Resilience of critical infrastructures: review and analysis of current approaches

C. Curt, J.M. Tacnet

To cite this version:

C. Curt, J.M. Tacnet. Resilience of critical infrastructures: review and analysis of current approaches. Risk Analysis, 2018, pp.18. 10.1111/risa.13166 . hal-02607701

HAL Id: hal-02607701
https://hal.inrae.fr/hal-02607701v1
Submitted on 16 May 2020

Resilience of critical infrastructures: review and analysis of current approaches

Corinne Curt[1*], **Jean-Marc Tacnet**[2]

[1] Irstea, UR RECOVER, Centre d'Aix-en-Provence, 3275 Route de Cézanne, CS 40061, 13182 Aix-en-Provence Cedex 5, France – corinne.curt@irstea.fr

[2] Univ. Grenoble Alpes, Irstea, UR ETGR, Centre de Grenoble, 38402 St-Martin-d'Hères, France – jean-marc.tacnet@irstea.fr

---

[*] Corresponding author

Abstract

In crisis situations, systems, organizations and people must react and deal with events that are inherently unpredictable before they occur: vital societal functions and thus infrastructures must be restored or adapted as quickly as possible. This capacity refers to resilience. Progress concerning its conceptualization has been made but it remains difficult to assess and apply in practice. The results of this paper stem from a literature review allowing the analysis of current advances in the development of proposals to improve the management of infrastructure resilience. The article: (i) identifies different dimensions of resilience; (ii) highlights current limits of assessing and controlling resilience; (iii) proposes several directions for future research that could go beyond the current limits of resilience management, but subject to compliance with a number of constraints. These constraints are taking into account different hazards, cascade effects and uncertain conditions, dealing with technical, organizational, economical and human domains, and integrating temporal and spatial aspects.

200-character summary

The article identifies different dimensions of the resilience of critical infrastructures, highlights current limits of assessing and controlling resilience and proposes several directions for future research.

Keywords

Resilience

Critical Infrastructure

Disaster

1. INTRODUCTION

A critical infrastructure (CI) is defined as a “point, system or part of one […] essential for maintaining the vital functions of a society, and the health, safety, security and economic and social well-being of the community, whose cessation or destruction would have a significant impact” (Union Européenne, 2008). CIs fulfil this role in different sectors: transport (road and rail networks, etc.), energy, communication, water supply, the nuclear industry, etc. The impact of their failure can be expressed by the severity of its effect (duration of lack of service, economic losses), the extent of the area and the number of persons affected, and the speed of recovery from the failure.

The concept of risk is based on identifying a threat and its associated consequences and losses. Its management is aimed at analyzing the level of risk, proposing measures of reducing it, anticipating crises, setting up contingency planning, etc. Unfortunately, it is practically impossible to fully protect CIs: they are complex and vulnerable systems faced with a wide array of natural and anthropic threats that are also evolutive (Boin & McConnell, 2007; Fritzon, Ljungkvist, Boin, & Rhinard, 2007). History has shown that many natural events (the tsunami in Southeast Asia in 2004; the fires in Greece during summer 2007; Hurricane Katrina in 2005; the Xynthia storm in February 2010; the accident of Fukushima in March 2011, etc.) and human ones (the terrorist attack at Atocha station in 2004; the accident at the AZF plant at Toulouse in 2001; an increasing number of attacks on the CIs of the members of the European Thematic Network on Critical Energy Infrastructure Protection in 2012, mainly in the form of thefts, vandalism and cyberterrorism (TNCEIP, 2012), etc.) have had considerable impacts on these infrastructures.

It is obvious that in spite of significant progress, risk management procedures, particularly in contexts that combine natural phenomena and technological accidents, are particularly fallible. The limits of risk management procedures can be attributed notably to:

- Lack of knowledge (unknown threats – “black swan events”) and uncertainty (unexpected severity of natural phenomena, low-probability events, accidents). Crisis planning is in itself contradictory: how can one plan for a phenomenon that by nature does not match the hypotheses that planners use as their basis for predicting it (Boin & McConnell, 2007)? This situation is aggravated by global changes and the increasing threat of terrorist attacks.

- The growing complexity of large socio-technical systems and combinations of organizational and technical failures, leading to unexpected situations and/or cascade effects exacerbated by the strong relations forged between infrastructures. Indeed, CIs interact reciprocally, notably due to the increased use of information and communication technologies (Vinchon et al., 2011). These interactions are dependencies (one-way relation) and interdependencies (two-way relation) liable to possess different natures: physical, geographic, cyber or logical (Rinaldi, Peerenboom, & Kelly, 2001). Strengthening risk management systems in a context of interconnected networks becomes prohibitive financially and in terms of the time needed to implement them (Linkov et al., 2014).
- Insufficient or poorly designed or maintained defense barriers (Kadri, Châtelet, & Chen, 2014; Landucci, Argenti, Tugnoli, & Cozzani, 2015).
- Errors of procedure (error of application or poorly drafted procedures), insufficient safety training effectiveness or too long response time (Khakzad, Khan, Amyotte, & Cozzani, 2014; Landucci et al., 2015).

CIs are therefore vulnerable to threats and possible transmitters of malfunctions, but vital for reconstruction. During an event, risk management measures may be overcome, and systems, organizations and populations can be confronted with events that were intrinsically unforeseeable before their occurrence, and against which they must react and cope. Vital societal functions, and thus infrastructures, must be restored or adapted as quickly as possible. This capacity refers to the concept of resilience. From the political standpoint, in the beginning of the 2000s, it was asserted that it meant “living with” rather than “fighting against” risks, as exemplified in the 2002 draft of the UNISDR report “Living with Risk” (Quenault, 2015). The impossibility of eradicating disasters and the need for preparedness to cope with these major crises led to a fracture in the use of concepts, hence the gradual slide from vulnerability to resilience. The Hyogo (United Nations/International Strategy for Disaster Reduction (UNISDR), 2005) and Sendai (United Nations/International Strategy for Disaster Reduction

(UNISDR), 2015) Frameworks for Disaster Risk Reduction emphasized the concept of societal resilience at the global scale.

Resilience is a term for which many definitions exist. They generally include different capacities (Bruneau et al., 2005; Francis & Bekera, 2014; Johnsen & Veen, 2013; Labaka, Hernantes, & Sarriegi, 2016; Matzenberger, Hargreaves, Raha, & Dias, 2015; National Academy of Sciences, 2012; Petit et al., 2013; Rosati, Flynn Touzinsky, & Lillycrop, 2015; Vugrin, Warren, Ehlen, & Camphouse, 2010): to plan and prepare to the adverse events (*planification*), to reduce the impact of events (*absorption* or *resistance*), to minimize the time to recovery (*recovery*) and to evolve through the development of specific processes (*adaptability*). Aggregation at a higher level was proposed by Holling, who distinguished engineering resilience which he linked to the capacity of *resistance* and the speed of return to a state of equilibrium, and ecological resilience which he associated with *adaptability* (Holling, 1973). Other terms can also be found in the literature and are combinations of capacities mentioned at the beginning of this paragraph. For example, the term *restoration* refers to the capacities of *recovery* and *adaptability* (Kahan, Allen, George, & Thompson, 2009).

From the technical, organizational, social and economic standpoints, the territories and infrastructures impacted will be capable to a certain extent of reducing the impact of a disruption (natural, human or a combination of both) and end by recovering and returning to an "acceptable" state. The level reached after the crisis could be poorer than, equal to, or better than the initial level (cf. Figure 1). Thus the level of service of a road infrastructure after a major event could be degraded (a section of the road is closed permanently, alternative routes exist but lengthen the journey), restored to normal, improved (following an event, lanes are widened and thus improve traffic in terms of safety and fluidity). The recovery phase can be more or less rapid. Variables assessing the acceptable threshold of performance or characterizing dynamics of recovery have been proposed in the literature: for instance, the *minimum performance boundary* is "the lowest acceptable level of performance for the defined function" (Kahan et al., 2009) while the *latency limit* describes "the maximum amount of time allowable for a function to remain in a degraded or suboptimal state before it must begin to recover" (Kahan et al., 2009) and *rapidity* is "the rate or speed at which a system is able to recover to an acceptable level of functionality, after the occurrence of a disaster event" (Bruneau et al., 2003). Figure 1 shows a graphical representation of these variables.

