Proxy	Units	Source
Economic well-being (EC)	National wealth	GDP per capita	US$ PPP	WB
	Income inequality	GINI coefficient	0-1 (dimensionless)	WIID
	Economic autonomy	Debt repayments	% Gross national income (GNI), decadal averages	WB
	National wealth	Gross national income (GNI)	Total, PPP	WB
Health and nutrition (HN)	State support for health	Health expenditure per capita	US$ PPP	HDI
	State support for health	Public health expenditure	% of GDP	HDI
	Burden of ill health	Disability adjusted life expectancy	Disability adjusted life years (DALY)	WHO
	General health	Life expectancy at birth	Years	HDI
	Healthcare availability	Maternal mortality	Ratio of maternal deaths to live births per year, expressed per 100,000 live births.	HDI
	Removal of economically active population	AIDS/HIV infection	% of adults	HDI
	Nutritional status	Caloric intake	Kilocalories per day per capita	GRID
	General food availability	Food production index	Annual change averaged over 1981-90 and 1991-99	WB
	Access to nutrition	Food price index	Annual change averaged over 1981-90 and 1991-99	WB
Education (EDU)	Educational commitment	Education expenditure	% of GNP	HDI
	Educational commitment	Education expenditure	% of government expenditure	HDI
	Entitlement to information	Adult literacy rate	% of population over 15	HDI
	Entitlement to information	Youth literacy rate	% of 15-24 year olds	HDI
	Entitlement to information	Literacy ratio	Ratio: female to male	HDI
Physical infrastructure (INF)	Isolation of rural communities	Roads	km, scaled by land area with 99% of population	WB
	Commitment to rural communities	Rural population without access to safe water	%	HDI
	Quality of basic infrastructure	Population with access to sanitation	%	HDI
Institutions, governance, conflict and "social capital" (GOV)	Priorities other than adaptation	Internal refugees	% of population	WB
	Effectiveness of policies	control of corruption	Aggregate index	KKZ
	Ability to deliver services	government effectiveness	Aggregate index	KKZ
	Willingness to invest in adaptation	political stability	Aggregate index	KKZ
	Barriers to adaptation	regulatory quality	Aggregate index	KKZ
	Willingness to invest in adaptation	rule of law	Aggregate index	KKZ
	Participatory decision making	voice and accountability	Aggregate index	KKZ
	Influence on political process	civil liberties	Aggregate index	FH
	Influence on political process	political rights	Aggregate index	FH

Indicator	Variable	Proxy	Units	Source
Geographic and demographic factors (GDEM)	Coastal risk	km of coastline (scale by land area)		GRID
	Coastal risk	Population within 100km of coastline	%	GRID
	Infrastructure/disease	population density	Persons per km^2	CIESIN
Dependence on agriculture (AG)	Dependence on agriculture	Agricultural employees	% of total population	WB
	Dependence on agriculture	Rural population	% of total population	WB
	Dependence on agriculture	Agricultural employees	% of male population	WB
	Dependence on agriculture	Agricultural employees	% of female population	WB
	Agricultural self sufficiency	Agricultural production index	Aggregate index	WB
Natural resources and ecosystems (ECO)	Environmental stress	Protected land area	%	
	Environmental stress	Forest change rate	% per year	GRID
	Environmental stress	Percent forest cover	%	GRID
	Environmental stress	Unpopulated land area	%	CIESIN
	Sustainability of water resources	Groundwater recharge per capita	m^3 per person	GRID
	Sustainability of water resources	Water resources per capita	m^3 per person	GRID
Technical capacity (TECH)	Commitment to and resources for research	R&D investment	% GNP	WB
	Capacity to undertake research and understand issues	Scientists and engineers in R&D	Number per million population	WB

Data sources: the World Bank (WB); Human Development Index (HDI); UNEP/GRID-Geneva (GRID); Kaufmann, Kray and Zoido-Lobaton governance dataset (KKZ);Freedom House (FH); Center for International Earth Sciences Information Network (CIESIN) at Columbia University; United Nations World Income Inequality Database (WIID).

10.2 Climate Change and Territorial Effects on Regions and Local Economies -Indicators (ESPON Climate, 2011)

Indicators			Measurement
Exposure Indicators	Direct climate events	Change in annual mean temperature	Average annual air temperature 2 m above surface
		Change in annual mean number of frost days	Average annual number of days with minimum temperatures below 0°C
		Change in annual mean number of summer days	Average annual number of days with maximum temperatures above 25°C
		Change in annual mean winter precipitation	Relative change in annual mean precipitation in December, January, February
		Change in annual mean summer precipitation	Relative change in annual mean precipitation in June, July, August
		Change in annual mean number of heavy rainfall days	Average annual number of days with heavy rainfall (above 20 kg/m^2 or 20 mm/m^2)
		Change in annual mean evaporation	Relative change in annual mean evaporation
		Change in annual mean number of days with snow cover	Average annual number of days with snow covering the surface of the reference area
	Triggered climate effects	Change in occurrence of river flooding	Changes in inundation heights of a 100 year return flood event
		Change in occurrence of coastal flooding	Changes in inundation heights of a 100 year return storm surge event (with 1 meter sea-level rise)
Sensitivity Indicators	Physical sensitivity	Settlements sensitive to flash floods	Multiple: topography, soil, inundation, size, area, population, etc.
		Roads and railways sensitive to flash floods	Multiple: topography, soil, inundation, size, area, population, etc.
		Settlements sensitive to river flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Roads and railways sensitive to river flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Airports and harbours sensitive to river flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Thermal power plants and refineries sensitive to river flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Settlements sensitive to coastal flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Roads and railways sensitive to coastal flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Airports and harbours sensitive to coastal flooding	Multiple: topography, soil, inundation, size, area, population, etc.
		Thermal power plants and refineries sensitive to coastal flooding	Multiple: topography, soil, inundation, size, area, population, etc.
	Environmental sensitivity	Forests sensitive to forest fires	Multiple: number, size and ratio of forest fires and forest areas
		Protected natural areas	Multiple: size and ratio of NATURA 2000 areas
		Areas prone to soil erosion	Multiple: slope steepness, land cover, and soil characteristics
		Soil organic carbon	Calculated form multiple databases: land cover, climate, topography
	Social sensitivity	Population sensitive to summer heat	Multiple: number and % of people over 65 in high density urban areas, based on land cover, settlement size, and population density
		Population sensitive to coastal flooding	Multiple: number and % of people living in settlements sensitive to coastal flooding
		Population sensitive to river flooding	Multiple: number and % of people living in settlements sensitive to river flooding
		Population sensitive to flash floods	Multiple: number and % of people living in settlements sensitive to flash floods
	Cultural sensitivity	UNESCO Cultural World Heritage Sites sensitive to river flooding	Multiple: UNESCO sites exposed to river flooding (absolute & relative)
		UNESCO Cultural World Heritage Sites sensitive to coastal flooding	Multiple: UNESCO sites exposed to coastal flooding (absolute & relative)
		Museums sensitive to river flooding	Multiple: Museums and museum area exposed to river

Indicators			Measurement
			flooding (absolute & relative)
		Museums sensitive to coastal flooding	Multiple: Museums and museum area exposed to coastal flooding (absolute & relative)
	Economic sensitivity*	Agriculture sensitive to water availability	Average: % sectoral employment, & % of Gross Value Added (GVA)
		Forestry sensitive to water availability	Average: % sectoral employment, & % of Gross Value Added (GVA)
		Summer tourism sensitive to summer temperatures	Tourism Comfort Index (TCI)
		Winter tourism sensitive to snow cover changes	Number of beds in regions with 100 days of snow cover annually.
		Energy demand sensitive to summer heat	Multiple: summer days (days with temperature over 25°C), population, primary sector sensitivity to climatic change
		Energy demand sensitive to winter frost	Number of frost days (days with temperature below 0°C)
		Energy supply sensitive to changing river water levels	Multiple: decrease in precipitation, increase in summer days, exposure to river and coastal flooding
Adaptive capacity Indicators	Aware-ness	Knowledge and awareness	Education expenditure per capita within a region.
			Percentage of people who have never used a computer.
			Eurobarometer question (surveyed in 2008) related to attitudes in regards to the perceived seriousness of climate change.
	Ability	Technology	Percentage of GDP in R&D investment.
			Number of scientists and engineers in R&D per million labour force.
			Number of patent applications per million inhabitants.
		Infrastructure	Density of road networks measured as kilometres of road per surface area of a region.
			EEA water exploitation index (WEI) - mean annual total abstraction of freshwater divided by mean annual total renewable freshwater resource.
			Number of hospital beds per 100 000 inhabitants.
	Action	Institutions	Data on government effectiveness from the World Bank.
			Concerns, recommendations and measures - countries are ranked and classified into quintiles on each category - the indicator value is formed as the mean of these values.
			Female participation in political life, using the gender weighted democratisation index.
		Economic resources	GDP per capita (€ PPP) of a region.
			The old-age dependency ratio - the ratio of elderly persons (65+) divided by working age persons (15-64).
			Unemployment rates, or long-term rates. Unclear in text.
Mitigative Capacity Indicators	Aware-ness	Knowledge and awareness	Education expenditure per capita within a region.
			Eurobarometer question (surveyed in 2008) related to attitudes in regards to the perceived seriousness of climate change.
	Ability	Technology	Percentage of GDP in R&D investment.
			Number of patent applications per million inhabitants.
		Infrastructure	Data on "PV output" and "wind energy potential" for European regions.
			Carbon sinks - estimated amount of GHG absorbed (GWP) at national level.
	Action	Institutions	Data on government effectiveness from the World Bank.
			Number of environmental policy instruments in use in the region.
			Female participation in political life, using the gender weighted democratisation index.
		Economic resources	GDP per capita (€ PPP) of a region.
			The old-age dependency ratio - the ratio of elderly persons (65+) divided by working age persons (15-64).
			Unemployment rates, or long-term rates. Unclear in text.

10.3 RESPONSES Project: "Report on potential impacts of climatic change on regional development and infrastructure" (Lung et al., 2011)

Indicator	Parameter	Name	Description
Exposure	Heat	HE_T2MAX25	Number of summer days with Tmax > 25°C in summer period (June, July, August)
		HE_T2MIN20	Number of tropical nights with Tmin > 20°C in summer period (June, July, August)
		HE_HWDI	Number of 7-day heat wave events in summer period (June, July, August)
	Floods	FE_AREA	Percentage of flooded area, recurrence interval of a 100-year event flood
		FE_DPTH	Mean water depth (in m) of flooded area, recurrence interval of a 100-year event flood
	Drought	DE_CDDMAX	Maximum number of consecutive days per year with daily precipitation < 1 mm
		DE_PRECgr	Growing season precipitation (March to August)
		DE_ARID	Aridity Index (ratio of precipitation to potential evaporation) , annual mean
	Forest Fire	FFE_CDDMAX	Greatest number of consecutive days per year with daily precipitation < 1 mm
		FFE_T2MEAN	Mean of daily mean summer temperature (June, July, August)
		FFE_PRECsu	Summer precipitation (June, July, August)
Sensitivity	Heat	HS_POP75	Percentage of elderly people > 75 years
		HS_HH65	Percentage of households composed of one adult > 65
		HS_POPD	Population density
	Floods	FS_POPD	Population density within areas affected by 100-year recurrence interval flood
		FS_COM	Percentage of commercial & industrial areas affected by 100-year recurrence interval food
	Drought	DS_AGRI	Percentage of agricultural area (CLC classes 211, 221, 222, 223, 241, 242 and 244)
		DS_EMPL	Percentage of employment in primary sector
		DS_SOIL	Topsoil available water capacity
	Forest Fire	FFS_WILDL	Percentage of wildland (CLC classes 311, 312, 313, 321, 323, 324)
		FFS_COMBU	Mean fuel type combustibility
		FFS_ACCESS	Wildland accessibility by roads (functional road classes 1 to 6)
Adaptive Capacity	Financial Capital	AC_PPS	Gross domestic product GDP [in purchasing power standard, PPS per capita], 2007
	Human capital	AC_EDU	Educational attainment (people aged 25-64 with tertiary education, ISCED L5-6), 2008
		AC_DOC	Health infrastructure (physicians/doctors per capita), 2007
	Technological capital	AC_R&D	Research & development expenditure per capita (business, government, education, non-profit), 2007
		AC_INET	Internet use (percentage of people with internet use from home at least once per week), 2010

