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There are a number of different future-city visions being developed around the world at the moment: one of them is Smart Cities: ICT and big data availability may contribute to better understand and plan the city, improving efficiency, equity and quality of life. But these visions of utopia need an urgent reality check: this is one of the future challenges that Smart Cities have to face.

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SMART CITIES CHALLENGES

SMART ENVIRONMENT FOR SUSTAINABLE RESOURCE MANAGEMENT

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Contents

TeMA

Journal of
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CONSIDERING RESILIENCE

STEPS TOWARDS AN ASSESSMENT FRAMEWORK

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ABSTRACT

As threats from climate change related hazards increase in cities around the world, communities are faced with an urgent requirement for self-evaluation. It is essential to expose and assess potential hazards facing cities, as well as to consider potential impacts and responses. While the promotion of efficiency and promise of protection have been common approaches to hazards in the past, recent events have exposed weaknesses in existing tactics. It has also become more apparent that existing mitigation efforts will be insufficient to prevent some level of climate change, associated hazards, and impacts. Complete protection against all threats is not only impossible but potentially hazardous, as extreme or unanticipated events can exceed the capacity for defence, potentially resulting in catastrophic failures.

From this realization of the fallibility of the existing paradigm, resilience has emerged as a useful concept for framing the response of cities to an expanding collection of potential threats. The aim of this article is to consider resilience as it applies to cities, their architecture and infrastructure systems, subsystems, and components, as well as their inhabitants. Resilience characteristics are identified and considered in order to inform the eventual development of a resilience framework with which to assess architecture and infrastructure resilience. This state of the art is instrumental to determine the conditions under which architecture and infrastructure resilience can be defined and measured, in order to guide the consideration of attributes and determine suitable criteria to select and elaborate indicators to help guide future actions and investments.

KEYWORDS:
Resilience, Vulnerability, Adaptation, Climate Change, Cities, Adaptation

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关于恢复性建筑和基础设施的指标

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摘要

本文旨在鉴别和分析目前可用于评估建筑和基础设施恢复力的恢复特性、框架和相应指标。此最新的技术发展水平将有助于确定：
对建筑和基础设施恢复力进行定义和测量的条件。
能够为行动和投资提供指导的适当的指标属性。
对这类指标进行选择和/ 或详细描述的适用标准。
在本文对城市建筑和基础设施的恢复力定义及框架和相应要求的鉴别和讨论过程中，重点参阅了科学、经济和规划等领域中的专家文献，同时还涉及气候变化适应和成本核算。通过对文献的审阅、分析、归类和仔细评估，总结出了各类恢复力特性。在针对利益相关人和研究专家分别进行的两次研讨会中，将这些特性和主要信息提出并进行了讨论，以找出目前恢复力定义和特性的缺漏之处、在各类城市评估方法中比较优势和劣势、并就城市建筑和基础设施的恢复力指标的优先顺序进行讨论。

关键词

气候变化；建筑环境；建筑；城市设计和规划；适应；恢复力

1 CLIMATE CHANGE AND CITIES

Cities are urban agglomerations, consisting not only of clustered structural, physical and natural artefacts, but the resident population itself, as well as the social structures and governance which provide cohesion and organization. Physical artefacts include not only architectural elements such as residential and commercial buildings that provide homes for people and facilities for business and government activities, but the physical infrastructure networks connecting and servicing these buildings and facilities - with overhead, surface, and buried elements. People live, work, communicate, and travel, in, around and between these different architecture and infrastructure networks on a daily basis, while a generally less visible network of norms, rules, and regulations coordinates and maintains order and functionality.

Climate change is now considered unequivocal, and includes atmospheric and ocean warming, diminishing snow and ice, rising sea levels and increasing greenhouse gas (GHG) concentrations (IPCC, 2013). These changes in the basic elements of Earth's support systems are expected to alter many of the historical patterns that societies and communities have come to rely upon. In many cases, these changes and alterations will result in an increasing quantity and magnitude of hazards: 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. The confluence of impacts and settlements leads to increasing numbers of "natural disasters" (UNISDR, 2012, p. 15).

Climate change related hazards threaten cities around the world, confronting communities with an urgent requirement for self-evaluation. In order to properly address these potential threats, cities will need to not only expose and assess potential hazards, but consider the exposure, sensitivity, and vulnerability of the different systems that comprise the urban fabric. Beyond vulnerability assessment, the reaction of these systems becomes important - resilience has emerged as a useful concept for framing the response of cities to an expanding collection of potential threats.

2 WORKING DEFINITIONS

The wide variety of actors involved in climate change bring with them different understandings, making it is essential to attempt to define the terminology surrounding climate change and find the proper role for resilience. The presentation of definitions for the different terms central to the climate change discourse is by no means intended to imply that there is complete agreement surrounding them. Many of the terms invoke different meanings within different fields, and the ensuing semantic battles within the different fields involved in climate change science have become a mainstay of academic journals worldwide. The definitions presented may be considered some of the more popular or best accepted definitions, though this claim is likely to bring criticism as well. These terms are presented to provide a central basis for the discussion that ensues, without implication that these represent the correct or final definition.

2.1 EXPOSURE

With regards to climate change, the external risk associated with the spatial arrangement of a system potentially at risk is referred to as exposure. The Intergovernmental Panel on Climate Change (IPCC) has defined exposure as "the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected" (IPCC, 2012, p. 5).

2.2 ADAPTIVE CAPACITY

Adaptive capacity is defined in the IPCC Third Assessment Report (TAR) as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC, 2001, p. 6). A slightly different take is presented in the IPCC Fourth Assessment Report (AR4) "the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies"(Adger et al., 2007, p. 727).