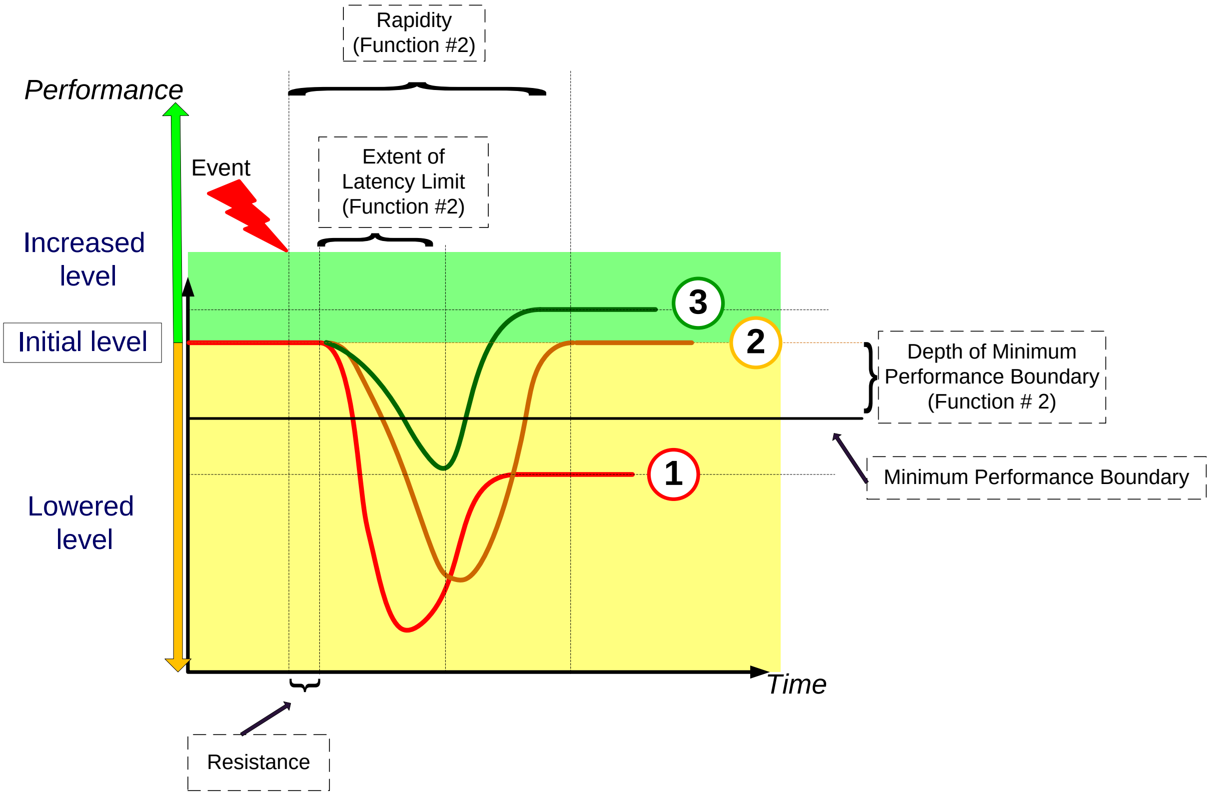

Figure 1. Evolution of levels before and after an event for three functions

Resilience engineering came into being several years ago with the objective of developing methods and tools to improve resilience. "Resilience Engineering looks for ways to enhance the ability at all levels of organizations to create processes that are robust yet flexible, to monitor and revise risk models, and to use resources proactively in the face of disruptions or ongoing production and economic pressures" (Resilience Engineering Association, 2015). Advances have been made regarding the conceptualization of resilience: D. Alexander (Alexander et al., 2011) presented a history of using the concept of resilience in crisis and risk management and described its evolution. Klein et al. also described its history in various fields: ecology, social sciences, economics, etc. (Klein, Nicholls, & Thomalla, 2003). Analyses of this concept in different fields have been proposed (Birkmann, Changseng, et al., 2012; Mc Lean & Guha-Sapir, 2013), and emphasize, for example, that the concept of institutional and organizational resilience is a relatively recent phenomenon in the literature (Mc

Lean & Guha-Sapir, 2013). Most existing definitions express essential aspects of resilience, though apart from a few rare exceptions, they fail to provide quantitative measures, and definitely lack an operational basis for resilience (Alderson, Brown, & Carlyle, 2015). Thus this concept remains difficult to measure and apply in practice.

The paper aims at performing an analysis of current approaches for the assessment and control of resilience for critical infrastructures. It is based on a literature review. Different dimensions of resilience are identified in Section 2; these are necessary for a relevant analysis of current approaches. Sections 3 and 4 point out the current limits of systems for evaluating and managing resilience. The article ends with Section 5 in which several directions for future research that could go beyond the current limits of resilience management are proposed, provided that a certain number of constraints are taken into account. It also opens the notion of resilience to encompass sustainable development and wider scales (cities, territories, and the community).

2. LITERATURE REVIEW: METHODOLOGY AND FIRST LESSONS

2.1 Methodology

To present a breadth coverage of literature review of resilience study, we developed an approach in five steps.

First, to identify the relevant papers, we carried out an analysis on the Web of Science (https://www.webofknowledge.com) and the SCOPUS databases (https://www.elsevier.com/solutions/scopus), two comprehensive multidisciplinary content search platforms for academic researchers. The requests were:

WoS Research: TI=(Resilience AND (Infrastructure OR Network NOT Social)) AND TO=(Manag* OR Assess* OR Control OR Indicator OR Metric OR Measure OR Characteri* OR Evaluat* OR Scenario) AND TO=(Resilience AND (Infrastructure OR Network NOT Social)))
Refined by:

- Document Types: (Article or Review)
- And Languages: (English)
- And Research Areas (Automation Control Systems Or Physical Geography Or Instruments Instrumentation Or Physics Or Computer Science Or Mathematics Or Construction Building Technology Or Science Technology Other Topics Or Energy Fuels Or Engineering Or Telecommunications Or Transportation Or Operations Research Management Science Or Urban Studies Or Geography Or Water Resources)

Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, IC.

SCOPUS Research: TITLE (*resilience* AND (*infrastructure* OR *network* AND NOT *social*)) AND ABS(*manag** OR *assess** OR *control* OR *indicator* OR *metric* OR *measure* OR *characteri** OR *evaluat** OR *scenario*) AND (LIMIT-TO(DOCTYPE , *"ar "*))
AND (EXCLUDE (SUBJAREA , *"MEDI "*) OR EXCLUDE (SUBJAREA , *"AGRI "*) OR EXCLUDE (SUBJAREA , *"BIOC "*) OR EXCLUDE (SUBJAREA , *"ARTS "*) OR EXCLUDE (SUBJAREA , *"NEUR "*) OR EXCLUDE (SUBJAREA , *"PSYC "*) OR EXCLUDE (SUBJAREA , *"PHAR "*)) AND (LIMIT-TO (LANGUAGE , *"English "*))

As our study concerns current approaches, the research was carried out from 2013 until 11/2017. At this step, 223 references were collected (after duplicates removing). They represent 70 % of the papers published since 1990 justifying the choice of the analysis period.

Secondly, survey papers, papers dealing with national policies or resilience conceptualization were mainly used for the analysis of the resilience dimensions (Part 3) and removed from the further analysis in step 3. Fifteen papers were identified leading to consider 208 articles for the next step.

Thirdly, abstract and full review refinements were performed. Only papers dealing with assessment and control of CIs' resilience were kept; articles related to other domains such as ecology or medicine, or presenting territorial approaches, etc. were removed. This operation led to keep 151 references.

Step 4 provides an analysis of papers selected at step 3. Distribution over time, by journals, by types of CIs are presented in the following section (§ 2.2) while distributions concerning methods used or developed and types of resilience will be further used to highlight the limits of current approaches (§ 3 and 4).

2.2 Distribution analyses

2.2.1 Distribution by year of publication

The dynamics of academic research on the assessment and control of resilience of critical infrastructures are analyzed through its distribution over time. The number of publications dealing with resilience and critical infrastructure has increased significantly over the last five years in comparison to the previous years as they represent 70 % of the total number of articles for the period (1990-2017). Around 30-35 articles have been published on the topic since the last 4 years (cf. Figure 2). The major disasters mentioned at the beginning of this article were most certainly the reasons underlying these works. These academic searches have been coupled with the recent government and policy emphasis on resilience mentioned above.

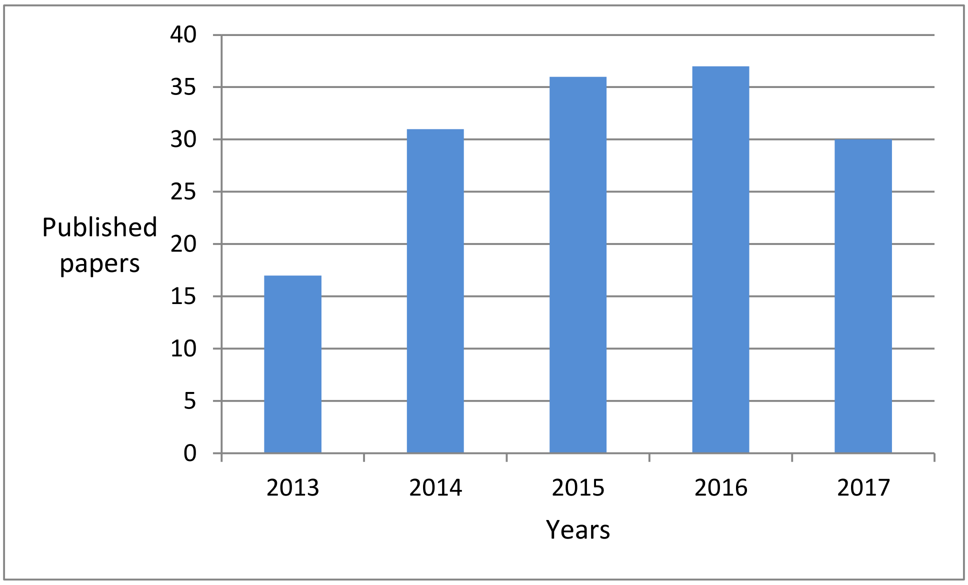

Figure 2. Distribution of papers by year of publication (as of November 2017)

2.2.2 Distribution by journal

Ninety-seven different journals from various disciplines were included in this literature review. Table 1 lists 12 journals that contributed at least 3 articles examined in this literature review. Among these, *Reliability Engineering and Systems Safety* is the most significant source followed by *Risk Analysis* and *Transportation Research Part E: Logistics and Transportation Review*. To complete the list, 14 (resp. 71) different journals published 2 (resp. 1) articles.

Journal Title	**Number of papers**
Reliability Engineering and System Safety	10
Risk Analysis	6
Transportation Research Part E: Logistics and Transportation Review	5
Journal of Structural Engineering (United States)	4
Computers & Industrial Engineering	3
IEEE Communications Magazine	3
International Journal of Critical Infrastructures	3
Journal of Infrastructure Systems	3
Natural Hazards	3
Optical Switching and Networking	3
Physica A: Statistical Mechanics and its Applications	3
Telecommunication Systems	3

Table 1. Top article sources and corresponding number of papers published

2.2.3 Distribution by type of infrastructure

Table 2 shows the distribution of papers related to the various types of infrastructures considered. The main studied infrastructures are clearly transport (road, railways, maritime and air transport) followed by water and communication networks and energy (electricity and gas) infrastructures. Conversely, works concerning infrastructure such as flood risk management or health are very scarce. Thirty-two papers deal with methodological developments without specific applications (infrastructure or critical infrastructure or network in Table 2) with possible applications to different types of critical infrastructures.