10.4 Climate-Friendly Cities: A Handbook on the Tracks and Possibilities of European Cities in Relation to Climate Change (VÁTI, 2011)

Reference Chapter	Indicator	Units
Consequences of climate change in European regions	Annual winter and summer medium temperature and its changes	°C
	Annual winter and summer rainfall quantity and its changes	mm
	Change in the number of drought days	day
	Change in the number of freezing days	day
	Annual number of extreme rainfall events	case/annum
	Change of the groundwater level	cm
	Annual number of days with snow cover	day
	Frequency of showers	case/annum
	Frequency of hail	case/annum
	Highest absolute temperature of the year	°C
	Lowest absolute temperature of the year	°C
	Largest annual amount of rainfall	mm
	Smallest annual amount of rainfall	mm
	Highest amount of rainfall in 24 hours	mm
	Highest amount of rainfall in 60 minutes	mm
	Strongest blast of wind	m/s
	Annual number of snowy days	day
	Highest daily minimum temperature	°C
	Highest daily average wind speed	m/s
Climate-friendly urban governance for forming economic and other urban policies	Memberships in climate-aware networks and organisations	piece
	Number of climate-aware legislation and policy initiations	piece/annum
	Rate of green (climate-aware) public procurement actions	%
	Rate of public companies run by the city having climate-aware business policy	%
	Rate of divisions at the municipality having climate protection and adaptation tasks officially	%
	The total number of partners (individuals and organisations) in climate partnership initiations	piece
	Rate of local enterprises and firms taking part in climate partnership initiations	%
Integrated strategic planning for climate-friendly cities	Aims towards climate protection or climate adaptation at high decision making levels (policy level)	yes/no
	Rate of city plans and programmes incorporating principles on climate protection and adaptation to climate change	%
	Rate of strategic environmental assessments of the city's planning processes integrating the issue of climate change	%
	Number of involved partners (individuals and organisations) into climate planning actions	piece
Climate friendly urban structure	Housing density	person/ha
	Height of buildings	floor
	The number of days on which in a three-year period (on rolling average) per annum measures had to be ordered concerning the information grade of the smog alert or the rate of alert.	day
	The size of covered/built in (biologically inactive) surfaces of the green areas compares to the total green area	%
	Change of the quantity of green areas (biologically active) in the past 5 (-10) years	%
	The size of green roofs	m^2
	The size of protected nature areas of local interest	ha
	Registered, protected species	piece
	The share of green areas and nature protection areas in the vicinity of larger than 500m	%
	The amount of costs spent on the maintenance of protected nature areas of local interest	currency
	Number of parking lots established in order to improve access to nature protection areas	piece
	Forest density of the settlements	%
	Share of protected forests	%

Reference Chapter	Indicator	Units
	Area of public parks	ha
	Number of public parks	piece
	Total size of community parks and public spaces	ha
	Total size of green surface of public purpose	ha
	Green area per person	m^2/capita
	Aggregated green area cover of the settlement	%
	Share of domestic plants in public parks	%
	Share of strongly allergic plants in public parks	%
	Share of plants damaged from health point of view	%
	Total number or park objects	piece
	Number of park object service relaxation (benches, wells, lighting, waste bins) in public green areas	piece
	Number of playgrounds in public green areas	piece
	Number of sports facilities (sports courts, table tennis and chess tables, etc.) in public green areas	piece
	Visitors in public green areas	person
	Share of damaged plants as the result of vandalism	%
	Share of damaged park objects as the result of vandalism	%
	Number of venues held in public green areas in the vegetation period	case
	Change of the real values of amounts spent on the treatment of green areas	currency
	Number of persons participating in the maintenance/protection works of green areas	person
	Labour force expenditure falling on one unit of green area	work hour/m^2
	Size of areas drawn out of cultivation	ha
	Share of areas drawn out of cultivation	%
	Balance of land use	ha
	Functional distribution of forest area	%
	Composition of forests by tree species	%
	Share of the trees, which are losing their leaves in the forest	%
	Number of park objects in the forest	piece
	Number of reported damaged caused by wild animals	case
	Number of reported damage caused by storms	case
	Number of reported forest fires	case
	Number of surveyed brown field areas	piece
	Size of surveyed brown field areas	ha
	Number of surveyed areas to be mitigated separately in brown field areas in the landscape wounds	piece
	Size of surveyed areas to be mitigated separately in brown field areas in the landscape wounds	ha
	Number of mitigated areas separately in brown field areas and landscape wounds	piece
	Size of areas mitigated from damages separately in brown field areas in the landscape wounds	ha
	Visitors in the forests	person
	Size of green areas established on brown field areas	ha
	Share of utilised brown field areas	%
	Number of constructed sports fields	piece
	Length of constructed running tracks	km
	Number and share of local, landscape-specified products with trade mark	piece, %
	Number of heritage inventories of the settlement	piece
	Number of historical monuments under local protection	piece
	Number of buildings proposed for local protection	piece
	Number of world heritage area	piece
	Size of world heritage area	ha
	The amount spent on an annual basis for refurbishment and condition maintenance of protected buildings being managed by the settlement itself	currency
	The amount of funding intended to be spent by the town for the refurbishment of locally protected buildings	currency
	Quantity of waste collected from green areas	ton
Climate friendly urban transport	The number of hourly exceedances of the limit value (100 μg/m^3) of nitrogen-dioxide pollution	piece
	The annual average concentration of PM10 (flowing dust with the diameter of 10	μg/m^3

Reference Chapter	Indicator	Units
	micrometre)	
	The number of 24-hour exceedances of the limit value (100 μg/m^3) of nitrogen-dioxide pollution	case
	Pollution by fine flowing dust (PM2.5)	μg/m^3
	Bicycle and pedestrian traffic in proportion of the local traffic	%
	Costs spent on the reduction of air pollution currency	currency
	Number of vehicles	piece
	Share of bio-fuel utilised for transportation purposes	%
	The distribution of passenger transportation	%
	Greenhouse gas emission of transportation	ton CO_2 eq.
Low carbon energy management of the settlement	The total amount of sold electrical energy; of this separately to the households	TWh
	Total gas sales of this separately to households	PJ
	Gas consumption per household costumers	GJ/household
	Greenhouse gas inventory of towns (CO_2, CH_4, N_2O emission and consolidation)	Mton CO_2 eq.
	Electricity production generated from primary energy carriers (e.g. agricultural products)	ton
	Primary energy generated from renewable energy source	ton oil eq.
	The formation of the utilisation of renewable energy carriers	%
	Share of renewable energy in electricity generation	%
	Emission of greenhouse gases	ton CO_2 eq.
Climate friendly architectural solution	The sustainable heat energy demand of one apartment	kWh/m^2 annum
	The sustainable electrical energy demand of one apartment	kWh/day
	Quantity of generated waste	l/capita
	Size of greening on facades	m
	Household water consumption/annum	m^3
	The share of dwellings with public sewerage	%
	District heating provided for households	PJ
	Average electricity consumption per household consumer	MWh/household
	Average district heating consumption per household consumer	GJ/household
	Number of municipality institutions holding energy audit	U
	Temperature indicators of the heat island effect of the settlement	-
	Number of dwellings built	piece
	Share of dwellings built newly	%
	Share of the re-utilised construction waste	%
Adaptable water management and urban communal infrastructure	Drinking water demand	l/capita
	Rainwater demand	l/capita
	Proportion of selective waste collection	%
	Waste transported to landfills	ton/annum
	Valuation of under surface waters in compliance with the Directive of the Water Framework	-
	Valuation of surface waters in compliance with the Directive of the Water Framework	-
	Number of drinking water wells	piece
	Distribution of water generating plant by water source	-
	Length of drinking public water network	km
	Drinking water production	m^3
	Quantity of provided water	m^3
	Total water consumption	m^3
	Length of public sewerage network	km
	Collected wastewater and rainwater	m^3
	The distribution of the treatment of collected water quantity among the wastewater treatment plants	m^3
	The share of biological and tertiary wastewater treatment	%
	Length of unified system of rainwater collection	km
	Length of separated system of rainwater collection	km
	Other rainwater collection solutions (thickening)	number of dwellings
	Open-trench rainwater collecting system	km
	Length of ditch system and small water flows	km
	The proportion of area keeping the rainwater on sport with surface drainage	%
	Existence of the quality control system of rainwater	-

Reference Chapter	Indicator	Units
	Application of rainwater utilisation systems	-
	Urban solid waste per capita	kg/capita
	Share of solid waste collected selectively	%
	Share of urban solid waste put in landfills	%
	Share of urban solid waste incinerated	%
	Share of the utilisation in the material of green and bio-waste	%
	Share of the utilisation of wastewater sludge	%
	Number of waste yards piece	piece
	Number of selective waste collection points	piece
	Surface and under-surface water abstraction	m^3/annum
	Share of people are connected to sewerage systems	%
	Share of the population living in areas provided with natural type of wastewater treatment	%
Preparing for disaster management and health care	Healthy life years and life expectancy at age 35, by type of settlement	year
	Number of bronchitis sicknesses	piece
	Healthy life years and life expectancy at birth	year
	Share of children struggling with chronic bronchitis and asthma illnesses	%
	Change of the air hygienic index, Number of days of 3rd and 4th grade	day
	Allergic species in public spaces covered with plants	piece/m^2
	The annual total pollen concentration of weeds	piece/m^3
	Monthly change of the total pollen concentration	piece/m^3
	Annual number of days with concentration of 30 pollen grade/m^3	day
	NO_2 pollution along bicycle roads	µg/m^3
	The quantity parameters of drinking water targeted for human use	mg/l
	The number of exceedances of limit values specified in the legal regulation in case of the individual pollutants	case
	Number of heat waves	day
	Number of heat days	day
	Number of additional deaths as the result of the heat waves	case
	Number of days of UV alarm	day
	Number of deaths due to freezing	case
	Number of deaths due to melanoma	case
	Number of detected and reported new melanoma cases per 10000 inhabitants	case
	The risk of the population by the atmosphere solid material emission	µg/m^3
	The risk of the population by ozone emission	µg/m^3
	Ageing index (60-x years/0-14 years)	%
	Number of health service centres operating at the settlements	piece
	Number of persons participating at training preparing for emergency situations (heat wave, flood)	person
	Existence of forecast or rioting system concerning emergency situations (storm surge, flood, heat wave)	yes/no
Creation of climate-conscious attitude and lifestyle	Number of visitors in environment protection areas	person
	Number of awareness and scientific dissemination programmes	piece
	Number of participants at awareness and scientific dissemination programmes	person
	Number of inhabitants achieved by shaping social attitudes of environment	1000 person
	Number of students at ecological schools	1000 person
	Number of employees participating in environment protection training in Mayor's offices and municipality institutions	person
Supporting deprived groups in adapting to climate change	Average number of persons per dwelling	capita
	Number of disabled people	person
	Share of persons receiving social support	%
	Share of persons living in poverty	%
	Funding provided for deprived groups for energy efficiency and construction	currency
	Migration balance	person
Economic effects and the enhancement of urban economy	Flood control costs	currency
	Extent of flooded area	ha
	Frequency of forest fires in the urban and suburban areas	piece/year
	Irrigation costs of the public parks, urban green areas	currency
	Changes in the average heating costs	currency
	Changes in the real estate prices	currency

Reference Chapter	Indicator	Units
	Ratio of products sold locally	%
	Amount of recycled waste	m^3
	Cost of road reconstruction	currency
	The number of factories producing alternative energy in the city	piece
	Number of factories producing environmentally friendly products	piece
	Number of factories applying green technology	piece
	Ratio of operating environmentally friendly enterprises	%
	The number of public workers at building renovations	person
	The city's environmental tax revenues	currency
	Public money spent on environmental protection	currency
	Changes in the length of tourist season	day
	The change in the number of guest nights spent in the city	piece
	Changes in tourism tax revenues	currency