2.3 SENSITIVITY

The IPCC TAR defines sensitivity as "the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli" (IPCC, 2001, p. 6).

2.4 CRITICALITY

Criticality is a relative concept related to how essential a component, system, or function is to the needs of society (Cabinet Office, 2012; Fisher and Norman, 2010; GAO, 2007; Luiijf et al., 2003). Infrastructure criticality has been defined as dependent on both the "level of contribution … to society in maintaining a minimum level of … law and order, public safety, economy, public health and environment" and the "impact level to citizens or to the government from … loss or disruption" (Theoharidou et al., 2009, p. 40).

2.5 VULNERABILITY

A succinct definition of vulnerability as related to climate change is provided by the IPCC, where it is defined as "the propensity or predisposition to be adversely affected" (IPCC, 2012, p. 5). Adger defined vulnerability as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt"(2006, p. 268). The European Climate Adaptation Platform (CLIMATE-ADAPT) defines vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity"(EC and EEA, 2014).

2.6 ADAPTATION

Adaptation depends on adaptive capacity (Smit et al., 2001), and represents an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation" (EC and EEA, 2014). The IPCC differentiates between adaptations in different systems: "In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate" (IPCC, 2012, p. 5).

2.7 RESILIENCE

Milman and Short refer to Folke (2006) when defining resilience as a system’s ability to "maintain (or improve) upon its current state over time" and "adapt to stresses and changes and to transform into more desirable states" (2008, pp. 758, 759). In this context, resilience represents a system characteristic in the form of absorptive and adaptive capacity, a function of system stresses and accommodative responses. A more current and specific definition by the IPCC considers resilience to be "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions" (IPCC, 2012, p. 5). Extremely similar, but tailored to communities, the UNISDR and ICLEI definition is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of the hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNISDR). Resilience focuses investment on increasing a city area's overall ability to support a vibrant, healthy society and economy under a wide range of circumstances (ICLEI)" (UNISDR, 2012, p. 85).

3 FRAMING RESILIENCE

3.1 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), presented one of the initial conceptual frameworks for climate change vulnerability research, documenting the development of terminology related to vulnerability as well as the evolution of approaches to vulnerability assessment. The framework itself provides a visual linkage map between many of the terms and concepts within the climate change discourse. The framework has been utilized and expanded by other research groups (e.g. EEA, 2012; ESPON Climate, 2011; Lung et al., 2011). and presents a compelling image to describe the system in ways that help lead to quantifiable definitions and explanatory equations. (Figure 1).

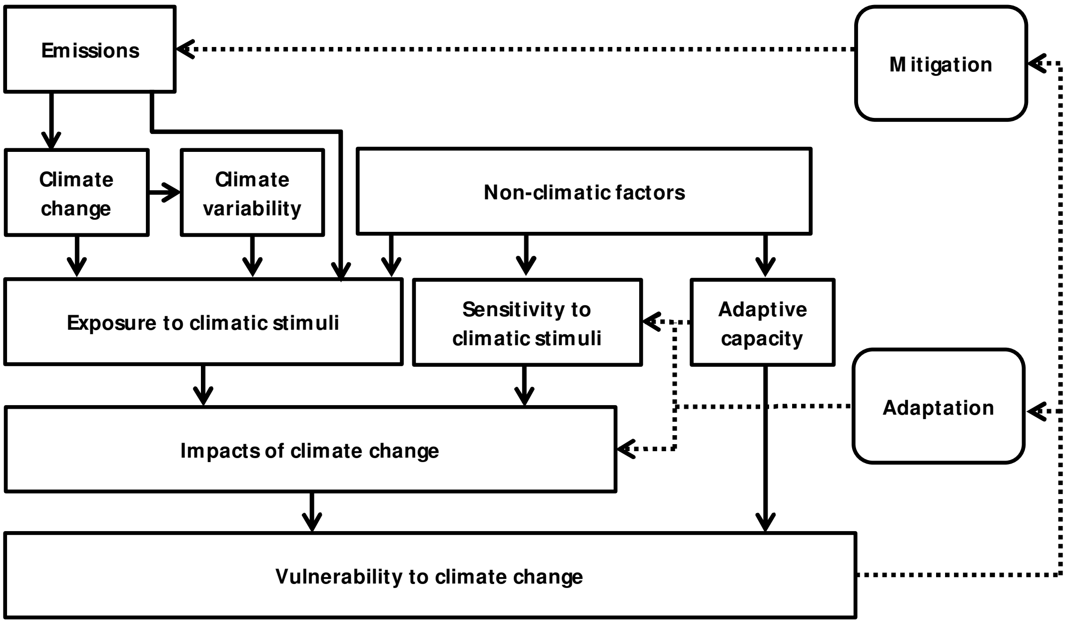

Fig. 1 vulnerability assessment framework (ESPON Climate, 2011); adapted from (Füssel and Klein, 2006)

Much of the current research on climate change impacts, adaptation, and vulnerability (IAV) follows the conceptual framework above, 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 from climate change. In order to conceptualize this interaction and confluence between socioeconomic processes, climatic factors, and risk and impacts, the IPCC has presented an alternate conceptualization (Figure 2). Here exposure, vulnerability, and hazards are used to determine the risk of impacts from climate change.