Types of infrastructure	Number of papers
Transport	40
Infrastructure or critical infrastructure	22
Communication network	14
Water distribution network	14
Energy infrastructure	13
Interdependent infrastructures	11
Network	11
Supply chain	10
Industrial infrastructures	7
Flood risk infrastructure	4
Health (Emergency services – Hospital)	2
Data Acquisition - Supervisory Control	1
Heat network	1
Logitics networks	1

Table 2. Distribution of the articles following the studied type of infrastructure

2.3 Resilience must be understood as a function of different dimensions

A bibliographical analysis was performed to identify the specific dimensions of resilience. It is based on the articles collected during the WoS and SCOPUS researches completed with other papers dealing with conceptualization of resilience. The results lead to a better perception of this concept and put in evidence main elements for the analysis of current approaches.

The analysis allows us identifying four dimensions characterizing resilience (cf. Figure 3):

- The phases of managing an event in relation to the capacities of the system presented above (National Academy of Sciences, 2012; Petit et al., 2013): *ex ante* (*planning/preparation*), during the event (*absorption*) or *ex post* (*recovery and adaptation*). They correspond to the phases in which infrastructure managers have the opportunity to increase resilience by reducing vulnerability or the level of risk (McDaniels, Chang, Cole, Mikawoz, & Longstaff, 2008). Resilience is characterized by a temporality that combines the present with the future but also deals actively with problems of insecurity in the past (Cavelty, Kaufmann, & Kristensen, 2015). Resilience must consider different time frames: immediately during the crisis (for example, organizing rescue operations), intermediate (for example, repairs) and long-term (for example, reconstruction, relocalization) (Linkov et al., 2014).
- The components of resilience management: *anticipation*, i.e. predicting the occurrence of an event; *monitoring/detection*, i.e. identifying and interpreting precursory signals; *control*, i.e. implementing actions of recovery and/or adaptation by evaluating indicators defined beforehand; collecting *feedback from experience*, i.e. analyzing and understanding past events in order to fuel *anticipation*, *monitoring* /*detection* and *control* (Hollnagel, 2015; Park, Seager, Rao, Convertino, & Linkov, 2013; Sakukai & Kim, 2008).
- The fields (*technical*, *organizational*, *social*, *economic*, *political*, *hydrological*, etc.) concerned by resilience (Bruneau et al., 2003; Francis & Bekera, 2014; Roege, Collier, Mancillas, McDonagh, & Linkov, 2014). Resilience therefore includes “hard” components that refer to the structural and technical capacities of infrastructures and “soft” institutions and components relating to social and human aspects, etc. (Kahan et al., 2009). The influence of CIs on the resilience of communities remains to be studied (Birkmann, Chang Seng, et al., 2012).
- The finalities (*robustness* and *rapidity*) and resources (*redundancy* and *resourcefulness*) defined by Bruneau et al (Bruneau et al., 2003):
    - ✓ *robustness*: the inherent strength of the system or its elements to withstand external stress or demand without degradation of functioning;

- ✓ *rapidity*: the speed with which disruption can be overcome and services restored;
- ✓ *redundancy*: the extent to which the elements of the system can be substituted;
- ✓ *resourcefulness*: the capacity to identify problems, establish priorities, and mobilize resources (monetary, physical, technological, informational, and human) in the case of crisis.

Resources permit improving the finalities: providing redundancy to a CI increases its *robustness* and thus its resilience. Nonetheless, *robustness* does not only depend on *redundancy* and *resourcefulness*, it also stems from protection works or equipments planned such as dikes, drainage systems, firewalls... These elements, external to the system studied in terms of resilience, are important resources leading to an improvement of the system *robustness*. Consequently we propose adding a fifth element, namely of the type “resource” to this list:

- ✓ *protectiveness*: the capacity of external works or equipments to protect the system from threats.

The literature shows that resilience must consider several fields (Bach, Bouchon, Fekete, Birkmann, & Serre, 2014; Provitolo, 2013; Zevenbergen et al., 2015). In line with Bruneau et al. (Bruneau et al., 2003) and Labaka et al. (Labaka et al., 2016), we consider the *technical*, *organizational*, *human* and *economic* (TOHE) fields as essential. These dimensions were defined by Francis and Bekera (Francis & Bekera, 2014), and Bruneau et al (Bruneau et al., 2005). The CI must be considered in its environment: its resilience naturally depends on its *technical* resilience (capacity to fulfil the function, at the necessary level during and after an adverse event) but also *organizational* resilience (the capacity of organizations to manage installations, maintain key functions and take decisions to maintain/improve the situation during the event), *human* (measures specifically designed to decrease the level to which communities and government jurisdictions may be subject to impacts caused by the loss of critical services due to an event, human behaviors during disastrous events), and *economic* (the capacity to reduce direct and indirect economic losses, the allocation of resources, maintaining activity).

Technical resilience is linked to the performance of physical systems including their components, interconnections and the global systems. Man-Machine Interfaces (MMI) are one of the components of the system to be considered in the case of infrastructures. Works have been performed on interface resilience, the latter being defined as the capacity of an MMI to ensure the performances and stability of a system whatever the circumstances, which is to say the occurrence of unexpected or unprecedented disruptions (Enjalbert, Vanderhaegen, Pichon, Ouedraogo, & Millot, 2011; Ouedraogo, Enjalbert, & Vanderhaegen, 2013; Ruault, 2015).

A more resilient system would have lower recovery costs than one less resilient both subject to the same risk. If no effort is made after the disruption, the impacts on the system's performance can be severe. Conversely, the impacts may be reduced if resources are deployed quickly (Vugrin et al., 2010).

These fields are not independent. For example, the action of emergency services (*organizational* section) can be adversely affected if the population moves instead of remaining in place (*human* section), generating problems of access for these services (Chatry et al., 2010; T. Curt & Frejaville, 2018).

It is clear that the three dimensions of resilience (*management phases*, *management components*, *domains*) must be taken into account in a single framework to obtain an overall view of this concept. These three dimensions lead to use or develop tools and actions for improving *robustness* and *rapidity* of recovery defined as resilience finalities (Bruneau et al., 2003). Figure 3 presents examples of tools or actions according to these three dimensions. Types of resource (redundancy, resourcefulness and protectiveness) are also shown for each example. For instance, the Municipal Information Document on Major Risks (MIDMR) is a French anticipatory tool that participates in planning in the human behavior domain and confers *protectiveness* to the system. Another example concerns personnel assignment to monitoring and watchtowers is a way of detecting forest fires in the framework of preparing for the organizational section and belongs to *protectiveness*. The choice of alternative sites for crisis management involves planning and anticipation and is part of the *redundancy* element. The fund allocation for recovery actions concerns economic aspects by the control resources and is part of *resourcefulness*.

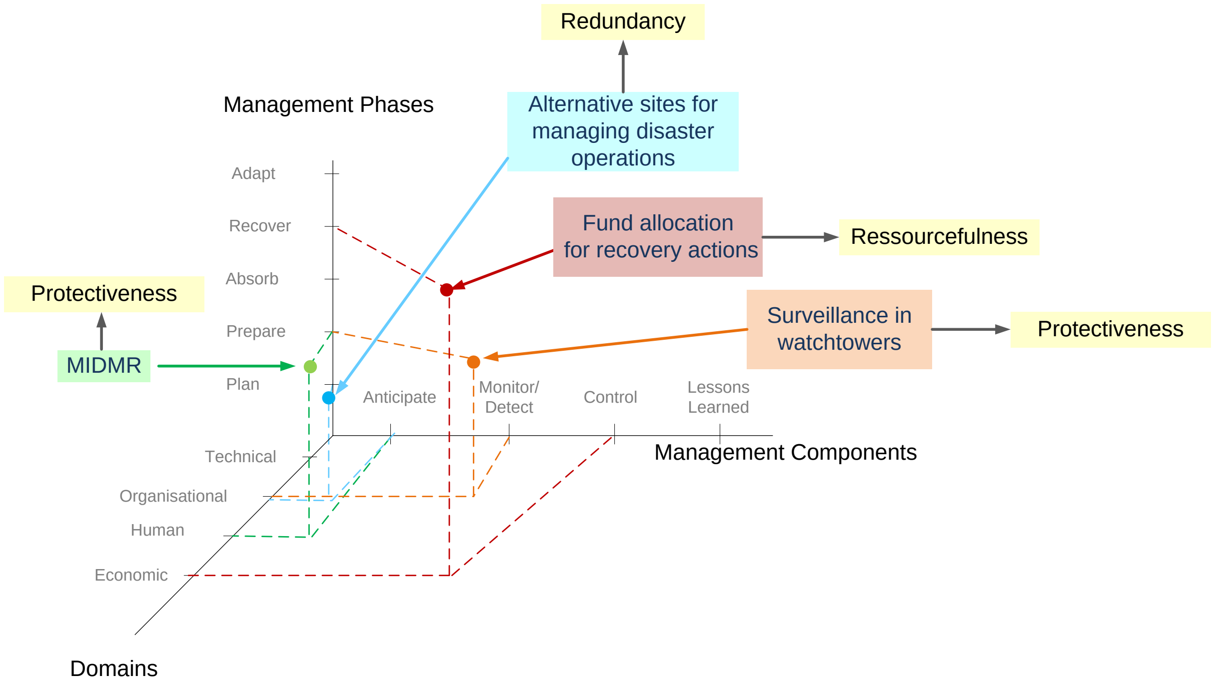

Figure 3. Different dimensions of resilience – illustration by examples.

We analyzed the approaches presented in the literature which aim to improve resilience and belong to resilience engineering. These approaches comprise two categories of limitation: those linked to the very principle of the approaches (Section 3) and those linked to the implementation of the process of the evaluation and preventive or corrective control of resilience (Section 4).