10.5 Climate change, impacts and vulnerability in Europe 2012 - An indicator-based report (EEA, 2012b)

Changes in the climate system		
	Key climate variables	Global temperature
		European temperature
		Precipitation
		Storms
	Cryosphere	Snow cover
		Greenland ice sheet
		Glaciers
		Permafrost
		Arctic and Baltic Sea ice
Climate impacts on environmental systems		
	Oceans and marine environment	Ocean acidification
		Ocean heat content
		Sea surface temperature
		Phenology of marine species
		Distribution of marine species
	Coastal zones	Global and European sea-level rise
		Storm surges
		Coastal erosion
	Freshwater quantity and quality	River flow
		River floods
		River flow drought
		Water temperature
		Lake and river ice cover
		Freshwater ecosystems and water quality
	Terrestrial ecosystems and biodiversity	Plant and fungi phenology
		Animal phenology
		Distribution of plant species
		Distribution and abundance of animal species
	Soil	Soil organic carbon
		Soil erosion
		Soil moisture
Climate impacts on socio-economic systems and human health		
	Agriculture	Growing season for agricultural crops
		Agrophenology
		Water-limited crop productivity
		Irrigation water requirement
	Forests and forestry	Forest growth
		Forest fires
		Fisheries and aquaculture
	Human health	Floods and health
		Extreme temperatures and health
		Air pollution by ozone and health
		Vector-borne diseases
		Water- and foodborne diseases
	Energy	Heating degree days
	Transport	Land-based and water-based transport infrastructure and operation
	Tourism	Climatic suitability for general tourism activities

10.6 Guidelines for Project Managers: Making vulnerable investments climate resilient (EC, 2013a)

Themes, Indicators, and Risk Areas		
Assessment Themes	On-site assets and processes	
	Inputs (water, energy, others)	
	Outputs (products, markets, customer demand)	
	Transport links	
Sensitivity and Exposure	Primary climate drivers	Annual / seasonal / monthly average (air) temperature
		Extreme (air) temperature (frequency and magnitude)
		Annual / seasonal / monthly average rainfall
		Extreme rainfall (frequency and magnitude)
		Average wind speed
		Maximum wind speed
		Humidity
		Solar radiation
	Secondary effects/ climate-related hazards	Sea level rise (SLR) (plus local land movements)
		Sea/ water temperatures
		Water availability
		Storm (tracks and intensity) including storm surge
		Flood
		Ocean pH
		Dust storms
		Coastal erosion
		Soil erosion
		Soil salinity
		Wild fire
		Air quality
		Ground instability/ landslides/ avalanche
		Urban heat island effect
		Growing season length
Risk Areas	Asset damage/ Engineering/ Operational	
	Safety and Health	
	Environment	
	Social	
	Financial (single extreme event or annual average impact)	

10.7 The ResilUS Resilience Framework: Types of capital and variables (Miles and Chang, 2008)

Capital Type	Variable	Description
Physical Capital	BYR	Year building or lifeline component built.
	BL	Ratio of resources (materials, labor etc.) expended in reconstruction to building replacement value. Alternatively, percent to which reconstruction is complete. 0 to 1, with 1 being reconstructed.
	CRIT	Probability that critical facilities network component service is fully restored.
	CYR	year seismic (or other building) code effective
	DMG	Damage of building or lifeline component expressed as ratio of building replacement value.
	ELEC	Probability that electrical network component service is fully restored.
	FACILITY	Service level of a business's facility. 0 to 1, with 1 indicating operation at pre-event service level.
	MAINT	Probability that component has been well-maintained.
	MIT	Pre-event structural mitigation of building or lifeline component. Currently 1 (maximum) indicates a 25% increase is fragility curve median.
	SHEL	Probability that household has adequate shelter and associated services.
	STH	Probability that short-term housing is available, Y/N.
	TRNS	Probability transportation network component service is fully restored.
	TYPE	Type of building or lifeline component—a proxy for size and/or complexity for reconstruction. 0 to 1, with 1 indicating largest or most complex.
	WAT	Probability that water network component service is fully restored.
	WAT_ALT	Provision for alternate water sources (water trucks) for neighborhood. 0 to 1, with 1 being equivalent to maximum total water service in neighborhood (WATn=1)
Economic Capital	AID	Normalized post-event grant amount.
	DEBT	Normalized level of debt. The inverse of LOAN.
	DEMAND	Post-event demand for product. 0 to 1, with 1 indicating pre-event demand level.
	EMPL	Probability that employment is available.
	FAIL	Occurrence of business failure (Y(1)/N(0))
	INC	Normalized annual income.
	INS	Whether or not an agent has insurance.
	LOAN	Normalized amount of reconstruction loan taken out. Implicitly related with DMG (ratio of building replacement value).
	LOAN_MAX	Limit on post-event loan amount.
	MARG	Pre-event financial marginality.
	OUTLAY	Whether or not an agent has received an insurance payment. 1 is implicitly defined as the replacement value of their building.
	PROD	Probability that business is at pre-event production level.
	SAVINGS	Normalized savings or assets.
	SECT	Type of business sector (0:local or 1:export).
	SIZE	Normalized number of employees.
Socio-Cultural Capital	CAP	Recovery capacity of community (proxy for integration and consensus). 0 to 1, with 1 being highest capacity.
	CONSTR	Probability that necessary construction resources available for restoration.

Capital Type	Variable	Description
	INSP	Time in weeks after event that safety inspections are completed.
	MUT	Provision for mutual aid in lifeline restoration. 0 to 1, with 1 equal to maximum construction resources without mutual aid (i.,e., MUT can at most double construction resources)
	PLAN	Probability of an effective restoration plan.
	PRTY	An absolute score given at the neighborhood level, indicating priority. The score can range from NBRHD (number of neighborhoods) to 1, with higher numbers indicating higher priority.
Personal Capital	HEALTH	Probability that household is healthy
	INJURY	Probability that household health or business demand has been injured.
	LEAVE	Whether or not household has left region.
Ecological Capital	HAZ	Severity of earthquake's (or hazard event) physical effects. 0 to 10, Conceptually equivalent to ShakeMap intensity/MMI

10.8 Urban Audit indicators (Eurostat, 2004)

Urban Audit Indicators					
Demography (DE)					
Population (DE1)	Variables				
	Code	Variable			Spatial Unit
	DE1001-3V	Number of resident population - total/male/female			A,L,S
	DE1040V-DE1057V	Number resident population - total male and female and in age groups 0-4*, 5-14, 15-19, 20-24, 25-54, 55-64, 65-74, 75 and over			A,L
	*also for Sub-Districts				
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	DE1001I	Total resident population	DE1001V	-	A,L,S
	DE1011I	Total population of working age	DE1046V + DE1049V + DE1052V + DE1025V	-	A,L
	DE1040I	Proportion of total population aged 0-4	DE1040V	DE1001V	A,L,S
	DE1043-55I	Proportion of total population in age groups 5-14, 15-19, 20-24, 25-54, 55-64, 65-74 and 75 and over	DE1043-55V	DE1001V	A,L
	DE1003I	Proportion of females to males in total population	DE1003V	DE1002V	A,L,S
	DE1057I	Proportion of females to males – aged 75 and over	DE1057V	DE1056V	A,L
	DE1061I	Total population change over 1 year	DE1001V (t)	DE1001V (t-1)	A,L,S
	DE1062I	Total annual population change over 5 years	DE1001V (t)	nSQR (DE1001V) (t-n)	A,L,S
	DE1058I	Demographic dependency: (<20 + >65) / 20-64 years	DE1040V + DE1043V + DE1046V + DE1028V + DE1055V	DE1049V + DE1052V + DE1025V	A,L
	DE1059I	Demographic young age dependency: <20 / 20-64 years	DE1040V + DE1043V + DE1046V	DE1049V + DE1052V + DE1025V	A,L
	DE1060I	Demographic old age dependency: > 65 / 20-64 years	DE1028V + DE1055V	DE1049V + DE1052V + DE1025V	A,L
Nationality (DE2)	Variables				
	Code	Variable			Spatial Unit
	DE2001V	Number of residents who are nationals			A,L
	DE2002V	Number of residents who are nationals of another EU Member State			A,L
	DE2003V	Number of residents who are not EU nationals			A,L
	DE2004V	Number of nationals born abroad			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	DE2001I	Nationals as a proportion of the total population	DE2001V	DE1001V	A,L
	DE2002I	EU nationals as a proportion of the total population	DE2002V	DE1001V	A,L
	DE2003I	Non-EU nationals as a proportion of the total population	DE2003V	DE1001V	A,L
	DE2004I	Nationals born abroad as a proportion of total population	DE2004V	DE1001V	A,L
ld Stru ctur e	Variables				
	Code	Variable			Spatial

Urban Audit Indicators					
					Unit
	DE3001V	Total number of households			A,L,S
	DE3002V	Lone-person households (total number)			A,L,S
	DE3005-7V	Lone-parent households – total/male*/female* number			A,L,S
	DE3008-10V	Lone-pensioner (above retirement age) households - total/male*/female*			A,L,S
	DE3011V	Households with children aged 0 to under 18			A,L
	DE3012V	Nationals that have moved into the city during the last two years			A
	DE3013V	EU nationals that have moved into the city during the last two years			A
	DE3014V	Non-EU nationals that have moved into the city during the last two years			A
	*only A, L				
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	DE3003I	Total number of households	DE3001V	-	A,L,S
	DE3001I	Average size of households	DE1001V	DE3001V	A,L,S
	DE3002I	Proportion of households that are lone-person households	DE3002V	DE3001V	A,L,S
	DE3005I	Proportion of households that are lone-parent households	DE3005V	DE3001V	A,L,S
	DE3006I	Lone-parent households: male/female	DE3006V	DE3007V	A,L
	DE3008I	Proportion households that are lone-pensioner households	DE3008V	DE3001V	A,L,S
	DE3009I	Lone-pensioner households: male/female	DE3009V	DE3010V	A,L
	DE3011I	Proportion of households with children aged 0-17	DE3011V	DE3001V	A,L
	DE3012I	Nationals that have moved to the city over the last 2 yrs as a proportion of the population	DE3012V	DE1001V	A
	DE3013I	EU nationals that have moved to the city over last 2 yrs as a proportion of the population	DE3013V	DE1001V	A
	DE3014I	Non-EU nationals that have moved to the city over the last 2 yrs as a proportion of the population	DE3014V	DE1001V	A
Social Aspects (SA)					
Housing (SA1)	Variables				
	Code	Variable			Spatial Unit
	SA1001V	Number of dwellings			A,L,S
	SA1004-5V	Number of houses – apartments			A,L
	SA1007-8V	Number of households living in houses – apartments			A,L
	SA1011V	Households owning their own dwelling			A,L
	SA1012V	Households in social housing			A,L,S
	SA1013V	Households in private rented housing			A,L
	SA1015V	Number of homeless persons			A
	SA1016V	Average price for an apartment per m2 in Euro			A,L
	SA1023V	Average price for a house per m2 in Euro			A,L
	SA1017V	Annual rent for social housing per m2 in Euro			A,L
	SA1021V	Average annual rent for an apartment per m2 in Euro			A,L
	SA1024V	Average annual rent for a house per m2 in Euro			A,L
	SA1018V	Dwellings lacking basic amenities			A,L,S
	SA1019V	Average occupancy per occupied dwelling			A,L
	SA1025V	Empty conventional dwellings			A,L
	SA1026V	Non-conventional dwellings			A,L
	SA1022V	Average area of living accommodation (m2 per person)			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	SA1001I	Number of dwellings	SA1001V	-	A,L,S
	SA1015I	Number of homeless people / total resident population	SA1015V	DE1001V	A
	SA1016I	Average price per m_2 for an apartment	SA1016V	-	A,L