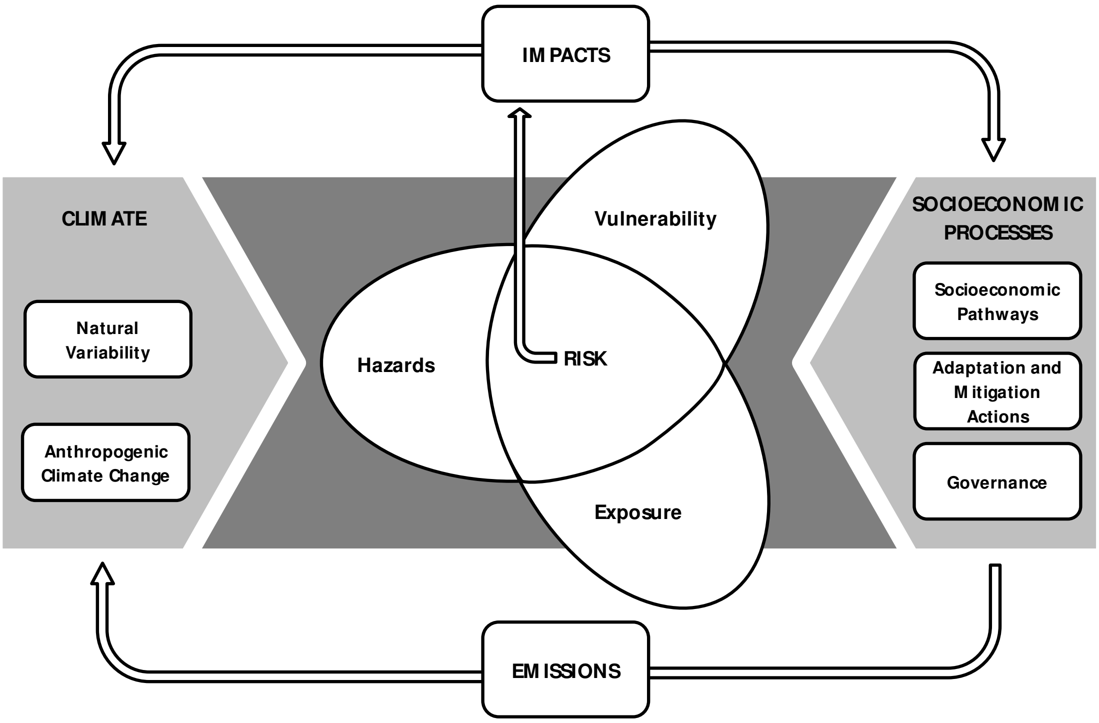

Fig. 2 risk assessment framework (IPCC, 2014)

3.2 VULNERABILITY AND RESILIENCE

As noted above, climate change vulnerability is related to the exposure and sensitivity of an object or system to risk, moderated by its capacity for adaptation (EC and EEA, 2014). Vulnerability is generally considered as a relative concept, used in reference or in comparison with another system (Wolf et al., 2013). Vulnerability can be reduced through adaptation to reduce either exposure or sensitivity, or both together. In physical systems such as architecture and infrastructure, an example of exposure reduction would be through relocation of components, while sensitivity can be reduced through hardening and protection of components and subsystems (DOE, 2010). The goal of vulnerability reduction in the context of architecture and infrastructure is to reduce the risk of damage to components and subsystems in order to manage risk.

Resilience in the built environment, on the other hand, refers to the maintenance of function in spite of damage. While components themselves may be resilient, the resilience of the system does not depend on this, only that the desired function persists or is able to resume with minimal time and resources after a disruption. A resilient system can be comprised of resilient components and subsystems, or alternately individual components can be protected, distributed, redundant, or even expected to fail. As long as these lower level components are well understood and managed spatially and functionally, the resilience at a higher scale can be maintained. The goal of the system is persistence of provision of desired functions, regardless of the specific methodology used to attain this.

4 PROMOTING RESILIENCE

Resilience is not assumed or promoted here to be the only, or the best, approach to minimizing impacts from climate change hazards and threats. What the concept of resilience does provide, however, is a middle ground: a safe haven between two competing paradigms. On the one side, efficiency has been promoted as the best way to achieve sustainability, though it often works in opposite manner, increasing consumption through the rebound effect (Walker and Meyers, 2004; Walker and Salt, 2006). On the other side, defence and protection have been promoted in the past as ways to prevent potential threats from causing impacts (Garbin and Shortle, 2007). Efficiency and protection have their place, but both have been demonstrated to be fallible. The quest for efficiency can reduce options (i.e. removal of redundancies) and funnel resources into specific regimes, which are then prone to complete or sudden failure – the proverbial "all your eggs in one basket." Protection is never absolute, and efforts to provide protection can increase exponentially in response to linear threat increases (Garbin and Shortle, 2007). At a small enough scale, efficiency may provide cost and resource benefits, but when efficiency applied to components of a system or sector can results in critical susceptibilities where even isolated events can wreak havoc on provision of a necessary function.

As an example, district heat has been promoted as an efficient, environmentally friendly way to provide urban heat in a cold environment (Rosenthal, 2010; Tagliabue, 2013). In some cold communities district heat is relied upon as the sole method of heating residences. Reliance on this single point of provision can result in vulnerabilities in function provision; a single construction mistake in Oslo, Norway resulted in damage to the single protected (buried) pipe providing heat and hot water to downtown Oslo - a neighbourhood of 30000 inhabitants, resulting in a total loss of service for up to 3 days (Bakken et al., 2014; Sigurjonsdottir, 2014; Solberg, 2014). As this was an isolated incident, and electricity was still functional, vouchers were provided by the utility to refund the purchase of electric heaters (Hafslund, 2014). The result of this event is a loss of efficiency (redundant heating systems) but an increase in resilience (two separate systems providing the same functional capacity).