3. LIMITS LINKED TO THE PRINCIPLE OF CURRENT APPROACHES

3.1 Essentially one dimensional approaches

The great majority of approaches are one-dimensional which reduces the scope of the results: for example, they only consider the technical domain, the planning phase, etc. Links between dimensions are rarely envisaged; but when they are, they are limited, for example, to modeling how physical losses can affect the economic dimension (technical & economic in Table 3). Different frameworks have focused on organizational resilience though have not provided information on how to improve the other dimensions of resilience (technical, economic, and social) (Labaka et al., 2016). The "soft and "hard" aspects of resilience have often been treated separately by different research and political communities (technical & organizational or technical & human in Table 3) whereas they present inter-relations (Kahan et al., 2009). Thus the quantification of resilience involving the different domains remains a challenge (Birkmann, Changseng, et al., 2012).

Types of resilience	Number of papers
Technical	90
Technical & economic	39
Multiple (> 2 types)	8
Organizational	6
Economic	4
Technical & organizational	2
Technical & human	2

Table 3. Types of resilience addressed in the literature survey

However, some approaches considering several types of resilience ("Multiple" item in Table 3) have been pinpointed: for instance, technical, organizational, human and economic types (Labaka, Hernantes, & Sarriegi, 2015; Labaka et al., 2016); technical, organizational and environmental ones (Hosseini & Barker, 2016; Omer, Mostashari, & Nilchiani, 2013). Moreover, examples of combinations of two dimensions can be found in the literature (Domain x Resource in O'Rourke (O'Rourke, 2007)). At present only one approach combines several dimensions of resilience and probably provides the fullest framework of analysis. It is the Resilience Matrix developed by the US Army Corps of Engineers (Linkov et al., 2013). It mixes three dimensions: the event management phases (columns of the matrix), the control of resilience and the domains. However, it keeps a certain number of limits: economic aspects are not dealt with and it presents (the lines of the matrix) both the capacities ("social" and "physical" aspects) and the control processes ("information" and "cognitive" aspects) of the system according to the same dimension. It is important to emphasize that this multifaceted approach is not specifically devoted to the resilience of CIs.

3.2 Approaches barely cover the event in terms of causes, propagation and effects

Scenario approach permits covering the event in terms of causes, propagation and effects (see for example Figure 4 where scenarios are represented as a bowtie diagram dedicated to a system comprising critical infrastructures protected by a dike). Different authors have stated that the resilience process must deal with multi-risk sources, multiple scenarios and cascade effects (Alderson et al., 2015; Chang, McDaniels, Fox, Dhariwal, & Longstaff, 2014; McDaniels, Chang, Hawkins, CHex, & Longstaff, 2015; OECD, 2012, 2014; Ouyang, Duenas-Osorio, & Min, 2012). But, at the same time, the improvement of resilience is mostly defined in the literature as a process with two tasks: the characterization of resilience within system and the establishment of priorities for *ex ante* and *ex post* mitigation actions such as strengthening the resistance of the system, reorganizing resources, etc. (Chang et al., 2014; Francis & Bekera, 2014; McDaniels et al., 2015) which essentially correspond to the effects (receptor and consequences in Figure 4). Some authors even consider that system malfunctioning is “agnostic to the source of disruption” (Alderson et al., 2015). Nonetheless, in practice, the infrastructure must face different types of risk linked to deliberate and involuntary human actions (human errors, vandalism, terrorism) and natural hazards which generate different scenarios and thus different impacts on the CI. The sources and scenarios leading to the disruptive event are actually seldom taken into account but works have recently addressed this issue and explicitly quantified resilience against specific scenarios (Hamilton, Lambert, Connelly, & Barker, 2016; Thorisson, Lambert, Cardenas, & Linkov, 2017). These developments allow considering different uncertain future conditions across the system lifecycle, including technology, climate, economy, and others.

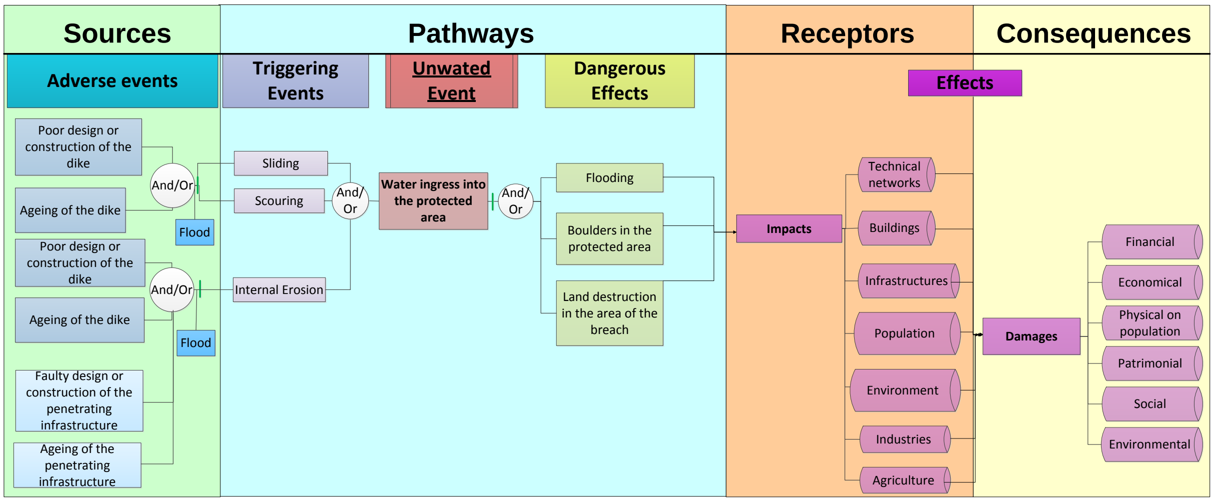

Figure 4. Example of the Source Pathway Receptor Consequence scenario - Figure designed using a bowtie diagram for an area protected by a river dike (Ferrer, Curt, Peyras, & Tourment, 2015).

We think that it is necessary, in the design of resilience metrics and tools, to take into account sources and scenarios for several reasons:

- the metrics used for evaluating, modeling and controlling resilience must be adapted for all situations whatever the cause of the event. As myriad hazards of variable magnitudes and durations generate different trajectories for the system (Y.Y. Haimes, 2009), it is important to define a set of metrics which could assess the nature and magnitude of the event regardless of the origin of the event;

- interdependencies (physical, cyber, geographic and logical) between infrastructures and thus cascade effects must be taken into account in the scenarios. However, it appears, for example, that not enough account is taken of the links between the CIs of different sectors, or those beyond the borders of a country (European Commission, 2013);

- preventive actions are characteristic of each source: a natural hazard such as a flood could be dealt with by the existence of a dike, an act of cyber piracy by firewalls, unauthorized access by detection, etc.

These proposals agree with the works of Bialas (Bialas, 2016).

Representation in the form of scenarios allows grouping all the possibilities considered at a given moment, since this group may evolve with time and as a function of the situation (day/night in relation to different land-uses such as shopping precincts, residential districts, etc.) (Vinchon et al., 2011). The ensemble of scenarios defined may cover a wide range of potential events, thereby leading to more efficient decisions for investment during the prevention phase (Turnquist & Vugrin, 2013).

However, it is impossible to enumerate all the scenarios. Thus, the system must be flexible and adaptable regardless of the attack scenario: solutions must be proposed through resilience control systems.

4. LIMITS LINKED TO IMPLEMENTING RESILIENCE CONTROL SYSTEMS

Progress has been made regarding the conceptualization of resilience, and approaches to control have been developed in the literature. Control entails diagnosing the state of the system with respect to its capacities of resilience on the basis of metrics (metrics, indexes), then proposing corrective actions intended to improve these capacities. A chart of this process is shown in Figure 5. This process is repeated until reaching a predetermined threshold for the metrics. Control can be performed *ex-ante* or preventive actions. *Ex-ante* or preventive actions and *ex post* corrective actions must be implemented at the right moment to cope with a disruptive event. Different types of action can be implemented (Jha, Miner, & Stanton-Geddes, 2013) during the risk management phases: localization (land use, relocalization, rerouting traffic), structural (redundancy of several components, construction of protective structures), operational (planning rescue operations, verification of the state of protective structures) and fiscal (the speed of transferring funds after an event). A crisis occurs when these measures are insufficient during an event or if adequate measures have not been planned. The concept of resilience implies the return to a situation in which CIs function at the requisite level, the latter being specified.

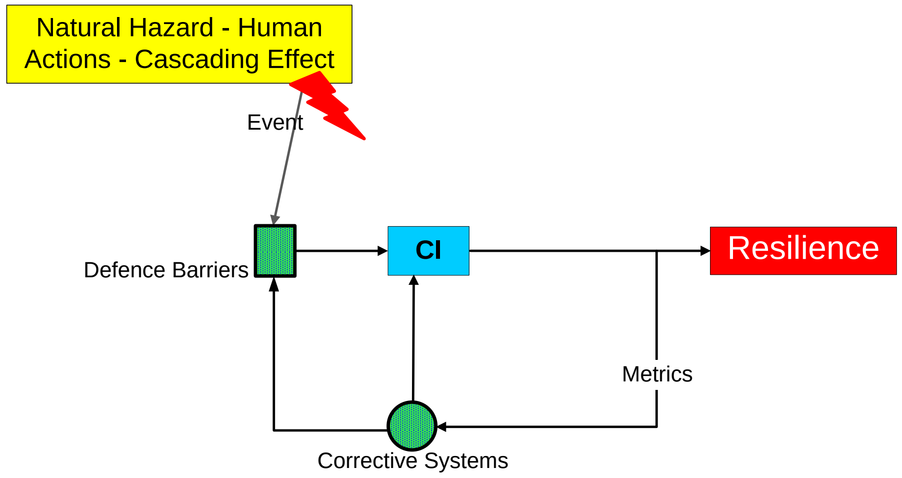

Figure 5. Resilience of critical infrastructures: causes and *ex ante* and *ex post* measures

4.1 Resilience metrics are many and barely formalized; the emergence of analytical formulations

4.1.1 Adapted metrics are required

A key challenge remains, that of defining resilience (1) quantitatively and rigorously for precise and objective evaluation; (2) sufficiently flexibly to capture several facets of this concept; and (3) in relation to operational aspects (Alderson et al., 2015; Carlson et al., 2012). Metrics allow evaluating a system (cf. Figure 5). They are variables evaluated on different types of scale: nominal, ordinal, interval and ratio.