Urban Audit Indicators					
	SA1023I	Average price per m^2 for a house	SA1023V	-	A,L
	SA1036I	Average price per m^2 for apartment / median household income	SA1016V	EC3039V	A,L
	SA1021I	Average annual rent for an apartment per m^2	SA1021V	-	A,L
	SA1024I	Average annual rent for a house per m^2	SA1024V	-	A,L
	SA1037I	Ratio of average price to average rent for an apartment	SA1016V	SA1021V	A,L
	SA1038I	Ratio of average price to average rent for a house	SA1023V	SA1024V	A,L
	SA1017I	Average annual social housing rents per m^2	SA1017V	-	A,L
	SA1039I	Average social housing rents to median household income	SA1017V	EC3039V	A,L
	SA1018I	Proportion of dwellings lacking basic amenities	SA1018V	SA1001V	A,L,S
	SA1011I	Proportion of households living in owned dwellings	SA1011V	DE3001V	A,L
	SA1012I	Proportion of households living in social housing	SA1012V	DE3001V	A,L,S
	SA1013I	Proportion of households living in private rented housing	SA1013V	DE3001V	A,L
	SA1007I	Proportion of households living in houses	SA1007V	DE3001V	A,L
	SA1008I	Proportion of households living in apartments	SA1008V	DE3001V	A,L
	SA1026I	Proportion of non-conventional dwellings	SA1026V	SA1001V	A,L
	SA1019I	Average occupancy per occupied dwelling	SA1019V	-	A,L
	SA1022I	Average living area in m^2 per person	SA1022V	-	A,L
	SA1025I	Empty conventional dwellings per total dwellings	SA1025V	SA1001V	A,L
Health (SA2)	Variables				
	Code	Variable			Spatial Unit
	SA2001-3V	Life expectancy at birth – total/male/female (in years)			A,L
	SA2004-6V	Infant mortality per year – total/male/female			A,L
	SA2007-9V	Number of live births per year - total/male/female			A,L
	SA2013-15V	Number of deaths per year under 65 due to heart diseases and respiratory illness – total/male/female			A,L
	SA2016-18V	Total deaths under 65 per year – total/male*/female*			A,L,S
	SA2019-21V	Total deaths per year – total/male*/female*			A,L,S
	SA2022V	Number of hospital beds			A,L
	SA2025V	Number of hospital patients			A,L
	SA2023V	Number of doctors (FTE)			A,L
	SA2024V	Number of dentists (FTE)			A,L
	* only A, L				
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	SA2001I	Life expectancy at birth for males and females	SA2001V	-	A,L
	SA2013I	Mortality rate for <65 from heart diseases and respiratory illness	SA2013V	DE1040V + DE1043V + DE1046V + DE1049V + DE1052V + DE1025V	A,L
	SA2014I	Mortality rate males <65 from heart diseases and respiratory illness	SA2014V	DE1041V + DE1044V + DE1047V + DE1050V + DE1053V + DE1026V	A,L
	SA2015I	Mortality rate females <65 from heart diseases and respiratory illness	SA2015V	DE1042V + DE1045V + DE1048V + DE1051V + DE1054V +	A,L

Urban Audit Indicators					
				DE1027V	
	SA2022I	Number of hospital beds per 1000 residents	SA2022V* 1000	DE1001V	A,L
	SA2023I	Number of doctors per 1000 residents	SA2023V* 1000	DE1001V	A,L
	SA2024I	Number of dentists per 1000 residents	SA2024V* 1000	DE1001V	A,L
Crime (SA3)	Variables				
	Code	Variable			Spatial Unit
	SA3001V	Total number of recorded crimes within city [country for national data]			A,L,S
	SA3005V	Number of murders and violent deaths			A,L
	SA3006V	Number of car thefts			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	SA3001I	Number of recorded crimes per 1000 population	SA3001V* 1000	DE1001V	A,L,S
	SA3005I	Number of murders and violent deaths per 1000 population	SA3005V* 1000	DE1001V	A,L
	SA3006I	Number of car thefts per 1000 population	SA3006V* 1000	DE1001V	A,L
Economic Aspects (EC)					
Labour Market (EC1)	Variables				
	Code	Variable			Spatial Unit
	EC1001-3V	Economically active population - total/male/female			A,L,S
	EC1142-44V	Economically active population 15-24 - total/male/female			A,L,S
	EC1145-47V	Economically active population 55-64 - total/male/female			A,L
	EC1010-12V	Residents unemployed - total/male*/female*			A,L,S
	EC1148-50V	Residents unemployed 15-24 - total/male*/female*			A,L,S
	EC1151-53V	Residents unemployed 55-64 - total/male/female			A,L
	EC1154-56V	Unemployed continuously for more than six months, 15-24 - total/male/female			A,L
	EC1157-59V	Unemployed continuously for more than one year, 55-64 - total/male/female			A,L
	EC1025-27V	Residents in self employment - total/male/female			A
	EC1028-30V	Residents in paid employment - total/male/female			A
	EC1034-36V	Full-time employment - total/male/female			A
	EC1088-90V	Part-time employment - total/male/female			A
	EC1160-62V	Full-time employment 15-24 - total/male/female			A
	EC1163-65V	Full-time employment 55-64 - total/male/female			A
	EC1166-68V	Part-time employment 15-24 - total/male/female			A
	EC1169-71V	Part-time employment 55-64 - total/male/female			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EC1201I	Annual average change in employment over 5 years	EC1001V(t) - EC1001V(t-n)	nSQR (EC1001V - C1001V)(t-n)	A,L,S
	EC1010I	Number of unemployed	EC1010V	-	A,L,S
	EC1020I	Unemployment rate	EC1010V	EC1001V	A,L,S
	EC1011I	Unemployment rate – male	EC1011V	EC1002V	A,L
	EC1012I	Unemployment rate – female	EC1012V	EC1003V	A,L
	EC1148-53I	Proportion of residents unemployed in age groups 15-24, 55-54 – total male*/female*	EC1148-53V	EC1142-47V	A,L,S
	EC1154-56I	Proportion of long term unemployed (>6 months) aged 15-24 - total* male*/female*	EC1154-56V	EC1148-50V	A,L
	EC1157-59I	Proportion of long term unemployed (>1 year) aged 55- 64 - total* male*/female*	EC1157-59V	EC1151-53V	A,L
	EC1202I	Proportion of unemployed under 25	EC1148V	EC1010V	A,L,S
	EC1034I	Ratio of employment to population of working age	EC1034V + EC1088V	DE1046V + DE1049V +	A

Urban Audit Indicators					
				DE1052V + DE1025V	
	EC1035I	Ratio of employment to population of working age – male	EC1035V + EC1089V	DE1047V + DE1050V + DE1053V + DE1026V	A
	EC1036I	Ratio of employment to population of working age – female	EC1036V + EC1090V	DE1048V + DE1051V + DE1054V + DE1027V	A
	EC1025-27I	Self-employment rate (residents) – total/male/female	EC1025- 27V	EC1001V	A
	EC1001I	Activity rate	EC1001V	DE1046V + DE1049V + DE1052V + DE1025V	A,L
	EC1002I	Activity rate – male	EC1002V	DE1047V + DE1050V + DE1053V + DE1026V	A,L
	EC1003I	Activity rate – female	EC1003V	DE1048V + DE1051V + DE1054V + DE1027V	A,L
	EC1142I	Activity rate 15-24	EC1142V	DE1046V + DE1049V	A,L
	EC1143I	Activity rate 15-24 – male	EC1143V	DE1047V + DE1050V	A,L
	EC1144I	Activity rate 15-24 – female	EC1144V	DE1048V + DE1051V	A,L
	EC1145I	Activity rate 55-64	EC1145V	DE1025V	A,L
	EC1146I	Activity rate 55-64 – male	EC1146V	DE1026V	A,L
	EC1147I	Activity rate 55-64 – female	EC1147V	DE1027V	A,L
	EC1088I	Proportion in part-time employment	EC1088V	EC1088V + EC1034V	A
	EC1089I	Proportion in part-time employment – male	EC1089V	EC1089V + EC1035V	A
	EC1090I	Proportion in part-time employment – female	EC1090V	EC1090V + EC1036V	A
	EC1166I	Proportion in part-time employment, 15-24	EC1166V	EC1166V + EC1160V	A
	EC1167I	Proportion in part-time employment, 15-24 – male	EC1167V	EC1167V + EC1161V	A
	EC1168I	Proportion in part-time employment, 15-24 – female	EC1168V	EC1168V + EC1162V	A
	EC1169I	Proportion in part-time employment, 55-64	EC1169V	EC1169V + EC1163V	A
	EC1170I	Proportion in part-time employment, 55-64 – male	EC1170V	EC1170V + EC1164V	A
	EC1171I	Proportion in part-time employment, 55-64 – female	EC1171V	EC1171V + EC1165V	A
Economic Activity (EC2)	Variables				
	Code	Variable			Spatial Unit
	EC2001V	Gross Domestic Product of city/region/country (Euro)			A,L
	EC2002V	Total resident population of area [country] relating to reported GDP			A,L
	EC2015V	Total employment of area [country] relating to reported GDP			A,L
	EC2021V	All companies			A
	EC2003V	Companies quoted on the national stock exchange with headquarters within the town / city [country]			A
	EC2004V	New business that have registered in the reference year			A
	EC2014V	Companies that have gone bankrupt in the reference year			A
	EC2006V	Total net office floor space 1st January (in 1000 m^2)			A

Urban Audit Indicators					
	EC2013V	Vacant net office floor space 1^{st} January (in 1000 m^2)			A
	EC2020V	Total employment (jobs) (work-place based)			A
	EC2008V	Employment (jobs) in agriculture, fishery (NACE Rev.1: A-B) & ESA95 A3			A
	EC2009V	Employment (jobs) in mining, manufacturing, energy (NACE Rev.1: C-E)			A
	EC2022V	Employment (jobs) in construction (NACE Rev.1: F)			A
	EC2010V	Employment (jobs) in trade, hotels, restaurants (NACE Rev.1: G-H)			A
	EC2023V	Employment (jobs) in transport, communication (NACE Rev.1: I)			A
	EC2011V	Employment (jobs) financial intermediation, business activities (NACE Rev.1: J-K)			A
	EC2012V	Employment (jobs) in public admin., health, education, other (NACE Rev.1: L-P)			A
	EC2016V	Employment (jobs) in NACE Rev.1 C-F (ESA95 A3)			A
	EC2017V	Employment (jobs) in NACE Rev.1 G-P (ESA95 A3)			A
	EC2018V	Employment (jobs) - employees			A
	EC2019V	Employment (jobs) – self-employed			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EC2001I	GDP per head of resident population	EC2001V	EC2002V	A,L
	EC2015I	GDP per employed person	EC2001V	EC2015V	A,L
	EC2003I	N° of companies with HQs in city quoted on stock market	EC2003V	-	A
	EC2008I	Proportion of employment in agriculture and fisheries	EC2008V	EC2020V	A
	EC2016I	Proportion of employment in mining, manufacturing, energy and construction	EC2016V	EC2020V	A
	EC2017I	Proportion of employment in industries G-P (NACE Rev.1)	EC2017V	EC2020V	A
	EC2009I	Proportion of employment in industries C-E (NACE Rev.1)	EC2009V	EC2020V	A
	EC2022I	Proportion of employment in construction	EC2022V	EC2020V	A
	EC2010I	Proportion of employment in trade, hotels and restaurants	EC2010V	EC2020V	A
	EC2023I	Prop. of employment in transport and communication	EC2023V	EC2020V	A
	EC2011I	Prop. of employment in financial and business services	EC2011V	EC2020V	A
	EC2012I	Prop. of employment public admin., health and education	EC2012V	EC2020V	A
	EC2018I	Proportion of employment (jobs) – employees only	EC2018V	EC2020V	A
	EC2019I	Proportion of employment (jobs) – self-employed only	EC2019V	EC2020V	A
	EC2020I	Average employment per company	EC2020V	EC2021V	A
	EC2014I	Proportion of companies gone bankrupt	EC2014V	EC2021V	A
	EC2004I	New businesses registered as a proportion of existing companies	EC2004V	EC2021V	A
	EC2013I	Net office space that is vacant	EC2013V	-	A
	EC2033I	Proportion of net office space that is vacant	EC2013V	EC2006V	A
Income Disparities and Poverty (EC3)	Variables				
	Code	Variable			Spatial Unit
	EC3039V	Median disposable annual household income (Euro)			A,L,S
	EC3045V	Household income: Quintile 4 (income with 20 % households above, 80 % below)			A,L
	EC3048V	Household income: Quintile 3 (income with 40 % households above, 60 % below)			A,L
	EC3051V	Household income: Quintile 2 (income with 60 % households above, 40 % below)			A,L
	EC3054V	Household income: Quintile 1 (income with 80 % households above, 20 % below)			A,L
	EC3057V	Total number of households with less than half of the national average income			A,L,S