4.1 SCALES OF RESILIENCE

In keeping with the other terms in the climate change discourse, resilience is a common target for semantic debate. Much of the debate surrounding resilience centres on the different approaches to resilience by different fields. Engineering resilience is differentiated from social ecological resilience, as well as resilience in complex social ecological systems (SES), and systems of systems. Different fields employ slightly different understandings, with one essential difference being whether the system returns to its prior state (engineering resilience) or can move or transform to a different state (SES resilience), while maintaining provision of the desired function (Walker et al., 2004). It can be argued that these differing definitions consist simply of application of the same concept at different scales, and not a fundamental difference in understanding.

At smaller scales, engineering resilience may be the most relevant, whereby system components can reasonably be expected or hoped to return to their original state after a disturbance. As the scale increases, the resilience options may increase, if there are other methods available of providing the same service or function. At the city scale, resilience could presumably be assessed with a broad application to sectors, such as provision of clean water, shelter, and energy, regardless of the specific methodology of the provision.

While spatial scales may be the easiest to visualise and use as metaphors (Walker et al., 2004) derivation of the relationships both between resilience characteristics, and between characteristics and systemic resilience, is needed across multiple scales (i.e. spatial, temporal, and organizational) (UN-ESCAP, 2013).

4.2 MULTISCALE VULNERABILITY, RESILIENCE AND CRITICALITY

The relationship between vulnerability and resilience is often discussed and often confused – they are "different but complementary framings" (Turner II, 2010, p. 573), and are not subsets of each other, nor are they opposites – the absence of vulnerability does not equate with resilience (Manyena, 2006, p. 443). 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). Reduction in vulnerability and increase in resilience can be synergistic, however – both work to limit the extent of damage inflicted by a hazard. Reducing the vulnerability of system components 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).

Trees and forests provide 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 to exhibit resilience, and non-resilient systems need to limit their vulnerability.

The vascular system of a tree is comprised of a vast network of vessels and organs providing different functions. The leaves produce energy from sunlight through photosynthesis, and individually are relatively exposed and sensitive to injury. They are heavily networked and redundant however, allowing the system to tolerate a certain amount of peripheral damage while maintaining function at an acceptable level, and have a high capacity for recovery (healing); as a system they exhibit most if not all of the characteristics used to define resilience. Leaves are connected to stems and branches, which contain vessels for the transport of water to the leaves and the products of photosynthesis (photosynthate) from the leaves. As the scale increases from leaves and stems up to secondary and primary branches, both vulnerability and resilience decrease, while criticality increases. Failure of the smaller stems has lower consequences than failure of larger branches: they are less critical. The more critical larger branches have less redundancy and less capacity for recovery from damage yet they are less vulnerable: less exposed by being protected behind a thicker layer of bark, and less sensitive by being thicker and more fibrous (stronger). Branches terminate in the trunk, which provides structure to the tree, and provides a conduit for the vessels transporting water up from the roots, and photosynthate down from the leaves. While a tree has different systems providing critical functions, it is difficult to describe any individual element of a tree as "critical" to its survival. The trunk could be considered the single critical element, yet it exhibits reduced vulnerability: the important systems are less exposed by being protected behind the thickest bark layer, and less sensitive by being thicker and more fibrous (stronger). Though the trunk is a single element, the longitudinal vessels providing critical functions within the trunk remain networked and redundant.

The evolution of trees has led to interesting survival mechanisms, whereby it is clear that resilience expands beyond the systems of the tree, or its parts, or the tree itself. The loss of a single tree to a forest is similar in scale to the loss of a leaf or branch on a tree. It is a redundant element, and the forest can continue to thrive while tolerating a certain amount of damage or loss. Trees and forests have adapted mechanisms to limit (or embrace) the widespread effects of destructive events; a large fire may destroy the trees but in the process trigger the beginning of the seed cycle (Schwilk and Ackerly, 2001).

Unlike trees, which must rely on evolution over long time scales to exhibit adaptation, people have a capacity to immediately influence the vulnerability and resilience of the organ systems providing essential functions. Also unlike trees, the human body has high level organs, such as the heart, spinal cord, and brain, which are critical to function and survival. These organs lack redundancy and have little recovery capability; they are not particularly resilient, but they are protected by solid bone, reducing their exposure and sensitivity, and therefore vulnerability. People 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, as well as the anticipated threat. Protecting the head and torso to reduce vulnerability are direct consequences of the high criticality, high vulnerability, and low resilience of these areas. Like a tree to a forest, the injury or death of a single person does not represent system failure or collapse of a larger group. Up to a certain level of population loss, the group (e.g. community, society) can survive.

In all cases, a resilient system would be defined as one that can tolerate or absorb a certain amount of damage, and heal, recover, or transform. 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 a hierarchical resilience framework to the built environment, architecture and infrastructure, it becomes apparent that vulnerable systems should either reduce their vulnerability (exposure and sensitivity), or increase their resilience. The resilience of a community is a function of the vulnerability and resilience of individual components (physical and social), as well as the fabric or network that connects them. Climate change adaptation strategies 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.

4.3 CRITICALITY AND THE PERSISTENCE OF NEEDED FUNCTIONS

While many national programs have moved from a focus on critical infrastructure protection to critical infrastructure resilience, often with explanations of why resilience is now the preferred method, they have been less explicit when explaining the specificity of what is critical and what is not (AU, 2010; Cabinet Office, 2010; GAO, 2010; Graham, 2011). Critical infrastructure is defined, and the sectors that comprise it are listed, but little effort is made to tease out which specific elements are essential to providing the needed services.