The multiple dimensions through which resilience can be understood may explain why such a wide variety of resilience metrics is found in the literature. Syntheses can be found in (Alexander et al., 2011; Birkmann, Chang Seng, et al., 2012). On the other hand, no consensus has been reached. Thus definitions do not naturally lead to the development of coherent metrics of resilience (Ayyub, 2014) and discussions on the resilience of infrastructures generally remain qualitative and descriptive (Baroud, Ramirez-Marquez, Barker, & Rocco, 2014). A large number of terms have been proposed and several of them appear to be synonyms, though this assumption is difficult to verify since these terms are rarely defined, making operationalization complex.

Furthermore, a serious lack of formalization was observed in the literature and has been mentioned in very recent works (Alderson et al., 2015; Chang et al., 2014; Hemond, 2013). Very few works have taken this direction (Hollnagel, 2015; Petit et al., 2013; Sikula, Mancillas, Linkov, & McDonagh, 2015). Thus there is no formal framework, norm or methodology for evaluating resilience (Hemond, 2013) and only a few studies have described how to measure the resilience metric (Birkmann, Chang Seng, et al., 2012). However, formalization is required in order to obtain a reliable and rigorous evaluation of metrics in real situations (C. Curt, Peyras, & Boissier, 2010; C. Curt, Trystram, & Hossenlopp, 2001).

It is therefore important to define and analyze all the facets of resilience and their interactions with metrics that can be used for different tasks:

- Comparing systems with each other (testing different design configurations for different hazard configurations);
- Designing resilient systems; diagnosing an existing system during periods outside a crisis; finding weak points; fueling policies (Rodriguez-Llanes, Vos, Yilmaz, & Guha-Sapir, 2013); aiding decision-making (planning, preparing, etc.);
- Performing evaluations of a system dynamically during an event, aiding decision-making (recovery, adapting);
- Assessing the adequacy of the process engaged to build resilience and evaluating the outcome achieved (OECD, 2012). Indeed, building resilience is a process that requires time and resources. Process oriented definitions have been developed more in social science research (Gilbert, 2010). For example, Norris et al. defined resilience as “a process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance” (Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008). The process implies learning, adaptation, anticipation, and improvements for better decision-making in view to ameliorating the capacity to manage hazards. In the literature, resilience is also understood as an outcome. According to Gilbert, “Outcome-oriented definitions define resilience in terms of end results. An outcome-oriented definition would define resilience in terms of degree of recovery, time to

recovery, or extent of damage avoided.” (Gilbert, 2010). The works of Kahan et al. are oriented according to this type of principle that places to the fore the capacity to recover after a disaster (Kahan et al., 2009);

- Contributing to feedback from experience after the crisis by assessing the success or failure of the actions implemented during the event and the effects of alternative strategies and adaptation. A typology of indicators has been proposed (OECD, 2014): System resilience indicators (outcome indicators) that monitor resilience with time completed by Negative resilience indicators that evaluate the negative impacts of alternative strategies (for transport networks, for example, this corresponds to increases in travel times and/or distances).

In our opinion and in agreement with other authors (Y. Y. Haimes, 2009; Villar & David, 2014), we think it is necessary, notably with operational use in mind, to consider different metrics to evaluate resilience for the following reasons:

- resilience is relative to different domains (TOHE): aggregating a single metric makes little sense. Not all the domains may contribute to reduce or minimize the impact in the same way and it is important to keep track of their different roles for the future decisions. Likewise, it also appears difficult to propose a unique metric for each of these domains. Indeed, two different scenarios can lead to the same resilience value whereas they are not equivalent in terms of decision-making (Khakzad et al., 2014).

- different types of hazard and frequency can threaten a CI with variable outcomes and their impact has to be evaluated by different variables. In the domain of natural risks, the same event must be analyzed through its potential effects. A torrential flood can cause a submersion, scouring, and impacts with intensities and frequencies that differ from the global frequency of flood events. The operationalization of organizational and institutional resilience appears to occur independently of a specific threat, leading to imprecise descriptions (Birkmann, Chang Seng, et al., 2012);

- Metrics may correspond to different spatial scales (local, regional, national, international) and represent subsystems of the global system;

- Metrics differ as a function of the phases of resilience management. For example, preparedness metrics appear to predominate in the case of organizational and institutional resilience (Birkmann, Chang Seng, et al., 2012).

Finally, the problem is to define a sufficient number of metrics necessary, adapted to the situation (CI type, hazard type, domain analyzed, scale, management phase) and to obtain a clear and legible image of the system's resilience, in particular for decision-makers and stakeholders. In addition, the metrics must be sensitive, robust (repeatable and reproducible) and permit the representation of uncertainties inherent in resilience evaluations. Measures of resilience do not generally include the temporal dimension (Francis & Bekera, 2014) but several recent works have indicated the importance of integrating this aspect in the definition of resilience (Gay & Sinha, 2013) and dynamic formulations started to be proposed (Ganin et al., 2016; Gao, Barzel, & Barabási, 2016; Gisladottir, Ganin, Keisler, Kepner, & Linkov, 2017). Finally, metrics must be presented carefully and take different forms, i.e. tables, maps, curves, etc., and they must be cost effective (Vinchon et al., 2011).

4.1.2 Evaluation of metrics

Three types of evaluation can be distinguished. Metrics can be evaluated directly or indirectly (proxies) or be obtained from models resulting from several measures. For example, the duration of lack of service is a direct assessment of resilience; connectivity is an indirect one (Feliciotti, Romice, & Porta); the metric Preparedness is evaluated on the basis of the following measures (Boin & McConnell, 2007): Preparing Respondents, Business Continuity planning, Joint preparations, Joint training operations and developing real-life simulation, Training leaders (creating expert networks, training for situational and information assessment, Organizing outside forces, Working with the media).

Difficulties specific to evaluation have been encountered and notably:

- Information difficult to access often leads to using indirect metrics or proxies that therefore provide only an approximate representation of reality (Vinchon et al., 2011);
- It can be difficult to quickly acquire information in order to perform actions and react as soon as possible: this improves resilience (Therrien, 2010)

- The aggregation of different elements to produce an metric can prove difficult due to the different natures of the elements, the time steps linked to them, their associated uncertainties, etc.;
- The data and information used to measure the metrics are often imperfect (uncertain, imprecise, incomplete, contradictory): such imperfections must be considered to better represent reality. Resilience is strongly linked to the concept of the progression of unknown transitional states not foreseen by the system. Up to now, few works have focused on taking imperfections into account in resilience management (Hosseini, Al Khaled, & Sarder, 2016; John, Yang, Riahi, & Wang, 2016; Mojtahedi, Newton, & Von Mading, 2017; Nogal, O'Connor, B., & Caufiled, 2017; Yodo, Wang, & Zhou, 2017). Appropriate models should be proposed to represent imperfection with a twofold constraint: adaptation to the type of data (elicitation of expertise, data, feedback from experience) and epistemic and aleatory uncertainties.

Three approaches are generally used to feed resilience metrics: knowledge formalization, feedback from experience and the analysis of historic and calculated data (Chang et al., 2014; McDaniels et al., 2015; Rosati et al., 2015). They are complementary insofar as resilience is a complex property involving different variables and in which (fortunately) disasters rarely occur.

In our literature analysis, we found that several works specifically dealt with the development of resilience metrics: 26 concern quantitative metrics and 3others qualitative ones (cf. Table 5).

4.2 Control systems must respond to various situations

The resilience control process relies on preventive and corrective actions based on the evaluation of metrics. Preventive actions reduce the level of risk through measures that do not necessarily change the vulnerability of the system and thus its state variables. These actions include detection, prevention, protection, prohibition, etc. They modify the effect of a potential hazard for a determined level of risk. Corrective actions control the states of the system by improving its resilience, for example, in terms of resistance (improvement of structural protection measures), adaptation (preventive information), etc.

Two kinds of measures are possible: “Structural measures are any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems. Non-structural measures are measures not involving physical construction which use knowledge, practice or agreement to reduce disaster risks and impacts, in particular through policies and laws, public awareness raising, training and education” (United Nations/International Strategy for Disaster Reduction (UNISDR), 2016). The goal is to restore a target level within an acceptable period of time and cost. These actions are aimed at absorbing shocks, and adapting so that the systems are less exposed to them, or transforming these systems so that they are no longer affected by these shocks (OECD, 2014). Different types of Technical, Organizational, Human and Economic action can be distinguished considering the types of action (structural or non-structural) and the management phase (preventive, corrective actions). Table 4 gives some examples of the various kinds of actions.

	Preventive actions	**Adaptive corrective actions**	**Recovery corrective actions**
Structural actions	Protective structures Creation of redundancies Stock management	Modification of the CI	Repair of the CI
Non-structural actions	Training operators to control abnormal situations Community risk culture Preparation of emergency services Increasing flexibility	New corporate organization Modifications of procedures in the case of crisis Relocalization	Increased allocation of funds

Table 4. Examples of different types of action

Models supplying these actions must be proposed and incorporated in decision-aid systems and concern the different management components (Anticipate, Monitor/Detect, Control, Feedback – cf. Figure 3).