Urban Audit Indicators					
	EC3060V	Total number of households reliant on social security benefits (>50 %)			A,L,S
	EC3063V	Individuals reliant on social security benefits (>50 %)			A,L,S
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EC3039I	Median disposable annual household income	EC3039V	-	A,L,S
	EC3054I	Ratio of first to fourth quintile earnings	EC3054V	EC3045V	A,L
	EC3057I	% households with less than half national average income	EC3057V	DE3001V	A,L,S
	EC3060I	Prop. of households reliant upon social security	EC3060V	DE3001V	A,L,S
	EC3063I	Prop. of individuals reliant on social security	EC3063V	DE1001V	A,L,S
Civic Involvement (CI1)					
Civic Involvement (CI)	Variables				
	Code	Variable			Spatial unit
	CI1001V	European elections: total electorate (eligible)			A
	CI1002V	European elections: total electorate (registered)			A
	CI1003V	European elections: total votes counted			A
	CI1004V	National elections: total electorate (eligible)			A
	CI1005V	National elections: total electorate (registered)			A
	CI1006V	National elections: total votes counted			A
	CI1007V	City elections: total electorate (eligible)			A
	CI1008V	City elections: total electorate (registered)			A
	CI1009V	City elections: total votes counted			A
	CI1011V	City elections: electorate aged less than 25			A
	CI1010V	City elections: total votes counted by voters aged less than 25			A
	CI1016-18V	Number of elected city representatives – total/male/female			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	CI1003I	Prop. of registered electorate voting in EU elections	CI1003V	CI1002V	A
	CI1006I	Prop. of registered electorate voting in national elections	CI1006V	CI1005V	A
	CI1009I	Prop. of registered electorate voting in city elections	CI1009V	CI1008V	A
	CI1002I	Prop. of eligible electorate registered for EU elections	CI1002V	CI1001V	A
	CI1005I	Prop. of eligible electorate registered for national elections	CI1005V	CI1004V	A
	CI1008I	Prop. of eligible electorate registered for city elections	CI1008V	CI1007V	A
	CI1010I	Prop. of young people (<25 yr) voting in city elections	CI1010V	CI1011V	A
	CI1016I	Number of elected city representatives	CI1016V	-	A
	CI1026I	No of elected city representatives per 1000 residents	CI1016V*1000	DE1001V	A
	CI1018I	Percentage of elected city representatives who are women	n CI1018V	CI1016V	A
Local Administration (CI2)	Variables				
	Code	Variable			Spatial Unit
	CI2001V	Total municipal authority income (Euro)			A
	CI2002V	Municipal authority income derived from local taxation (Euro)			A
	CI2003V	Municipal authority income transferred from national or regional government (Euro)			A
	CI2004V	Municipal authority income derived from charges for services (Euro)			A
	CI2005V	Municipal authority income derived from other sources (Euro)			A
	CI2006V	Total municipal authority expenditure (Euro)			A
	CI2007V	Total number of persons directly employed by the local administration			A

Urban Audit Indicators					
	CI2008V	Number of persons directly employed by the local administration in central administration			A
	CI2009V	Number of persons directly employed by the local administration in education			A
	CI2010V	Number of persons directly employed by the local administration in health and social services			A
	CI2011V	Number of persons directly employed by the local administration in public transport			A
	CI2013V	Number of persons directly employed by the local administration in other			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	CI2006I	Annual expenditure of the municipal authority per resident	CI2006V	DE1001V	A
	CI2101I	Annual expenditure of the municipal authority per city GDP	CI2006V	EC2001V	A
	CI2002I	Proportion of municipal authority income from local taxation	CI2002V	CI2001V	A
	CI2003I	Proportion of municipal authority income from national and regional transfers	CI2003V	CI2001V	A
	CI2004I	Prop. of municipal authority income from charges for services	CI2004V	CI2001V	A
	CI2005I	Proportion of municipal authority income from other sources	CI2005V	CI2001V	A
	CI2007I	Residents employed by local admin./labor force	CI2007V	EC2020V	A
	CI2008I	Employees in local admin. (central)/labor force	CI2008V	EC2020V	A
	CI2009I	Employees in local admin. (education)/labor force	CI2009V	EC2020V	A
	CI2010I	Employees in local admin. (health)/labor force	CI2010V	EC2020V	A
	CI2011I	Employees in local admin. (transport)/labor force	CI2011V	EC2020V	A
	CI2013I	Employees in local admin. (other)/labor force	CI2013V	EC2020V	A
Training and Education (TE)					
Education and Training provision (TE1)	Variables				
	Code	Variable			Spatial Unit
	TE1001-3V	Number of children 0-4 in day care – total/in private/in public			A,L
	TE1029V	Number of children 0-4 in other day care e.g. church			A,L
	TE1005V	Total students registered for final year of compulsory education			A,L
	TE1030V	Students leaving compulsory education without having a diploma			A,L
	TE1017-19V	Students continuing education after completing compulsory education - total/male/female			A,L,S
	TE1031-33V	Students in upper and further education (ISCED level 3-4) – total/male/female			A
	TE1026-28V	Students in higher education (ISCED level 5-6) – total/male/female			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	TE1001I	Children 0-4 in day care (public and private) per 1000 children	TE1001V * 1000	DE1040V	A,L
	TE1003I	Proportion of children 0-4 in public day care	TE1003V	TE1001V	A,L
	TE1002I	Proportion of children 0-4 in private day care	TE1002V	TE1001V	A,L
	TE1029I	Proportion of children 0-4 in other day care (e.g. church)	TE1029V	TE1001V	A,L
	TE1030I	Proportion of students not completing compulsory educ.	TE1030V	TE1005V	A,L
	TE1017I	Proportion of students continuing education after compulsory education	TE1017V	TE1005V	A,L
	TE1026I	Students in higher education per 1000 resident population	TE1026V * 1000	DE1001V	A
nal Qualifications	Variables				
	Code	Variable			Spatial

Urban Audit Indicators					
					Unit
	TE2016V	Total number of residents qualified at ISCED level 1			A,L,S
	TE2017V	Number of male residents qualified at ISCED level 1			A,L
	TE2018V	Number of female residents qualified at ISCED level 1			A,L
	TE2001V	Total number of residents qualified at ISCED level 2			A,L,S
	TE2002V	Number of male residents qualified at ISCED level 2			A,L
	TE2003V	Number of female residents qualified at ISCED level 2			A,L
	TE2019V	Total number of residents qualified at ISCED levels 3 and 4			A,L,S
	TE2020V	Number of male residents qualified at ISCED levels 3 and 4			A,L
	TE2021V	Number of female residents qualified at ISCED levels 3 and 4			A,L
	TE2022V	Total number of residents qualified at ISCED levels 5 and 6			A,L,S
	TE2023V	Number of male residents qualified at ISCED levels 5 and 6			A,L
	TE2024V	Number of female residents qualified at ISCED levels 5 and 6			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	TE1001I	Children 0-4 in day care (public and private) per 1000 children	TE1001V * 1000	DE1040V	A,L
	TE2016-18I	Proportion of population qualified at level 1 ISCED – total/male/female	TE2016-18V	DE1001-3V	A,L,S
	TE2001-3I	Proportion of population qualified at level 2 ISCED – total/male/female	TE2001-3V	DE1001-3V	A,L,S
	TE2019-21I	Proportion of population qualified at level 3-4 ISCED – total/male/female	TE2019-21V	DE1001-3V	A,L,S
	TE2022-24I	Proportion of population qualified at level 5-6 ISCED – total/male/female	TE2022-24V	DE1001-3V	A,L,S
Environment (EN)					
Climate/Geography (EN1)	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	EN1003V	Average temperature of warmest month (degrees Celsius)			A
	EN1004V	Average temperature of coldest month (degrees Celsius)			A
	EN1005V	Rainfall (litre/m^2)			A
	EN1001V	Number of days of rain per annum			A
	EN1002V	Total number of hours of sunshine per day			A
Air Quality and Noise (EN2)	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	EN2001V	Winter smog: Number of days sulphur dioxide SO2 concentrations exceed 125 µg/m^3			A
	EN2002V	Summer smog: Number of days ozone O3 concentrations exceed 120 µg/m^3			A
	EN2003V	Number of days nitrogen dioxide NO2 concentrations exceed 200 µg/m^3			A
	EN2005V	Number of days particulate matter PM10 concentrations exceed 50 µg/m^3			A
	EN2006V	Concentration of lead Pb in ambient air in µg/m^3			A
	EN2007V	Number of residents exposed to outdoor day noise levels above 55 dB(A)			A
	EN2008V	Number of residents exposed to sleep disturbing outdoor night noise levels above 45 dB(A)			A
	EN2014V	Total carbon dioxide CO2 emissions (tons)			A
	EN2009V	Total carbon monoxide CO emissions (tons)			A
	EN2010V	Total methane CH4 emissions (tons)			A
	EN2011V	Total non-methane volatile organic compounds NVOC emissions (tons)			A
	EN2012V	Total sulphur dioxide SO2 emissions (tons)			A
	EN2013V	Total nitrogen dioxide NO2 emissions (tons)			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EN2007I	Proportion of residents exposed to day noise >55 dB(A)	EN2007V	DE1001V	A
	EN2008I	Proportion of residents exposed to night noise >45 dB(A)	EN2008V	DE1001V	A
	EN2024I	CO2 emissions per capita	EN2014V	DE1001V	A

Urban Audit Indicators

Water (EN3)

Variables

Code	Variable	Spatial Unit
EN3001V	Total number of annual tests (on all parameters) on drinking water quality	A
EN3002V	Number of annual determinations which exceed the prescribed concentration values	A
EN3003V	Total consumption of water in m^3	A
EN3004V	Number of dwellings connected to potable drinking water system	A
EN3006V	Number of dwellings connected to sewerage treatment system	A
EN3008V	Number of water rationing cases, days per year	A
EN3009V	Number of scheduled water cuts, days per year	A

Indicators

Code	Indicator	Numerator	Denominator	Spatial Unit
EN3003I	Consumption of water (m^3 per annum) per capita	EN3003V	DE1001V	A
EN3004I	% of dwellings connected to potable water system	EN3004V	SA1001V	A
EN3006I	% of dwellings connected to sewerage treatment system	EN3006V	SA1001V	A
EN3008I	Number of water rationing cases, days per year	EN3008V	-	A
EN3009I	Number of scheduled water stoppages, days per year	EN3009V	-	A

Waste Management (EN4)

Variables

Code	Variable	Spatial Unit
EN4001V	Annual amount of solid waste (domestic and commercial) in tonnes	A
EN4002V	Annual amount of solid waste (domestic and commercial) processed by landfill sites, in tons	A
EN4003V	Annual amount of solid waste (domestic and commercial) processed by incinerators, in tons	A
EN4004V	Annual amount of solid waste (domestic and commercial) that is recycled, in tons	A
EN4006V	Annual amount of solid waste (domestic and commercial) given to other disposal units, in tons	A
EN4005V	Annual amount of toxic waste in tons	A

Indicators

Code	Indicator	Numerator	Denominator	Spatial Unit
EN4001I	Collected solid waste per capita per year	EN4001V	DE1001V	A
EN4002I	Proportion of solid waste processed by landfill	EN4002V	EN4001V	A
EN4003I	Proportion of solid waste processed by incinerators	EN4003V	EN4001V	A
EN4004I	Proportion of solid waste processed by recycling	EN4004V	EN4001V	A
EN4006I	Proportion of solid waste processed by other methods	EN4006V	EN4001V	A
EN4005I	Annual amount of toxic waste per capita	EN4005V	DE1001V	A

Land Use (EN5)

Variables

Code	Variable	Spatial Unit
EN5003V	Total land area (km^2) according to cadastral register	A,L,S
EN5015V	Water and wetland (km^2)	A,L
EN5012V	Green space area (km^2)	A,L,S
EN5016V	Land used for agricultural purposes (km^2)	A,L
EN5017V	Land area in mineral extraction (km^2)	A,L
EN5018V	Land area in industrial and manufactory use (km^2)	A,L
EN5019V	Land area in road network use (km^2)	A,L
EN5020V	Land area in rail network use (km^2)	A,L
EN5008V	Land area in ports use (km^2)	A,L