The large scale resilience of a city is a function of its intentions and ability to provide essential services and satisfy the needs of its inhabitants. This does not imply that every sub sector or component providing necessary functions needs to exhibit resilient characteristics - it is the persistence of function that is important. An alternate approach to defining criticality within a city would be to focus on the functions that are essential for urban survival. A place to start is with the seminal work on human needs and motivation by Abraham Maslow.

Necessary functions can be elucidated using Maslow's hierarchy of needs – introduced as motives for human behaviour, which been updated and revised through the years (Kenrick et al., 2010; Maslow, 1970, 1958, 1943). The hierarchy of needs posits a human motivation system whereby each subsequent need is predicated on the attainment or fulfilment of more basic needs (Figure 3).

While the hierarchy of needs is regularly scrutinized over the specifics of some certain segment of the hierarchy, the overall pattern remains well accepted (Clarke et al., 2006; Hagerty, 1999; Kiel, 1999; Koltko-Rivera, 2006; Wahba and Bridwell, 1976; Wicker et al., 1993). In the case of the defining and prioritizing human needs, there is little argument that survival is the most basic human need. These basic needs, the "immediate physiological need" for homeostasis (dynamic balance with the environment, including elements such as hunger, thirst, and temperature regulation), as well as the need for safety (self-protection) from direct harm, form the foundation from which other motivations and needs can build upon (Kenrick et al., 2010; Maslow, 1958, 1943).

Based on this hierarchy of needs we can propose that the provision of food, water, (temperature regulated) shelter, and the immediate and longer term minimization of risk of injury and death are the most critical human needs.

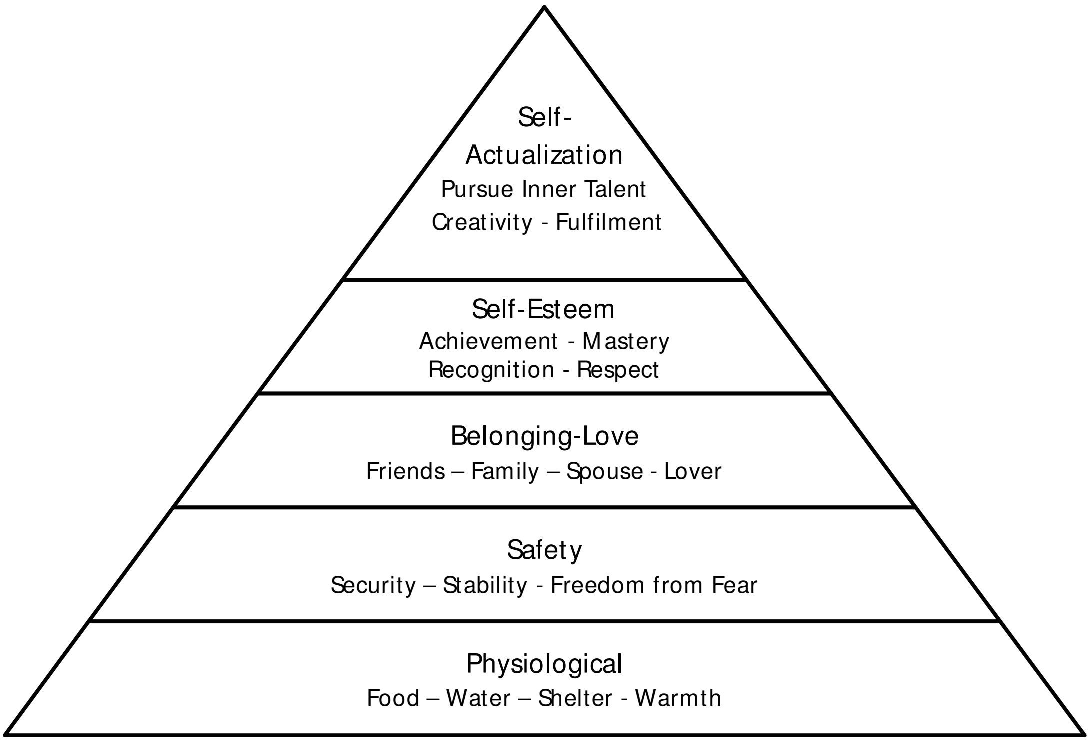

Fig. 3 Maslow's hierarchy of needs, adapted from (Maslow, 1970, 1943)

The hierarchical arrangement posits that these needs must be satisfied before moving up a level and confronting other needs and motivations.

Many of these critical needs are functions of the fabric of the urban city – they are dependent on, or consist of, services provided by architecture and infrastructure networks. In order to attempt to determine resilience at the city scale, the first task is to resolve which aspects of service provision could be considered critical to society. Beyond the definition and assessment of criticality, it is necessary to determine ultimate responsibility for these services – differentiating for example between personal, local, regional, and national responsibilities; as Maslow notes, there are various "paths to the same goal" (Maslow, 1943, p. 370). Admittedly, this differentiation is fuzzy, and subject to extreme cultural variability. An example of a potential needs hierarchy for services provided by architecture and infrastructure is shown in Figure 4.

5 CHARACTERISTICS FOR RESILIENT ARCHITECTURE AND INFRASTRUCTURE

5.1 TEMPORALITY

In addition to the varying potential scales of application, the three different temporal phases associated with resilience pose serious methodological challenges: Efforts necessary to anticipate, prevent, and prepare a system take place before a disruptive event; A system resists and absorbs during an event; Recovery occurs after a disruption.

These three phases (Figure 5) may correspond to different fields of expertise – vulnerability and risk management, crisis management, or adaptation – which are confronted with different challenges and develop specific methods accordingly.