All of these actions obviously have a cost. This is reflected in our literature review: one third of the published researches concerns the economic aspects alone or in combination (cf. Table 3). By definition, preventive strategies tie down resources and can become costly in the medium and long terms (Therrien, 2010): they over-protect a system under normal conditions. Kahan et al (2009) have proposed allocations of resources distributed for Resistance, Absorption and Restoration as a function of the resilience profile and more particularly gravity (the quality that determines the degree to which any particular function plays a key role within its host system) (Kahan et al., 2009). Recovery must be done at acceptable costs (Haimes, 2006). Here we converge with the concept of efficiency that seeks to balance the allocation of human, technical and financial resources with expected effects.

Different qualitative and quantitative approaches have been developed (cf. Table 5) with various purposes: optimization/improvement, assessment/diagnosis, prediction, and modeling/representation of resilience. The most widely used approach is based on network/graph theory; it represents forty percent of the whole set of articles. This can be related to the great majority of networked infrastructures studied as stated before (cf. Table 2): network/graph theory is applicable to all networked infrastructures and provides resilience specific tools (Gay & Sinha, 2013). In the articles selected for our survey, network/graph theory-based and numerical optimization approaches notably aim at optimizing design to improve the resilience of concerned infrastructures. Very recent works have proposed network science based frameworks to operationalize resilience of infrastructures (Ganin et al., 2016; Gao et al., 2016; Gisladottir et al., 2017): they rely on the definition of a single universal dynamic resilience function (called *critical functionality* in Ganin et al (2016) and Gisladottir et al (2017)) combined with network theory approaches. They are particularly well-suited to multi-dimensional systems consisting of a large number of components that interact through a complex network such are CIs in a given territory. As stated by Opdyke et al. (2017), a future step relies on innovative methods and greater mixed-method studies (Opdyke, Javernick-Will, & Koschmann, 2017).

Type of approach	**Number of papers**
Network/Graph theory based modeling	60
Quantitative metrics & modeling	26
Numerical optimization	18
Proposal of new methods or technological solutions	10
Framework	8
Bayesian Networks	6
Spatial Information approach	5
Lessons learned	4
Statistical/Probabilistic approach	3
Qualitative metrics	3
Collaborative Control Theory	2
Econometric model	2
Multi-criteria Decision Analysis Approach	2
Scenario analysis	2

Table 5. Types of approach

Models must be adapted for uncertain situations. Methods such as Bayesian networks (Simon & Weber, 2009), multicriteria aggregation (Tacnet, Dezert, Curt, Batton-Hubert, & Chojnacki, 2014) and knowledge-based systems (C. Curt, Talon, & Mauris, 2011; Talon & Curt, 2017) can be used to propagate these imperfections in decision models. Obviously, the spatial aspect is important for network infrastructures and because resilience management is generally performed at territorial level. The communication and visualization of model results on maps complete decision-aid tools intended for different users (infrastructure managers, political decision-makers, etc.) (Fekete, Tzavella, & Baumhauer, 2017; Shiraki, Takahashi, Inomo, & Isouchi, 2017; Vinchon et al., 2011). Decision-aid systems based on GIS (Geographical Information Systems) to manage spatial aspects appear essential.

At present, very few models of this type can be used to improve resilience (Alderson et al., 2015; Robert, Morabito, Cloutier, & Hémond, 2012). Guides and formal frameworks are beginning to emerge (Cavallini et al., 2014; Labaka et al., 2016; OECD, 2014). This situation is probably due to the following causes:

- the scarcity of genuinely operational metrics, as seen above;
- the large number of decision situations that have to be investigated comprising dimensions of resilience, decision-makers, information available on initiating events and those in cascade;
- the large number of *ex ante* and *ex post actions*, “hard” or “soft”;
- interactions between variables;
- different measurement situations: elicitation of expertise, data, feedback from experience.

Finally, 2 very recent papers deal with biomimicry approaches. Middleton and Latty (2017) stated that “human infrastructure management networks are rapidly becoming decentralized and interconnected; indeed, more like social insect infrastructures. Human infrastructure management might learn from social insect researchers” (Middleton & Latty, 2016). Gao et al (2016), for their part, exemplified their development dedicated to multi-dimensional systems and complex networks on ecological networks such as plants and pollinators but their developments can help to guide the design of technological systems resilient to both internal failures and environmental changes (Gao et al., 2016).

5. SYNTHESIS AND RESEARCH DIRECTIONS

We put forward the idea that future developments could respond to the current limits of resilience management on the basis of the elements discussed above. The aim is therefore to pursue methodological developments then develop the first prototype decision-aid tools. This type of approach converges with the DROP (disaster resilience of place) model proposed by Cutter et al (Cutter et al., 2008). Different qualitative and qualitative approaches like those presented in Table 5 offer interesting frameworks to enhance CIs’ resilience. These developments must conform to the following constraints. These constraints come from the analysis of the articles used in this review (cf. Figure 6):

- Consider different hazards, the cascade effects, thus the interactions between CIs and uncertain conditions across the system lifecycle, including technology, climate, economy, and others.
- Take several domains into account: the TOHE domains (and others as a function of application) must be considered to define resilience metrics and for corrective and preventive actions. Indeed, the actions taken can be economic (funds allocated to resources to protect forests against fire), technical (strengthening dikes), human (preparing the population), and organizational (training emergency services). This holistic approach has been implemented in the French MARATHON project (Léger et al., 2009) focused on risk.
- Consider different phases of resilience management (preparation, prevention, event / post-event, recovery) and incorporate the temporal aspect.
- Take into account spatial aspects and multi-scale effects. It should be recalled that CIs are points, systems or parts of systems […] essential for maintaining functions vital for society. They are intrinsically vulnerable and can accentuate the vulnerability of a territory when they can no longer ensure their mission. Their interruption can significantly disrupt societies at different scales: local, national and international. Infrastructures play a role in a given territory that can overlap the borders of countries such as those of Europe, leading to cooperation within the EU and the emergence of a joint policy to protect CIs, since small disruptions can quickly transform into crises (Fritzon et al., 2007). The resilience of CIs is intrinsically important but it is also a determinant of resilience at a larger scale of a community or region (Carlson et al., 2012; Rose & Liao, 2005): activities not directly affected can be impacted by the consequences of an event if they are deprived of electricity or communication networks. The analysis of these effects and changes of scale remains to be done (Birkmann, Chang Seng, et al., 2012).

- Integrate the role of dynamics. First, the dynamics of the system’s environment must be considered: change of technology, climate, economy, environment and other conditions; ageing, maintenance of CIs. Secondly, at the system’s level, the temporal profile of system recovery in response to adverse events should be evaluated in relation with the *recovery* capacity.
- Manage, in real-time, very heterogeneous and potentially imperfect information stemming from many unequally reliable sources.

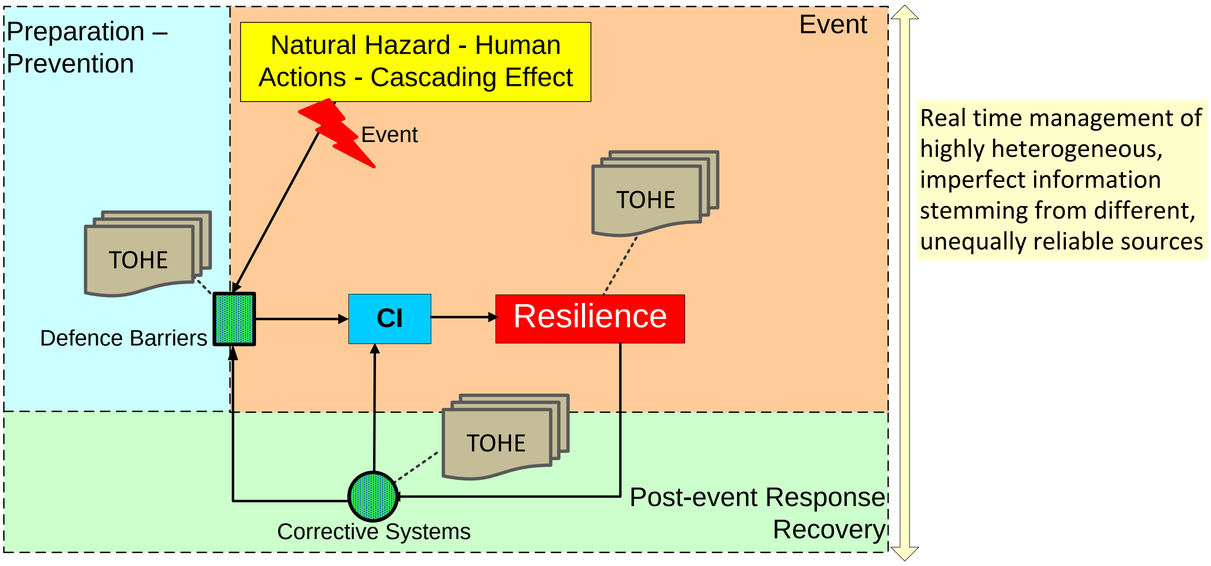

Figure 6. Synthesis of proposals

The last element of reflection we want to add to this article concerns the positioning of resilience with respect to sustainable development. These two approaches share common principles (European Environment Agency (EEA), 2016; Linkov et al., 2014; Morchain & Robrecht, 2012):

- the demand for continuous improvement;
- the minimization of the adverse effects of hazards on societies in a situation of global changes;
- the continuation and even improvement of the functionality of systems by adapting to and learning about the fundamental changes caused by these events.

However, there is no unified framework that combines resilience and sustainable development for the design, evaluation and maintenance of civil engineering infrastructures and convergence is slow. This can be explained by developments pursued independently (Bocchini, Frangopol, Ummenhofer, & Zinke, 2014). Using a comparison of concepts of resilience and sustainability these authors proposed a unified approach for these two concepts which considers the entire life of a structure and estimates its impact on society, though by focusing on events with different magnitudes and probabilities of occurrence.

6. REFERENCES

Alderson, D.L., Brown, G.G., & Carlyle, W.M. (2015). Operational Models of Infrastructure Resilience. *Risk Analysis, 35*(4), 562-586.