Urban Audit Indicators					
	EN5009V	Land area in airports use (km^2)			A,L
	EN5021V	Land area in water treatment use (km^2)			A,L
	EN5022V	Land area in waste disposal use (km^2)			A,L
	EN5023V	Land area in commerce, finance and business use (km^2)			A,L
	EN5011V	Land area in recreational, sports and leisure use (km^2)			A,L
	EN5004V	Land area in housing/residential use (km^2)			A,L
	EN5013V	Unused areas, including contaminated or derelict land areas (km^2)			A,L
	EN5014V	Urban area subject to special /physical planning conservation measures (km^2)			A,L
	EN5001V	Green space to which the public has access (hectares)			A,L,S
	EN5002V	Population within 15 minutes walking distance of urban green areas (number)			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EN5003I	Total land area (km^2) – from the cadastral register	EN5003V	-	A,L,S
	EN5001I	Green space to which the public has access per capita	EN5001V * 10 000	DE1001V	A,L,S
	EN5002I	Prop. of population within a 15 min. walk of green space	EN5002V	DE1001V	A,L
	EN5012I	Proportion of the area in green space	EN5012V	EN5003V	A,L,S
	EN5016I	Proportion of the area used for agricultural purposes	EN5016V	EN5003V	A,L
	EN5017I	Proportion of the area in mineral extraction	EN5017V	EN5003V	A,L
	EN5018I	Proportion of the area in industrial and manuf. use	EN5018V	EN5003V	A,L
	EN5019I	Proportion of the area in road network use	EN5019V	EN5003V	A,L
	EN5020I	Proportion of the area in rail network use	EN5020V	EN5003V	A,L
	EN5008I	Proportion of the area in ports use	EN5008V	EN5003V	A,L
	EN5009I	Proportion of the area in airports use	EN5009V	EN5003V	A,L
	EN5021I	Proportion of the area in water treatment use	EN5021V	EN5003V	A,L
	EN5022I	Proportion of the area in waste disposal use	EN5022V	EN5003V	A,L
	EN5023I	Proportion of the area in commerce and business use	EN5023V	EN5003V	A,L
	EN5011I	Proportion of the area in sports and leisure use	EN5011V	EN5003V	A,L
	EN5004I	Proportion of the area in housing/residential use	EN5004V	EN5003V	A,L
	EN5013I	Prop. of the area unused, including contaminated land	EN5013V	EN5003V	A,L
	EN5014I	Prop. of urban area under special conservation measures	EN5014V	EN5003V	A,L
	EN5101I	Population density: total resident population per km^2	DE1001V	EN5003V	A,L,S
	EN5102I	Net residential density – pop. per land area in housing	DE1001V	EN5004V	A,L
Energy Use (EN6)	Variables				
	Code	Variable			Spatial Unit
	EN6030V	Total petrol and gasoline use for private heating (Mio Tonnes of Oil Equivalents, Mtoe)			A
	EN6031V	Total petrol use for private and commercial transport (Mtoe)			A
	EN6010V	Total electricity use (1000 kWh)			A
	EN6011V	Total electricity use by the transport sector (1000 kWh)			A
	EN6012V	Total electricity use by the industrial sector (1000 kWh)			A
	EN6013V	Total electricity use by the domestic sector (1000 kWh)			A
	EN6014V	Total electricity use by the commercial (service) sector (1000 kWh)			A
	EN6015V	Total natural gas use (Mtoe)			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	EN6010I	Electricity consumption per capita (1000 kWh)	EN6010V	DE1001V	A
	EN6015I	Gas consumption per capita (Mtoe)	EN6015V	DE1001V	A

Urban Audit Indicators					
	EN6011I	Share of electricity use in transport sector	EN6011V	EN6010V	A
	EN6012I	Share of electricity use in industry sector	EN6012V	EN6010V	A
	EN6013I	Share of electricity use in domestic sector	EN6013V	EN6010V	A
	EN6014I	Share of electricity use in commercial sector	EN6014V	EN6010V	A
Travel and Transport (TT)					
Travel Patterns (TT1)	Variables				
	Code	Variable			Spatial Unit
	TT1064V	People commuting into the city (number)			A
	TT1065V	People commuting out of the city (number)			A
	TT1066V	Length of public transport network (km)			A,L
	TT1068V	Total kilometers driven in public transport (per day)			A
	TT1067V	Public transport supply: Number of places multiplied by the kilometers driven (places*km)			A
	TT1057V	Number of private cars registered			A,L
	TT1058V	Road accidents resulting in death or serious injury (number)			A,L
	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	TT1002V	Percentage of journeys to work by rail/metro			A,L
	TT1003V	Percentage of journeys to work by car			A,L
	TT1004V	Percentage of journeys to work by bus			A,L
	TT1005V	Percentage of journeys to work by tram			A,L
	TT1006V	Percentage of journeys to work by motor cycle			A,L
	TT1007V	Percentage of journeys to work by bicycle			A,L
	TT1008V	Percentage of journeys to work by foot			A,L
	TT1009V	Percentage of journeys to work by other modes			A,L
	TT1059V	Average number of occupants of motor cars			A
	TT1019V	Average time of journey to work (minutes)			A,L
	TT1062V	Average speed of inner-city car traffic (km/hour) during the rush hour			A
	TT1063V	Average waiting time for a bus (minutes) in the rush hour			A,L
	TT1071V	Accessibility by air (index, EU27=100)			A,L
	TT1072V	Accessibility by rail (index, EU27=100)			A,L
	TT1073V	Accessibility by road (index, EU27=100)			A,L
	TT1074V	Multimodal accessibility (index, EU27=100)			A,L
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	TT1057I	Number of registered cars per 1000 population	TT1057V * 1000	DE1001V	A,L
	TT1058I	Road accidents (death or serious injury) per 1000 population	TT1058V * 1000	DE1001V	A,L
	TT1064I	Proportion of those employed in the city who are in-commuters	TT1064V	EC2020V	A
	TT1065I	Proportion of those living in the city who are out-commuters	TT1065V	EC1034V + EC1088V	A
	TT1066I	Length of public transport network as a proportion of land area	TT1066V	EN5003V	A,L
	TT1076I	Length of public transport network per capita	TT1066V	DE1001V	A,L
	TT1101I	Ratio of day-time to night-time population	EC2020V	EC1034V + EC1088V	A
	TT1068I	Total km driven in public transport per capita per day	TT1068V	DE1001V	A
Information Society (IT)					
Users and Infrastructure (IT1)	Variables				
	Code	Variable			Spatial Unit
	IT1001V	Number of households with a computer			A
	IT1002V	Percent of population over 15 years who regularly use the Internet			A
	IT1004V	Number of telephone main lines within the city [country for national data]			A

Urban Audit Indicators					
	IT1010V	Households with broadband access			A
	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	IT1005V	Percentage of households with Internet access at home			A
	IT1006V	Computers per 100 pupils at primary education level			A
	IT1007V	Computers per 100 pupils at secondary education level			A
	IT1008V	Number of students of Information, Communications Technology (ICT) at university level or equivalent			A
	IT1009V	Number of Public Internet Access Points (PIAPs)			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	IT1001I	Proportion of households with a computer	IT1001V	DE3001V	A
	IT1010I	Proportion of households with access to broadband	IT1010V	DE3001V	A
Local e-Government (IT2)	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	IT2001V	Official city Internet website (Yes/No)			A
	IT2002V	Number of visits to official city Internet website			A
	IT2003V	Number of administrative forms available for download from official website			A
	IT2004V	Number of administrative forms which can be submitted electronically			A
ICT sector (IT3)	Variables				
	Code	Variable			Spatial Unit
	IT3001V	Number of local units manufacturing ICT products			A
	IT3002V	Number of persons employed in the manufacture of ICT products			A
	IT3003V	Number of local units providing ICT services			A
	IT3004V	Number of persons employed in the provision of ICT services			A
	IT3005V	Number of local units producing content for the Information Society			A
	IT3006V	Number of persons employed in production of content for the Information Society			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	IT3001I	Proportion of local companies that produce ICT products	IT3001V	EC2021V	A
	IT3002I	Percentage of labor force manufacturing ICT products	IT3002V	EC2020V	A
	IT3004I	Percentage of labor force providing ICT services	IT3004V	EC2020V	A
	IT3006I	Percentage of labor force producing ICT content	IT3006V	EC2020V	A
Culture and Recreation (CR)					
Culture and Recreation (CR1)	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	CR1001V	Concerts (per year)			A
	CR1002V	Concert attendance (per year)			A
	CR1012V	Number of concert seats			A
	CR1003V	Number of cinema seats (total capacity)			A
	CR1005V	Cinema attendance (per year)			A
	CR1006V	Number of museums			A
	CR1007V	Number of museum visitors (per year)			A
	CR1008V	Number of theatres			A
	CR1013V	Number of theatre seats			A
	CR1009V	Theatre attendance (per year)			A
	CR1010V	Number of public libraries (all distribution points)			A
	CR1011V	Number of books and other media loaned from public libraries (per year)			A

Urban Audit Indicators					
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	CR1005I	Annual cinema attendance per resident	CR1005V	DE1001V	A
	CR1003I	Number of cinema seats per 1000 residents	CR1003V* 1000	DE1001V	A
	CR1001I	Number of concerts per 1000 residents	CR1001V* 1000	DE1001V	A
	CR1002I	Annual attendance at concerts per resident	CR1002V	DE1001V	A
	CR1008I	The number of theatres	CR1008V	-	A
	CR1009I	Annual attendance at theatres per resident	CR1009V	DE1001V	A
	CR1006I	Number of museums	CR1006V	-	A
	CR1007I	Annual visitors to museums per resident	CR1007V	DE1001V	A
	CR1010I	The number of public libraries	CR1010V	-	A
	CR1011I	Total loans of books and other media per resident	CR1011V	DE1001V	A
	CR1012I	Number of concert seats per capita	CR1012V	DE1001V	A
	CR1013I	Number of theatre seats per capita	CR1013V	DE1001V	A
Tourism (CR2)	Variables (=Indicators)				
	Code	Variable			Spatial Unit
	CR2001V	Total annual tourist overnight stays in registered accommodation			A
	CR2009V	Number of available beds			A
	CR2004V	Number of air passengers using nearest airport			A
	CR2005V	Number of air passengers using nearest airport: Total arrivals			A
	CR2006V	Number of air passengers using nearest airport: Domestic arrivals			A
	CR2007V	Number of air passengers using nearest airport: Total departures			A
	CR2008V	Number of air passengers using nearest airport: Domestic departures			A
	Indicators				
	Code	Indicator	Numerator	Denominator	Spatial Unit
	CR2001I	Tourist overnight stays in reg. accommodation per year	CR2001V	-	A
	CR2011I	Tourist overnight stays per resident population	CR2001V	DE1001V	A
	CR2014I	Number of air passengers per resident	CR2004V	DE1001V	A
	CR2101I	Average occupancy rate of accommodation	CR2001V	CR2009V	A
	CR2009I	Number of available beds	CR2009V	-	A
	CR2004I	Number of air passengers using nearest airport	CR2004V	-	A
	CR2005I	Share of non-domestic departures from nearest airport	CR2007V-CR2008V	CR2007V	A

10.9 Generic indicators of response capacity, from "Urban Vulnerability Indicators" (Swart et al., 2012)

Dimension	Aspect of response capacity	Indicator	Relevance	Source	Credibility
Awareness	Human: Education	Proportion of population aged 15-64 qualified at tertiary level	The level of education may reflect awareness of the climate change problem and suggest that the population is open to a variety of adaptation solutions.	Urban Audit	Medium: indirect link with climate change
	Institutional: Equity	Percentage of elected city representatives who are women	The representation of women in cities may reflect a more equal society, which could be more aware of the need to protect vulnerable people.	Urban Audit	Low: weak link with climate change
	Human: Awareness of climate change	Perception of the city population that the authorities are committed to fight against climate change	The awareness of the city authorities and the population indicate higher response capacity.	Urban Audit	High: a direct link with climate change
	Human: Risk perception	Risk perceptions of European citizens	Relates to food and food chain risks, but could be used as a proxy for other risks.	Euro-barometer	Low: weak link with climate change
Ability	Infrastructure: Built environment	Proportion of dwellings lacking basic amenities	The worse the housing situation, the lower the response capacity. Poorer housing is likely to be more affected by extreme weather events.	Urban Audit	Medium: indirect link with climate change1
	Financial/ human: innovation	R&D expenditure, personnel and patent applications	The R&D expenditure indicates how technologically advanced the city is; this may indicate greater ability to develop technological response solutions.	ESPON	Low: weak link with climate change ESPON. Not used in EEA report due to lack of coverage – check data & updates.
	Human: Technology	Percentage of households with Internet access at home.	Internet access may increase the access to information about climate change hazards and enable users to exchange information with others.	Urban Audit	Low: weak link with climate change
	Human: Health	Life expectancy at birth for males and females	The healthier the population, the higher the response capacity.	Urban Audit	Medium: poor physical health linked to lower ability to cope with extreme weather events.
	Infrastructure: Hospital beds	Number of hospital beds / 1000 inhabitants	The more hospital beds, the higher city's response capacity in the case of an extreme weather event	Urban Audit	High: direct link to emergency response. Not used in EEA report due to data quality / coverage
n: Generic capacity to	Human: Demographic	Relationship of non-working age population to	The higher the proportion of potentially state-dependent or family-dependent people, the	Urban Audit	Medium: indirect link with climate