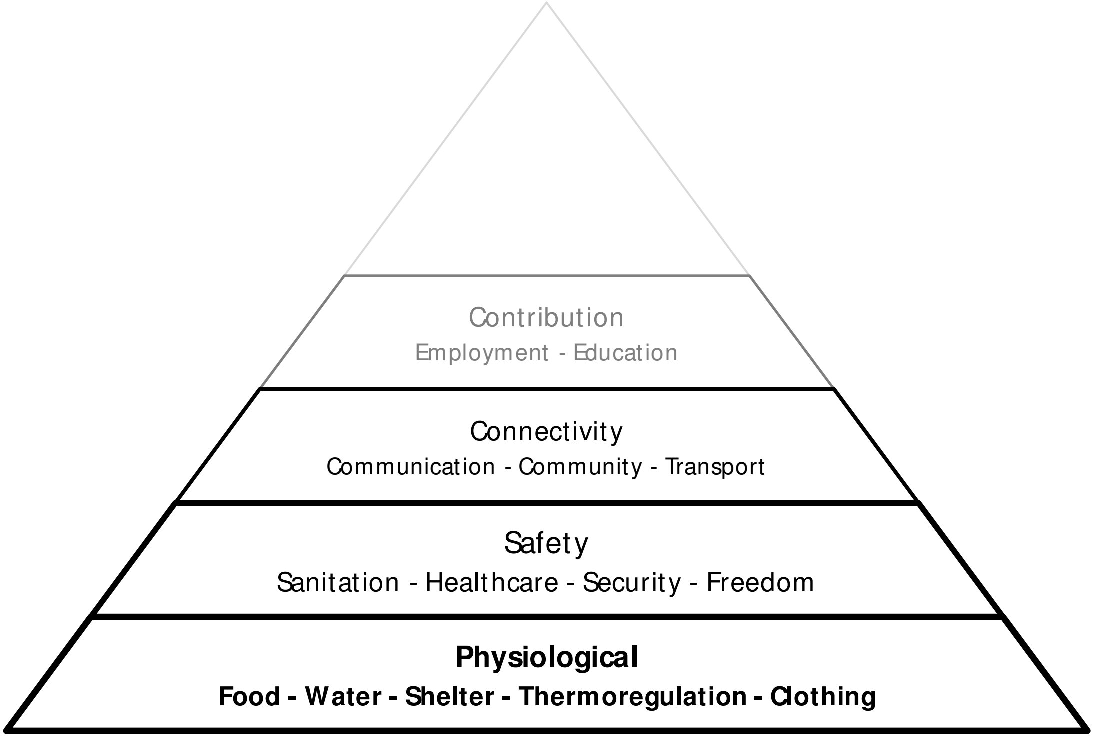

Fig. 4 hierarchy of service functions provided by architecture and infrastructure, based on (Maslow, 1970, 1943)

In the context of climate change, this cycle of phases related to events becomes more complicated. This resilience cycle operates within different temporal as well as spatial scales – climate change could be considered one huge event, where all three phases will be conflated and occur simultaneously. The effects of climate change will likely be realized in a recurring and successive manner with increasing intensity, so the temporal order retains its validity albeit in the form of miniature cycles that may occur within a larger phase.

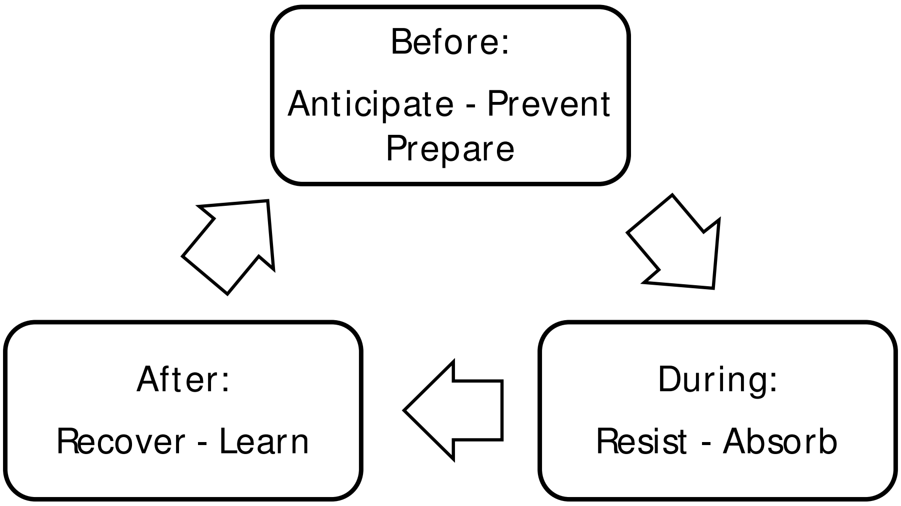

Fig. 5 temporal phases and corresponding activities related to resilience

5.2 PHYSICAL AND ORGANIZATIONAL RESILIENCE

The provision of critical services from architecture and infrastructure is imperative for people's quality of life. Architecture and infrastructure should be designed or adapted to reliably provide these services, resilient even in the face of potential hazards and threats. Resilient systems should be able to maintain function while maintaining or enhancing 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 (physical) and all the institutions that are required to maintain the standards of living of a community (organizational). Infrastructure can be considered in terms of physical objects and networks or in terms of services. Physical assets are designed to provide services to their users and owners – in terms of resilience to climate change it should be recognized that the services provided are more important than the structures themselves.

A set of characteristics attributed to resilient systems was derived through literature review, and categorized according to their application to physical (Table 1) or organizational (Table 2) systems and networks.