Alexander, D., Barbat, A., Carreño, M.L., Kienberger, S., Miniati, R., Welle, T. , . . . Glade, T. (2011). MOVE PROJECT - Handbook of Vulnerability Assessment in Europe.

Ayyub, M.B. (2014). Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making. *Risk Analysis, 34*(2), 340-355.

Bach, C., Bouchon, S., Fekete, A., Birkmann, J., & Serre, D. (2014). Adding value to critical infrastructure research and disaster risk management: the resilience concept. *SAPIENS, 6*.

Baroud, H., Ramirez-Marquez, J.E., Barker, K., & Rocco, C.M. (2014). Stochastic Measures of Network Resilience: Applications to Waterway Commodity Flows. *Risk Analysis, 34*(7), 1317-1335.

Bialas, A. (2016). Risk Management in Critical Infrastructure—Foundation for Its Sustainable Work. *Sustainability, 8*(3), 240.

Birkmann, J., Chang Seng, D., Abeling, T., Huq, N., Wolfertz, J., Karanci, N., . . . Jülich, S. (2012). EMBRACE / Systematization of Different Concepts, Quality Criteria, and Indicators.

Birkmann, J., Changseng, D., Wolfertz, J., Setiadi, N., Karancı, N., İkizer, G.K., . . . Fordham, M. (2012). EMBRACE - Early Discussion and Gap Analysis on Resilience.

Bocchini, P., Frangopol, D.M., Ummenhofer, T., & Zinke, T. (2014). Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. *Journal of Infrastructure Systems, 20*(2).

Boin, A., & McConnell, A. (2007). Preparing for Critical Infrastructure Breakdowns: The Limits of Crisis Management and the Need for Resilience. *Journal of Contingencies and Crisis Management, 15*(1), 50-59.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., . . . von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra, 19*(4), 733-752.

Bruneau, M., Filiatrault, A., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., & Tierney, K. (2005). White Paper on the SDR Grand Challenges for Disaster Reduction: Multidisciplinary Center for Earthquake Engineering Research (MCEER).

Carlson, L., Bassett, G., Buehring, W, Collins, M., Folga, S., Haffenden, B., . . . Whitflield, R. (2012). Resilience: Theory and Applications.

Cavallini, S., d'Alessandro, C., Volpe, M., Armenia, S., Carlini, C., Brein, E., & Assogna, P. (2014) A system dynamics framework for modeling critical infrastructure resilience. *Vol. 441. IFIP Advances in Information and Communication Technology* (pp. 141-154).

Cavelty, M.D., Kaufmann, M., & Kristensen, K.S. (2015). Resilience and (in)security: Practices, subjects,temporalities. *Security Dialogue, 46*(1), 3-14.

Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis, 34*, 416-434.

Chatry, C., Le Gallou, J., Le Quentrec, M., Lafitte, J., Laurens, D., Creuchet, D., & Grelu, J. (2010). Rapport de la mission interministérielle "Changements climatiques et extension des zones sensibles aux feux de forêts" (National Report on Climate Change and the Extension of Fire Prone Areas in France) (pp. 89): Ministère Alimentation Agriculture Pêche.

Curt, C., Peyras, L., & Boissier, D. (2010). A knowledge formalization and aggregation-based method for the assessment of dam performance. *Computer-aided Civil and Infrastructure Engineering, 25*, 171-183.

Curt, C., Talon, A., & Mauris, G. (2011). A dam assessment support system based on physical measurements, sensory evaluations and expert judgements. *Measurement, 44*, 192-201.

Curt, C., Trystram, G., & Hossenlopp, J. (2001). Formalisation of at-line human evaluations to monitor product changes during processing. Integration of human decision in the dry sausage ripening process. *Sciences des Aliments, 21*(6), 663-681.

Curt, T., & Frejaville, T. (2018). Wildfire Policy in Mediterranean France: How Far is it Efficient and Sustainable? *Risk Analysis, 38*, 472-488.

Cutter, S.L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environment Change, 18*, 598-606.

Enjalbert, S., Vanderhaegen, F., Pichon, M., Ouedraogo, K.A., & Millot, P. (2011). Assessment of Transportation System Resilience. In H. M. Cacciabue C., Luedtke A., Riccioli C. (eds.) (Ed.), *Human Modelling in Assisted Transportation* (pp. 335-341). Milan, Italy: Springer-Verlag Italia Srl.

European Commission. (2013). Commission Staff Working Document on a new approach to the European Programme for Critical Infrastructure Protection Making European Critical Infrastructures more secure.

European Environment Agency (EEA). (2016). Urban adaptation to climate change in Europe 2016 - Transforming cities in a changing climate - Report N° 12/2016 (pp. 135 pages).

Fekete, A., Tzavella, K., & Baumhauer, R. (2017). Spatial exposure aspects contributing to vulnerability and resilience assessments of urban critical infrastructure in a flood and blackout context. *Natural Hazards, 86*, 151-176. doi: 10.1007/s11069-016-2720-3

Feliciotti, A., Romice, O., & Porta, S. Design for change : five proxies for resilience in the urban form. *Open House International, 41*(4), 23-30.

Ferrer, L., Curt, C., Peyras, L., & Tourment, R. (2015, 27-29/05/2015). *Impact des réseaux techniques sur la performance d'une digue – Analyse système et Modèle fonctionnel.* Paper presented at the 33èmes Rencontres de l'AUGC, Anglet, France.

Francis, R., & Bekera, B. (2014). A metric and framework for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety, 121*, 90-103.

Fritzon, A., Ljungkvist, K., Boin, A., & Rhinard, M. (2007). Protecting Europe's Critical Infrastructures: Problems and Prospects. *Journal of Contingencies and Crisis Management, 15*(1), 30-41.

Ganin, A. A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J. M., Kott, A., . . . Linkov, I. (2016). Operational resilience: Concepts, design and analysis. *Scientific Reports, 6*.

Gao, J., Barzel, B., & Barabási, A. L. (2016). Universal resilience patterns in complex networks. *Nature, 530*(7590), 307-312.

Gay, L. F., & Sinha, S. K. (2013). Resilience of civil infrastructure systems: Literature review for improved asset management. *International Journal of Critical Infrastructures, 9*(4), 330-350.

Gilbert, S.W. (2010). Disaster Resilience: A guide to the literature, NIST Special Publication 1117: Office of Applied Economics, Engineering Laboratory, National Institute of Standards and Technology.

Gisladottir, V., Ganin, A. A., Keisler, J. M., Kepner, J., & Linkov, I. (2017). Resilience of Cyber Systems with Over- and Underregulation. *Risk Analysis, 37*(9), 1644-1651.

Haimes, Y. Y. (2006). On the definition of vulnerabilities in measuring risk to infrastructures. *Risk Analysis, 26*(2), 293-296.

Haimes, Y. Y. (2009). On the Complex Definition of Risk: A Systems-Based Approach. *Risk Analysis, 29*(12), 1647-1654.

Haimes, Y.Y. (2009). On the definition of resilience in sytems. *Risk Analysis, 29*(4), 498-501.

Hamilton, M. C., Lambert, J. H., Connelly, E. B., & Barker, K. (2016). Resilience analytics with disruption of preferences and lifecycle cost analysis for energy microgrids. *Reliability Engineering and System Safety, 150*, 11-21. doi: 10.1016/j.ress.2016.01.005

Hemond, Y. (2013). *Concepts et démarche d'évaluation du potentiel de résilience d'une infrastructure essentielle.* Ecole Polytechnique de Montréal.

Holling, C.S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4*, 1-23.

Hollnagel, E. (2015). RAG - Resilience Analysis Grid.

Hosseini, S., Al Khaled, A., & Sarder, M.D. (2016). A general framework for assessing system resilience using Bayesian networks: A case study of sulfuric acid manufacturer. *Journal of Manufacturing Systems, 41*, 211-227.

Hosseini, S., & Barker, K. (2016). A Bayesian network model for resilience-based supplier selection. *International Journal of Production Economics, 180*, 68-87. doi: 10.1016/j.ijpe.2016.07.007

Jha, A.K., Miner, T.W., & Stanton-Geddes, Z. (Eds.). (2013). *Building Urban Resilience - Principles, Tools, and Practice*: Directions in Development, Washington, DC: World Bank.

John, A., Yang, Z., Riahi, R., & Wang, J.Y.T. (2016). A risk assessment approach to improve the resilience of a seaport system using Bayesian networks. *Ocean Engineering, 111*(1), 136-147.

Johnsen, S. O., & Veen, M. (2013). Risk assessment and resilience of critical communication infrastructure in railways. *Cognition Technology & Work, 15*, 95-107.

Kadri, F., Châtelet, E., & Chen, G. (2014). Method for quantitative assessment of the domino effect in industrial sites. *Process Safety and Environmental Protection, 91*, 452-462.

Kahan, J., Allen, A., George, J., & Thompson, G. (2009). Concept development: an operational framework for resilience: Homeland Security Studies and Analysis Institute.

Khakzad, N., Khan, F., Amyotte, P., & Cozzani, V. (2014). Risk Management of Domino Effects Considering Dynamic Consequence Analysis. *Risk Analysis, 34*(6), 1128-1138.

Klein, R.J.T., Nicholls, R.J., & Thomalla, F. (2003). Resilience to natural hazards: How useful is this concept? *Global Environment Change PArt B: Environmental Hazards, 5*(1), 35-45.

Labaka, L., Hernantes, J., & Sarriegi, M. (2015). Resilience framework for critical infrastructures: An empirical study in a nuclear plant. *Reliability Engineering and System Safety, 141*, 92-105.

Labaka, L., Hernantes, J., & Sarriegi, M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting & Social Change, 103*, 21-33.

Landucci, G., Argenti, F., Tugnoli, A., & Cozzani, V. (2015). Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. *Reliability Engineering and System Safety, 143*, 30-43.