Dimension	Aspect of response capacity	Indicator	Relevance	Source	Credibility
	dependency	working age population	lower the response capacity.		change1
	Financial: GDP per capita	GDP per capita in European Cities	The richer the society, the higher the response capacity	Urban Audit	High: financial capacity is strongly linked to climate change
	Financial: Insurance penetration	Insurance penetration as proportion of national GDP	Insurance penetration reflects the overall level of insured lives and properties in a country, reflecting some degree of preparedness.	National level figures, CEA data	Medium: whilst in some countries flood insurance is available, in others (e.g. The Netherlands) it is not.
	Human: Social capital	Most people can be trusted (synthetic index 0-100)	Higher levels of trust increase the probability that city residents will work together in the case of emergency.	Urban Audit perception survey data	Low: weak link with climate change
	Institutional: Government effectiveness	National rankings on government effectiveness	The more effective government, the higher the response capacity	World Bank	Medium: indirect link with climate change
	Human: Political participation	Percentage of registered electorate voting in local elections	The more voters, the higher the trust of the citizens in the institutions and the higher the effectiveness of the institutions and citizens working together in response to climate change.	Urban Audit	Low: weak link with climate change
Action: Actual response	Actual adaptation at the city level	Urban adaptation strategies & measures	The presence of urban adaptation strategies and measures	COST action on urban adaptation; results not yet published; EU Cities Adapt	Relatively high: direct link with climate change.
	National measures	National adaptation strategy	Presence of a national strategy suggests a presence of supportive governance framework in which the city can develop its own adaptations measures.	UNFCCC	Medium: indirect link to city policies.

10.10 Assessing cities: a new system of cross-scale spatial indicators (Bourdic et al., 2012)

Theme	Concept	Type	Name	Scale	Equation
Land Use	Urban form	Intensity	Human density	D/N	$\frac{\text{population}}{\text{area of the selection (m}^2\text{)}}$
			Building density	D/N	$\frac{\text{floor area (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}}$
			Housing density	D/N	$\frac{\text{number of housing units}}{\text{area of the selection (m}^2\text{)}}$
			Density of legal entities	D/N	$\frac{\text{number of legal entities}}{\text{area of the selection (m}^2\text{)}}$
			Job density	D/N	$\frac{\text{number of jobs}}{\text{area of the selection (m}^2\text{)}}$
			Coefficient of land occupancy	D/N	$\frac{\text{land occupancy (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}}$
			Subdivision intensity	D/N	$\frac{\text{number of parcels}}{\text{area of the selection (m}^2\text{)}}$
		Diversity	Diversity of subdivisions size	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_{tot\,i}\,S_i^{\,m}}{A}\right]^2$
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{\,obj}}\right]^2$
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N	$\frac{1}{\text{Cat}}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{\,obj}}\right]^2$
Mobility	Urban form	Intensity	Surface occupied by pedestrian and bicycle paths	D/N	$\frac{\text{area occupied by ped and bike paths}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
			Surface occupied by the road network	C/D	$\frac{\text{area of the road network (m}^2\text{)}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
			Proportion of the road network dedicated to public transport	D	$\frac{\text{area dedicated to public transport (m}^2\text{)}}{\text{total area dedicated to transport (m}^2\text{)}} \text{ x } 100$
		Connectivity	Connectivity of the pedestrian/bike grid	D/N	$\frac{\text{number of intersections of the ped/bike grid}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
			Connectivity of the car grid	D	$\frac{\text{number of intersections of the car grid}}{\text{area of the selection (m}^2\text{)}} \text{ x } 100$
			Cyclomatic complexity of the car grid	D	$\mu = \text{L} - \text{N} + 1$ L = number of links; N = number of nodes
			Cyclomatic complexity of the pedestrian/bike grid	N	$\mu = \text{L} - \text{N} + 1$ L = number of links; N = number of nodes
			Average distance between intersections (bike/ped grid)	D/N	
			Average distance between intersections (car grid)	D	
		Proximity	Proportion of the population more than 300 meters away from a public transport stop	C/D	$\frac{\text{pop. more than 300 m away from p.t.}}{\text{population}} \text{ x } 100$

Theme	Concept	Type	Name	Scale	Equation
		Diversity	Number of public transport modes accessible within of 300 meters	D	
		Complexity	Scale hierarchy of the street network	C/D	$S = \frac{1}{\mathrm{Cat}} \sum_{i=1}^{Cat} \left[1 - \frac{n_i x_i^m}{A} \right]^2$ n_i the number of streets of width x_i (per category)
Water	Environmental	Intensity	Hydrological intensity	D	% of natural hydro. functions preserved or restored
			Impermeability of land	D	$\frac{\text{imperm. area (m}^2)}{\text{area of the selection (m}^2)}$
			Intensity of water treatment: Rate of wastewater collection and treatment	C/D	$\frac{\text{volume of collected and treated water (m}^3)}{\text{volume of water consumed (m}^3)}$
			Efficiency of water use	C	$\frac{\text{water needs (m}^3)}{\text{water cons. (m}^3)}$
			Accessibility of drinking water	C/D	% of the population with access to drinking water
Biodiversity	Environmental/ Urban form	Intensity	Proportion of agricultural surfaces	C/D	$\frac{\text{agri. land area (m}^2)}{\text{area of the selection (m}^2)} \times 100$
			Proportion of green fabric	D	$\frac{\text{green fabric area (m}^2)}{\text{area of the selection (m}^2)} \times 100$
		Connectivity	Connectivity of green habitats	D	$\frac{\text{area of connected green habitats (m}^2)}{\text{total area of green habitats (m}^2)} \times 100$
		Distribution	Distribution of green spaces (distance from an even distribution)	C/D	$\frac{Q}{Q-1}\left[1 - \sum_{district=1}^{Q} \left(\frac{S_{green\ area_{district\ i}}}{S_{district\ i}} \right)^2 \right]$
Equity	Socio-economic	Intensity	Proportion of jobs in relation to housing	D/N	$\frac{\text{number of jobs}}{\text{number of housing units}}$
			Proportion of social housing	D/N	$\frac{\text{number of social housing units}}{\text{number of housing units}}$
		Diversity	Diversity of ages (structural distribution)	D/N/B	$\frac{1}{Cat} \sum_{i=1}^{Cat} \left[1 - \frac{\text{number of people}_{\text{cat age i}}}{\text{number of people}^{\text{obj}}_{\text{cat age i}}} \right]^2$
			Diversity of incomes (structural diversity)	D/N/B	$\frac{1}{Cat} \sum_{i=1}^{Cat} \left[1 - \frac{\text{number of people}_{\text{income i}}}{\text{number of people}^{\text{obj}}_{\text{income i}}} \right]^2$
Economy	Socio-economic	Intensity	Resource productivity	C	$\frac{\text{material cons. (kg)}}{\text{GDP}}$
			Intensity of learning activities	D	$\frac{\text{learning activities (number of legal entities)}}{\text{total number of legal entities}}$
			Job potential	D	$\frac{\text{number of jobs}}{\text{number of active people}}$
		Diversity	Structural diversity of jobs		$\frac{1}{Cat} \sum_{i=1}^{Cat} \left[1 - \frac{\text{number of jobs}_{\text{cat i}}}{\text{number of jobs}^{\text{obj}}_{\text{i}}} \right]^2$
			Structural diversity of uses (shops, offices, housing, public buildings: schools, administrations, etc.)	C/D	$\frac{1}{Cat} \sum_{i=1}^{Cat} \left[1 - \frac{\text{number of legal entities}_{\text{cat i}}}{\text{number of legal entities}^{\text{obj}}_{\text{cat i}}} \right]^2$
	Urban form/ Socioeconomic	Proximity	Proximity of a convenience store	D	% of the population less than X m from a store

Theme	Concept	Type	Name	Scale	Equation
		Distribution	Distance of the distribution of each district from the global distribution of shops (in equation), or offices, or housing, or public buildings (schools, administrations, etc.)	C	$\frac{Q}{Q-1}\left[1-\sum_{district=1}^{Q}\left(\frac{\text{number of legal entities}_{shops_{district\ i}}}{\text{number of legal entities}_{district\ i}}\right)^2\right]$
Waste	Environmental	Intensity	Proportion of recycled materials in the construction of new buildings	C/D	$\frac{\text{quantity of recycled materials (m}^3\text{)}}{\text{total quantity of material used (m}^3\text{)}}$
			Productivity of urban metabolism	C/D	$\frac{\text{waste produced in the area (kg)}}{\text{waste imported into the area (kg)}}$
			intensity of GHG emissions per resident	C/D	$\frac{\text{GHG emissions (kg } CO_2 \text{ eq.)}}{\text{population}}$
			Intensity of emissions to produce wealth	C/D	$\frac{\text{GHG emissions (kg } CO_2 \text{ eq.)}}{\text{GDP}}$
Cultural/Well-being	Social	Intensity	Noise pollution	D/N	% of the population exposed to noises louder than 70db between 8am and 8pm
			Intensity of cultural activities	C/D	$\frac{\text{number of cultural activities per year}}{\text{population}}$
		Proximity	Proximity of leisure facilities	D	% of the population less than X m from a leisure facility
Energy & Bioclimatic	Environmental	Intensity	Energy intensity per resident	D/N	$\frac{\text{energy cons. (kWh)}}{\text{population}}$
			Surface energy intensity	D/N	$\frac{\text{energy cons. (kWh)}}{\text{floor area (m}^2\text{)}}$
			Proportion of local production	D/N	$\frac{\text{locally produced energy (kWh)}}{\text{energy cons. (kWh)}} \text{ x } 100$
			Rate of renewable energy used	C/D	$\frac{\text{renewable energy (kWh)}}{\text{energy cons. (kWh)}} \text{ x } 100$
			Rate of energy reuse	C/D	$\frac{\text{reused energy (kWh)}}{\text{energy cons. (kWh)}} \text{ x } 100$
	Urban form	Form	Volumetric compactness	N/B	$C=\frac{\sum S_i}{\sum V_i}$
			Size factor	N/B	$\alpha=\frac{1}{(\sum V_i)^{\frac{1}{3}}}$
			Form factor	N/B	$C_{adim}=\frac{\sum S_i}{(\sum V_i)^{\frac{2}{3}}}$
			Rate of passive volume	N/B	$Rate_{passive\ volume}=\frac{\sum V_{i\ passive}}{\sum V_i}$
			Energy consumed for heating	D/N/B	$\frac{\text{energy cons. for heating (kWh)}}{\text{floor area (m}^2\text{)}}$
			Energy consumed for air-conditioning	D/N/B	$\frac{\text{energy cons. for cooling (kWh)}}{\text{floor area (m}^2\text{)}}$

* Scale: C = city, D = district, N = neighbourhood, B = block

10.11 Climate variables - "Infrastructure and climate change risk assessment for Victoria" (CSIRO, 2007)

Climate Change Variables		
	Solar radiation	Changes to solar radiation levels and exposure
	Available moisture	Changes to evaporation rates and levels of rainfall impacting available moisture
	Variation in wet/dry spells	Changes to water table, surface and subsoil inundation cycles
	Temperature and heatwaves	Changes in frequency of extreme max temp, and length of heat spells
	Rainfall	Changes in annual rainfall
	Extreme daily rainfall	Changes to flood levels of extreme rainfall events
	Storm frequency and intensity	Changes to the intensity and number of storm events.
	Intensity of extreme wind	Changes in the intensity of low pressure system wind events
	Electrical storm activity	Changes in frequency and intensity of lightning events
	Bush fires	Changes in the frequency and intensity of bush fires
	Sea-level rise	Changes to average sea level
	Humidity	Changes in annual average relative humidity