PHYSICAL CHARACTERISTIC	DESCRIPTIONS
Connectivity, Feedbacks, Modularity	"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) in (Schultz et al., 2012, p. 54). "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) in (Schultz et al., 2012, p. 53). "Interacting components composed of similar parts that can replace each other if one, or even many, fail" (Tyler and Moench, 2012, p. 313).
Dependence on Local Ecosystems	Local control over the essential "services provided by local and surrounding ecosystems" (the city's green and blue infrastructure - providing "flood control, temperature regulation, pollutant filtration and local food production)" … "and taking steps to increase their health and stability" (da Silva et al., 2012, p. 136). "…presence of buffer stocks within systems that can compensate if flows are disrupted (e.g. local water or food supplies to buffer imports)" (Tyler and Moench, 2012, p. 313).
Diversity	The "different types of available resources that perform a particular function." Diversity in available resources for critical functions "provides a multitude of options for accomplishing those particular functions" (Longstaff et al., 2010b, p. 6). "…key assets and functions physically distributed so that they are not all affected by a given event at any one time (spatial diversity) and … multiple ways of meeting a given need (functional diversity)" (Tyler and Moench, 2012, p. 315).
Performance	The "general level of capacity and quality at which an element or elements of a system performs an essential role" (HSSAI, 2009) cited in (Longstaff et al., 2010b, p. 6).
Rapidity, Responsiveness	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, p. 738). "The ability to reorganise, to re-establish function and sense of order following a failure. Rapidity is a key part of responsiveness in order to contain losses and avoid further disruption" (da Silva et al., 2012, p. 135)

PHYSICAL CHARACTERISTIC	**DESCRIPTIONS**
Redundancy	Substitutable "elements, systems, or other units" ... "capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality" (Bruneau et al., 2003, p. 737; Schultz et al., 2012; Walker and Salt, 2006). "Superfluous or spare capacity to accommodate increasing demand or extreme pressures" (da Silva et al., 2012, p. 134). "Spare capacity for contingency situations, to accommodate extreme or surge pressures or demand" (Tyler and Moench, 2012, p. 313). A "quantifiable measure, or count, of a single resource type that performs a specific function. Redundant resources provide a failsafe, or back-up, when any individual unit fails. Redundancy is also a form of operational slack, or buffering from external shocks" (Longstaff et al., 2010b, p. 6).
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, p. 737). Robustness "depends on the ability of individuals, groups, or technologies to tolerate a broad range of conditions" ... determined as function of "performance, redundancy, and diversity" (Longstaff et al., 2010b, pp. 6, 21).
Safe Failure	The "ability to absorb shocks and the cumulative effects of slow-onset challenges in ways that avoid catastrophic failure if thresholds are exceeded. When a part of the system fails, it does so progressively rather than suddenly, with minimal impact to other systems. Failure itself is accepted" (da Silva et al., 2012, p. 135). "Ability to absorb sudden shocks (including those that exceed design thresholds) or the cumulative effects of slow-onset stress in ways that avoid catastrophic failure." Linkages designed such that "failures in one structure or linkage are unlikely to result in cascading impacts across other systems" (Tyler and Moench, 2012, p. 313).

Tab. 1 core dimensions of resilient physical systems and networks

ORGANIZATIONAL CHARACTERISTIC	**DESCRIPTIONS**
Adaptability, Flexibility	"Capacity to change as the surrounding environment changes while still maintaining functionality" (Walker and Salt, 2006) in (Schultz et al., 2012, p. 53). "The ability to change, evolve and adopt alternative strategies (either in the short or longer term) in response to changing conditions" (da Silva et al., 2012, p. 134). Adaptive capacity is represented as a function of "institutional memory, innovative learning, and connectedness" (Longstaff et al., 2010b, p. 7).
Connectivity, Feedbacks, Modularity	"Interpersonal and group connectedness is critical to the diffusion of institutional memory and innovative learning throughout the community" (Longstaff et al., 2010b, p. 8). The "ability to internalize past experiences, avoid repeated failures, and innovate to improve performance" (Tyler and Moench, 2012, p. 315).
Diversity	"Variety in the number of species, people, and institutions that exist in a social-ecological system" (Walker and Salt, 2006) in (Schultz et al., 2012, p. 53).

ORGANIZATIONAL CHARACTERISTIC	DESCRIPTIONS
Learning, Memory	Individual and institutional learning "from past experiences and failures" provides the ability to "use such experience to avoid repeating past mistakes and exercise caution in future decisions" (da Silva et al., 2012, p. 135). Accumulation of "shared experience and local knowledge of a group of people" resulting in institutional memory (Longstaff et al., 2010b, p. 7) Ability to use" information and experience to create novel adaptations to environmental changes or to avoid repeating old mistakes" (Longstaff et al., 2010b, p. 7).
Performance	The "general level of capacity and quality at which an element or elements of a system performs an essential role" (HSSAI, 2009) cited in (Longstaff et al., 2010b, p. 6).
Rapidity, Responsiveness	"The ability to reorganise, to re-establish function and sense of order following a failure. Rapidity is a key part of responsiveness" … but should achieve a balance so as not to compromise the ability to learn (da Silva et al., 2012, p. 135) "Capacity to organize and re-organize in an opportune fashion;" ability to establish function, structure, and basic order in a timely manner both in advance of and immediately following a disruptive event or organizational failure (Tyler and Moench, 2012, p. 315).
Redundancy	Substitutable "elements, systems, or other units" … "capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality" (Bruneau et al., 2003, p. 737; Schultz et al., 2012; Walker and Salt, 2006).
Resourcefulness	"The capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis" including "the ability to apply material (i.e., money, physical, technological, and informational) and human resources to meet established priorities and achieve goals" (Bruneau et al., 2003, pp. 737–8). "The capacity to visualise and act, to identify problems, to establish priorities and mobilise resources when conditions exist that threaten to disrupt an element of the system. This capacity is related to the ability to mobilise assets (financial, physical, social, environmental, technology and information) and human resources to meet established priorities and achieve goals" (da Silva et al., 2012, p. 135). "Capacity to mobilize assets and resources for action. It also includes the ability to access financial and other resources, including those of other agents and systems through collaboration" (Tyler and Moench, 2012, p. 315).