Léger, A., Weber, P., Levrat, E., Duval, C., Farret, R., & Iung, B. (2009). Methodological developments for probabilistic risk analyses of socio-technical systems *Prodeedings of the Instituion of Mechanical Engineers, Part O: Journal of Risk and Reliabilty, 223*, 313-332.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., . . . Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Climate Change, 4*, 407-409.

Linkov, I., Eisenberg, D.A., Bates, M.E., Chang, D., Convertino, M., Allen, J.H., . . . Seager, T.P. (2013). Measurable resilience for Actionable Policy. *Environmental Science & Technology, 48*, 10108-10110.

Matzenberger, J., Hargreaves, N., Raha, D., & Dias, P. (2015). A novel approach to assess resilience of energy systems. *International Journal of Disaster Resilience in the Built Environment, 6*(2), 168-181.

Mc Lean, L., & Guha-Sapir, D. (2013). EnNHANCE / Developing a resilience framework.

McDaniels, T., Chang, S., Cole, D., Mikawoz, J., & Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change - Human and Policy Dimensions, 18*, 310-318.

McDaniels, T., Chang, S.E., Hawkins, D., CHex, G., & Longstaff, H. (2015). Toward disaster-resilient cities: an approach for settting priorities in infrastructure mitigation efforts. *Environment Systems & Decision, 35*, 252-263.

Middleton, E. J. T., & Latty, T. (2016). Resilience in social insect infrastructure systems. *Journal of the Royal Society Interface, 13*(116). doi: 10.1098/rsif.2015.1022

Mojtahedi, M., Newton, S., & Von Mading, J. (2017). Predicting the resilience of transport infrastructure to a natural disaster using Cox's proportional hazards regression model. *Natural Hazards, 85*(2), 1119-1133.

Morchain, D., & Robrecht, H. (2012). Background paper for the Council of Europe's report on resilient cities: ICLEI – Local Governments for Sustainability.

National Academy of Sciences. (2012). Disaster Resilience: A national imperative: National Academy of Sciences, Washington D.C.

Nogal, M., O'Connor, A., B., Martinez-Pastor;, & Caufiled, B. (2017). Novel Probabilistic Resilience Assessment Framework of Transportation Networks against Extreme Weather Events. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems - Part A - Civil Engineering, 3*(3).

Norris, F., Stevens, S., Pfefferbaum, B., Wyche, K., & Pfefferbaum, R. (2008). Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness. *American Journal of Community Psychology, 41*, 127-150.

O'Rourke, T.D. (2007). Critical Infrastructure, Interdependencies, and Resilience. *The Bridge, 37*(1), 22-29.

OECD. (2012). Global modelling of natural hazard risks - Enhancing existing capabilities to address new challenges (pp. 26): Organisation for Economic Co-operation and Development.

OECD. (2014). Guidelines for resilience systems analysis: Organisation for Economic Co-operation and Development.

Omer, M., Mostashari, A., & Nilchiani, R. (2013). Assessing resilience in a regional road-based transportation network. *International Journal of Industrial and Systems Engineering, 13*(4), 389-408. doi: 10.1504/IJISE.2013.052605

Opdyke, A., Javernick-Will, A., & Koschmann, M. (2017). Infrastructure hazard resilience trends: an analysis of 25 years of research. *Natural Hazards, 87*(2), 773-789.

Ouedraogo, K.A., Enjalbert, S., & Vanderhaegen, F. (2013). How to learn from the resilience of Human–Machine Systems? *Engineering Applications of Artificial Intelligence, 26*, 24-34.

Ouyang, M., Duenas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. *Structural Safety, 36-37*, 23-31.

Park, J. , Seager, T. P. , Rao, P. S. C. , Convertino, M. , & Linkov, I. (2013). Integrating Risk and Resilience Approaches to Catastrophe Management in Engineering Systems. *Risk Analysis, 33*, 356-367.

Petit, F.D., Bassett, G.W., Black, R., Buehring, W.A., Collins, M.J., Diclinson, D.C., . . . Peerenboom, J.P. (2013). Resilience Measurement Index: an indicator of critical infrastructure resilience.

Provitolo, D. (2013). Resiliencery vulnerability notion - Looking in another direction in order to study risks and disasters. In D. Serre, B. Barocca & R. Laganier (Eds.), *Resilience and urban risk management*. London, UK: CRC Press, Taylor and Francis Group.

Quenault, B. (2015). De Hyōgo à Sendai, la résilience comme impératif d'adaptation aux risques de catastrophe : nouvelle valeur universelle ou gouvernement par la catastrophe ? *Développement durable et territoires, 6*(3).

Resilience Engineering Association. (2015). http://www.resilience-engineering-association.org/.

Rinaldi, S.M., Peerenboom, J.P., & Kelly, T.K. (2001). Identifying, understanding, and analysing critical infrastructure interdependencies. *IEEE Control Systems Magazine, December 2001*, 11-25.

Robert, B., Morabito, L., Cloutier, I., & Hémond, Y. (2012). Interdependent critical infrastructures: from protection towards resilience. *Disaster Prevention and Management: An International Journal, 24*(1), 70-79.

Rodriguez-Llanes, J.M., Vos, F., Yilmaz, L., & Guha-Sapir, D. (2013). EMBRACE / Developing indicators and indicators systems of societal resilience to disasters: benefits of systematic reviews.

Roege, P. E., Collier, Z. A., Mancillas, J., McDonagh, J. A., & Linkov, I. (2014). Metrics for energy resilience. *Energy Policy, 72*, 249-256.

Rosati, JD, Flynn Touzinsky, K., & Lillycrop, WJ. (2015). Quantifying coastal system resilience for the US Army Corps of Engineers. *Environment Systems and Decisions, 35*, 196-208.

Rose, A., & Liao, S-Y. (2005). Modeling regional economic resilience to disasters: a computable genral equiilibirum analysis of water service disruptions. *Journal of Regional Science, 45*(1), 75-112.

Ruault, J.R. (2015). *Proposition d'architecture et de processus pour la résilience des systemes : application aux systèmes critiques a longue durée de vie.* Université de Valenciennes et du Hainaut-Cambresis.

Sakukai, K., & Kim, T. (2008). Enhanced resilience approah. *Journal of Security Engineering, 6*, 193-200.

Shiraki, W., Takahashi, K., Inomo, H., & Isouchi, C. (2017). A proposed restoration strategy for road networks after an earthquake disaster using resilience engineering. *Journal of Disaster Research, 12*(4), 722-732. doi: 10.20965/jdr.2017.p0722

Sikula, N.R., Mancillas, J.W., Linkov, I., & McDonagh, J.A. (2015). Risk management is not enough: a conceptual model for resilience and adaptation-based vulnerability assessments. *Environment Systems & Decision, 35*, 219-228.

Simon, C., & Weber, P. (2009). Imprecise reliability by evidential networks. *Journal of Risk and Reliability in the Proceedings of the Institution of Mechanical Engineers, Part O, 223*(2), 119-131.

Tacnet, JM., Dezert, J., Curt, C., Batton-Hubert, M., & Chojnacki, E. (2014). How to manage natural risks in mountain areas in a context of imperfect information? New frameworks and paradigms for expert assessments and decision-making. *Environment Systems and Decisions, 34*(2), 288-311.

Talon, A., & Curt, C. (2017). Selection of appropriate defuzzification methods: Application to the assessment of dam performance. *Expert Systems with Applications, 17*, 160-174.

Therrien, M.C. (2010). Stratégies de résilience et infrastructures essentielles. *Téléscope, 16*(2), 154-171.

Thorisson, H., Lambert, J. H., Cardenas, J. J., & Linkov, I. (2017). Resilience Analytics with Application to Power Grid of a Developing Region. *Risk Analysis, 37*(7), 1268-1286. doi: 10.1111/risa.12711

TNCEIP. (2012). Position Paper of the TNCEIP on EU Policy on Critical Energy Infrastructure Protection.

Turnquist, M.A., & Vugrin, E.D. (2013). Design for resilience in infrastructure distribution networks. *Environment Systems & Decision, 33*(1), 104-120.

DIRECTIVE 2008/114/CE DU CONSEIL du 8 décembre 2008 concernant le recensement et la désignation des infrastructures critiques européennes ainsi que l'évaluation de la nécessité d'améliorer leur protection (2008).

United Nations/International Strategy for Disaster Reduction (UNISDR). (2005). Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters - Extract from the final report of the World Conference on Disaster Reduction. Kobe, Hyogo, Japan.

United Nations/International Strategy for Disaster Reduction (UNISDR). (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Sendai, Japan.

United Nations/International Strategy for Disaster Reduction (UNISDR). (2016). Report on the open-ended intergovernmental expert working group on indicators and terminology relating to disaster rik reduction.

Villar, C., & David, M. (2014). *La résilience, un outil pour les territoires ?* Paper presented at the Séminaire IT-GO Rosko.

Vinchon, C., Carreño, M.L., Contreras-Mojica, D.M., Kienberger, S. , Schneiderbauer, S. , Alexander, D., . . . Welle, T. (2011). MOVE Project - Assessing vulnerability to natural hazards in Europe:From Principles to Practice - A manual on concept, methodology and tools.

Vugrin, E.D., Warren, D.E., Ehlen, M.A., & Camphouse, R.C. (2010). A Framework for Assessing the Resilience of Infrastructure and Economic Systems. In K. G. S. Peeta (Ed.), *Sustainable & Resilient Critical Infrastructure Systems* (pp. 77-116). Berlin Heidelberg: Springer-Verlag

Yodo, N., Wang, PF, & Zhou, Z. (2017). Predictive Resilience Analysis of Complex Systems Using Dynamic Bayesian Networks. *IEEE Transactions on Reliability, 66*(3), 761-770.

Zevenbergen, C., van Herk, S., Escarameia, M., Gersonius, B., Serre, D., Walliman, N., . . . de Graaf, R. (2015). Assessing quick wins to protect critical urban infrastructure from floods: a case study in Bangkok, Thailand. *Journal of Flood Risk Management*.