10.12 Infrastructure risk indicators - "Infrastructure and Climate Change Risk Assessment for Victoria" (CSIRO, 2007)

Tray		Tool	Title
First Tray Understand the issues		1.1	Urban environments and climate change
		1.2	General climate change information and guidance for New Zealand
		1.3	An introduction to risk assessment
		1.4	Urban environments and climate change – Statutory context
		1.5	Council policy and plan auditing tool
		1.6	Sensitivity matrix prioritisation tool
		1.7	Sources of information, help and expertise for climate change impact assessments and glossary
Second Tray Assess the likely hazard	Bin 2.1 Flooding	2.1	Overview of flooding tools
		2.1.1	General guidance on climate change and flood modelling methods used in New Zealand
		2.1.2	Modelling future heavy rainfall
		2.1.3	Hydrological modelling of present-day and future floods
		2.1.4	Inundation modelling of present-day and future floods
		2.1.5	Linkages to risk assessment, adaptation options and decision tools
	Bin 2.2 Sea level rise	2.2	Overview of sea level rise and storm surge tools
		2.2.1	Guidance on assessing sea level rise in New Zealand
		2.2.2	Causes of sea level variation
		2.2.3	Guidance on assessing extreme sea level in New Zealand
		2.2.4	Inundation mapping of future high tides, SLR and storm surge
		2.2.5	Linkages to risk assessment, adaptation options and decision tools
	Bin 2.3 Landslides	2.3	Overview of landslide tools
		2.3.1	General information on the causes of rainfall-induced landslides
		2.3.2	Collection and analysis of historical landslide information and data
		2.3.3	Modelling present-day and future landslide potential
		2.3.4	Mapping the landslide hazard
		2.3.5	Linkages to risk assessment, adaptation options and decision tools
	Bin 2.4 Urban drainage	2.4	Overview of urban drainage tools
		2.4.1	Climate change and urban drainage modelling – data, issues and assumptions
		2.4.2	Incorporating climate change into urban stormwater management
		2.4.3	Climate change guidance material for urban stormwater management
		2.4.4	Modelling the North Shore City Council wastewater network – a case study of potential climate change impacts
		2.4.5	Linkages to risk assessment, adaptation options and decision tools
	Bin 2.5 Potable water	2.5	Overview of potable water tools
		2.5.1	General information on water supply and demand methods and issues
		2.5.2	Bulk water demand trend modelling

Tray		Tool	Title
		2.5.3	SYM approach to present-day and future potable water supply and demand
		2.5.4	Linkages to risk assessment, adaptation options and decision tools
	Bin 2.6 Other hazards	2.6	General information on the assessment of climate change effects on high winds, very high temperatures, snowfall, fog, lightning & hail and drought
Third Tray Identify the risks		3.1	Climate change risk assessment good practice
		3.2	Using RiskScape for risk analysis
		3.3	Case study example of risk assessment using RiskScape
		3.4	Investigating urban growth and change to inform the risk assessment process
		3.5	Subjective qualified risk analysis tool
		3.6	Linkages to hazard assessment, adaptation options and decision tools.
Fourth Tray Evaluate the options and their costs/ benefits		4.1	Climate change adaptation – key concepts
		4.2	Overview of an option screening tool
		4.3	Rapid cost/benefit evaluation of impacts and adaptation options
		4.4	Individual house flood mitigation measures - benefit/cost tool
		4.5	Overview of a multi-criteria analysis based decision tool
		4.6	Overview of a top-down decision tool
		4.7	Adaptation by design: impact of climate and land use change on the sizing of stormwater management devices
		4.8	Overview of a building flood protection decision framework
		4.9	Linkages to hazard and risk assessment tools
Fifth Tray Using the tools and improving practice		5.1	Managing information (including use of climate change check-lists)
		5.2	Keeping up to date
		5.3	Climate change - the long-term view
		5.4	Adopting a balanced approach
		5.5	Community resilience and sustainable development

10.13 Urban Impacts Toolbox: "Impacts of Climate Change on Urban Infrastructure and the Built Environment" (NIWA et al., 2012a)

Category	Infrastructure Service	Risk Indicator
Water	Water Storage and Supply	Water Shortage
		Degradation and Failure of Water Supply Piping
		Bushfire Impacts on Catchment and Storage
	Sewer	Degradation and Failure of Sewer Pipes
		Sewer Spills to Rivers and Bays
	Storm Water and Drainage	Storm Water Drainage and Flooding Damage
		Degradation and Failure of Drainage Infrastructure
Power	Electricity Generation, Transmission and Demand	Increase in demand pressure blackouts
		Decline in stability of structures and foundations
		Storm damage to above ground transmission
		Increased bushfire damage
		Substation flooding
		Arching faults of transmission lines
		Reduction of hydroelectricity generation
		Reduction of coal electricity generation
		Wind power inhibited
	Oil and Gas Extraction, Refining and Distribution	Decline in stability of structures and foundations
		Offshore infrastructure storm damage
		Inundation of refineries
Telecom	Fixed Line Network	Decline in stability of structures and foundations
		Degradation of cables
		Storm damage to above ground transmission
		Exchange station flooding of exchanges, manholes and underground pits
	Mobile Network	Wind damage to transmission towers
Transport	Roads	Asphalt degradation
		Road foundations degradation
		Flood damage to roads
	Rail	Rail track movement
		Storm damage to rail
	Bridges	Bridge structural material degradation
		Storm damage to bridges
	Tunnels	Tunnel flooding
		Sea level rise impacts on tunnels in proximity of coast
	Airports	Asphalt degradation
		Degradation of runway foundations
		Extreme event impacts to airport operations
	Ports (including jetties, piers and seawall protection)	Storm impacts on ports and coastal infrastructure
		Sea level rise impacts on port infrastructure materials
Building Infrastructure	Buildings and Structures	Degradation and failure of foundations
		Degradation and failure of building materials
		Increased storm and flood damage
		Coastal storm surge and flooding
		Increased bushfire damage
	Urban Facilities	Degradation and failure of foundations
		Degradation and failure of urban facilities' materials
		Increased storm and flood damage
		Coastal storm surge and flooding
		Increased bushfire damage

10.14 Categories and variables included in the Resilience Capacity Index (RCI) (BRR, 2013)

Category	Variable	Definition	Data source
Regional economic capacity	Economic diversity	Inverse of sum of absolute deviations of metropolitan area from all-metropolitan area average producing, service-producing, and government jobs	Bureau of Labor Statistics, Quarterly Census of Employment and wages
	Income	Median household income in last twelve months, inflation adjusted	American Community Survey (ACS)[30], Table B19013
	Income distribution	Inverse of Gini coefficient of income inequality	(ACS), Table B19083
Sociodemographic capacity	Education	Ratio of population aged 25+ with bachelor's degree to without high school diploma	(ACS), calculated from Tables 15003-21
	Working age	Percent of population aged 18-64	(ACS),, Table B01001
	Ability	Percent of population without a disability	(ACS), Table B18101
	Poverty	Percent of population above the poverty line	(ACS), Table B17001
Community connection capacity	Familiarity	Percent of population born in state	(ACS), Table B05002
	Linguistic connection	Percent of population not linguistically isolated	(ACS), Table B16002
	Housing	Percent of housing built before 1970	(ACS),Table B25034

[A]merican Community Survey (ACS): http://www.census.gov/acs/www/

10.15 Resilience checklist for infrastructure owners and operators (Cabinet Office, 2011)

Stage	Approach	Step	Checklist & Questions
Identify Risks	Understand your criticality	1	Determine the elements of infrastructure critical to the provision of essential services provided by your organisation.
		2	For your critical infrastructure, identify linkages with other elements of critical infrastructure within your supply chain.
	Understand Hazards	3	Using the scenarios in the Natural Hazards Guidance (Guide 1), identify which hazards are of greatest concern to your critical infrastructure and supply chains.
	Self-Assessment Questions		Have you worked with external agencies to assess the natural hazards risks to your organisation"s critical infrastructure?
			Does the location of your critical infrastructure make it more vulnerable to disruption from natural hazards?
			Have you identified your key / critical suppliers / customers? Do some of those deliver an essential service for your community?
Assess Risk	Understand your vulnerability	4	Understand what level of resilience you have to those hazards through design and service standards.
		5	For your critical infrastructure, identify linkages with other elements of critical infrastructure within your supply chain.
	Self-Assessment Questions		What standards (design, protection, network design, service, performance, recovery time) offer resilience to your critical infrastructure? Where are the gaps?
			Could there be a surge in demand for your services as a consequence of disruption from natural hazards? Will you be able to manage this?
			Have you worked with key / critical supply chain partners to understand their vulnerability to disruption by natural hazards? How could their disruption affect the delivery of your essential services?
			Have you worked with emergency responders, and others that your organisation would rely on during a period of disruption to improve your understanding of: a) Their vulnerability to disruption from natural hazards; b) The assistance that your organisation could expect to receive from them during a period of disruption from natural hazards?
Build Resilience	Build Resilience	6	What is the risk appetite within your organisation? How is resilience of critical infrastructure considered and weighted by the corporate Board in decision making? Does this need to change?
		7	Based on the conclusions of (6) and the principles set out in Section A of this Guide, decide what level of resilience is required and what resilience strategy will be adopted to provide the required level of resilience. Consider if the design of your infrastructure needs to evolve to provide greater resilience to future climates.
		8	Embed organisational resilience at the core of your strategic decision making processes.
		9	Engage with emergency responders for the area over which your organisation supplies essential services.
	Self-Assessment Questions		For disruption as a result of natural hazards, are you willing to: a) Accept the risk, do nothing (tolerate); or b) Mitigate the risk through emergency and business continuity plans (treat); or c) Outsource your product / service to another supplier or purchase insurance (transfer); or d) Cease the activity, move to another location or invest in greater resilience (terminate)?
			Is the Board aware of the risk of disruption from natural hazards?
			Has your organisation's risk appetite to disruption from natural hazards been agreed at Board level?
			Is the Organisational Resilience Strategy championed at Board level?

Stage	Approach	Step	Checklist & Questions
			Has the Board committed resources to improving the resilience of your critical infrastructure to disruption from natural hazards?
			Has the Board overseen the production of contingency plans to manage disruption from natural hazards?
			Do you have plans in place to manage (a combination of)? a) Loss of primary transport routes; b) Reduced staff availability; c) Impaired site access; d) Loss of power supplies; and lack of availability of alternative power supply; e) Loss of water supplies; and lack of availability of alternative water supplies; f) Closure of local businesses; g) Increased demand for health; emergency services, your products / services and those within your supply chain; h) Supply chain disruption
			Have these plans been shared with emergency responders and supply chain partners (up and down stream)?
			Does the Board seek assurances on the resilience of critical infrastructure to disruption from natural hazards at least annually?
			Do you have a resilience based education and awareness programme in place within your organisation? If not, do you have board / senior management level support to put in place a resilience based education and awareness programme?
			Have key staffs been trained to implement emergency and business continuity plans?
			Is there evidence that resilience, and particularly the risk from natural hazards, has been factored into the organisation's strategic decision making including medium to longer term investment plans?
			Have your business continuity plans been tested against the British Standard, BS25999?
			Does your organisation aim to achieve BS25999 alignment / certification?
			Are your critical suppliers aligned or certified to BS25999? Do you make this a requirement?
Evaluate Resilience	Evaluate Resilience	10	Challenge, test and exercise your organisational resilience strategy. Report to your Board, Regulator or Lead Government Department residual vulnerability of any CNI within your remit.
	Self-Assessment Questions		Have you reviewed your Organisational Resilience Strategy?
			Have you identified and tested any assumptions that underpin the delivery of your strategy?
			Do you have an exercise programme in place that addresses the risk from natural hazards? Has it been approved by the Board? Do Board members take part in exercises?
			Have you exercised more than one type of disruption at any one time - i.e. loss of primary transport routes, coupled with loss of power and water supplies?
			Are plans tested at least annually? Have findings been recorded and lessons learned?
			Were supply chain partners and emergency responders included in these tests / exercises?
			Were findings shared with the Board, supply chain partners, emergency responders, regulators and / or government?
			Have you taken part in your supply chains" and / or emergency responder's tests / exercises?