Tab. 2 core dimensions of resilient organizational systems and networks

5.3 CHARACTERISTICS AND DIMENSIONS OF RESILIENCE

Highlights from the various physical and organizational dimensions and understandings of resilience attainment and assessment were presented and discussed during two workshops:

- A RAMSES stakeholder workshop with city representatives in Brussels 11 October 2013 organised by ICLEI-Local Governments for Sustainability
- A researchers' workshop with climate change mitigation and adaptation experts in Helsinki 23 October 2013 organised within the framework of COST (European Cooperation in Science and Technology) Action TU0902 Integrated Assessment of Cities

During these workshops three aspects were emphasised: core dimensions of resilient systems, identification of resilience characteristics for architecture and infrastructure, and approaches in which indicators can be identified and applied to recognise opportunities for intervention.

One of the activities in the workshop focused on identifying and assessing the implications and understanding of resilience characteristics. In this activity 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 resilience characteristics derived from literature reviews. This set consisted of characteristics gleaned from the literature, separated from context and scale and presented without value in expert and stakeholder workshops. The purpose of this exercise was to tease out the current understanding of these terms - especially with respect to their relationship with resilience. The characteristics are used to inform the development of an operational understanding of resilience, while not necessarily maintaining (or narrowing debate into) existing patterns. Due to the variety of approaches of considering resilience in the literature, the list of characteristics includes both variables related to mechanisms of achieving, promoting, or enhancing resilience, as well as variables related to ex-post evaluation.

Table 3 summarises the main characteristics of resilient systems identified in literature and by RAMSES workshop participants (the latter's additional contribution *in italic*).

CHARACTERISTIC	**DESCRIPTIONS**
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*

CHARACTERISTIC	**DESCRIPTIONS**
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*

Tab. 3 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; 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; UN-ESCAP, 2008; Van Der Veen and Logtmeijer, 2005; Wilson, 2012)

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

5.4 DEVELOPING RESILIENCE INDICATORS

The development of indicators for resilience in architecture and infrastructure is a difficult task, as they must address the typical challenges of assessment (e.g. feasible, cost-effective, and informative) while simultaneously addressing and capturing the very complex nature of resilience. In practice, different indicators have been proposed to assess proxy properties of resilience. Any indicator framework developed for assessment of resilience must not only address its multi-scale nature, but must acknowledge the difference between measurement of ex-post resilience to a realized event, and system characteristics perceived to contribute to resilience:

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

The theoretical underpinnings and specific definition of resilience has been approached by many different disciplines, stakeholders and schools of thought. This extreme diversity is reflected in the nature and focus of understandings of resilience. 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. Three related capabilities are considered important (or necessary) for increasing resilience in systems and networks:

1. The provision of absorptive capacity so that the system or network can withstand disruptions;
2. Adaptive capacity so that service functions can be delivered via alternate paths;
3. Restorative capacity so that recovery from a disruptive event can be accomplished quickly and with minimum effort (Turnquist and Vugrin, 2013).

As such, 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.

6 CONCLUSIONS

Resilience in architecture and infrastructure networks refers to the maintenance of function in spite of damage. Individual components themselves may be resilient, but the resilience of the system does not depend on this, only that the desired function persists or is able to resume with minimal time and resources after a disruption. A resilient system can be comprised of resilient components and subsystems, or alternately individual components can be protected, distributed, redundant, or even expected to fail. As long as these lower level components are well understood and managed spatially and functionally, the resilience at a higher scale can be maintained. The goal of the system is persistence of provision of desired functions, regardless of the specific methodology used to attain this.

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 recommendations for "resilient" architecture and infrastructure adaptation to climate change impacts, such as adjustment in grey and green infrastructures (e.g. BRTF, 2013a, 2013b; BSA, 2013; DEFRA, 2012; KK, 2011). 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. Damage risks and costs can likely 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, low- and no-regret options could provide a range of co-benefits for climate change mitigation/adaptation as well as quality of life; for example, green areas and water bodies could provide storm water management, delay the urban heat island effect, and create local leisure facilities for the urban population. Costs could 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).

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. It may however be possible to learn from past examples of resilience which system characteristics help it exhibit resilience in the face of adversity - developing a database of events and responses in order to derive which characteristics are most associated with realized resilience. These characteristics can be cultivated in new developments and existing communities. Indicators based on these characteristics and determining factors are useful for phenomena that have yet to be observed, or are not directly measurable, but for which a conceptual understanding is available. The problem with applying this 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 successful restoration of functionality after a disruptive event, but indicator development requires working backward from ex-post assessment to ex-ante indicators of system characteristics.

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IMAGE SOURCES

Title image: Mining scars; Montaña La Sahorra, Tenerife, Spain. Photo: J. Kallaos

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He received consecutive Master's degrees in environmental science and management at (University of California, Santa Barbara) and sustainable design (Harvard University Graduate School of Design) before beginning a PhD in Civil Engineering at NTNU. While finishing the PhD, he works as a researcher in the Department of Architectural Design, History and Technology at NTNU.

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