



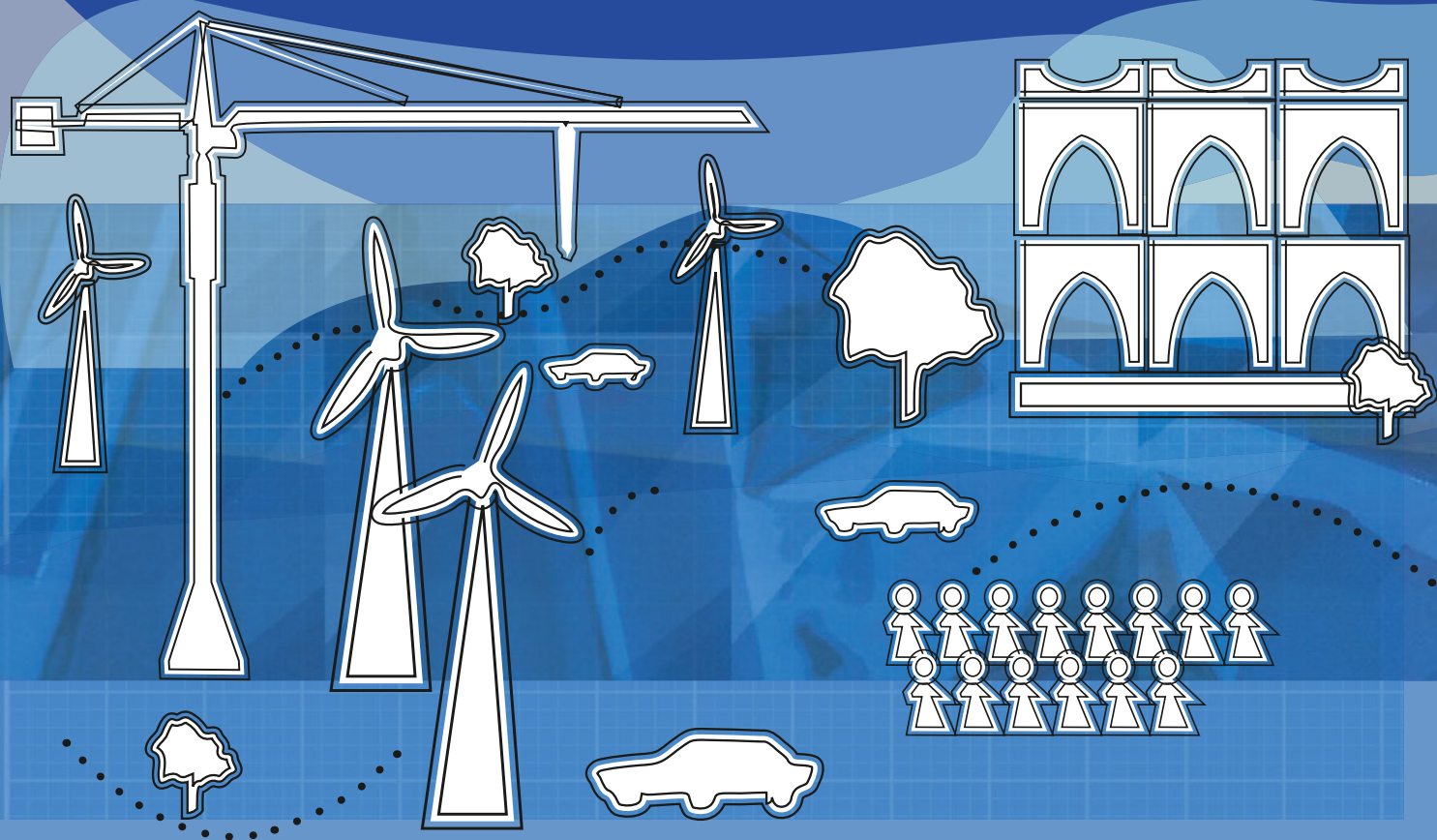
European
Commission

RESILIENCE

The 2nd International Workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment

14-16 December 2017

Ispra



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International workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment

The Joint Research Centre of the European Commission in close collaboration with NIST (National Institute of Standards and Technology, US Department of Commerce) and Colorado State University organised the **2nd International Workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment on 14-16 of December 2017.**

It followed the 1st International Workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment which took place in Washington, DC on 19-21 of October 2016, and was organised by NIST and Colorado State University.

Interest in resilience has been rising rapidly during the last twenty years, both among the policy makers and academia, as a response to increasing concern about the potential effect of shocks to individuals, civil infrastructure, regions, countries and social, economic and political institutions. The objective of the workshop was to bring together the scientific community and policy makers towards developing better policies and practices incorporating the element of resilience in various fields.

The JRC therefore is building on previous experience acquired during the JRC and the European Political Strategy Centre (EPSC) annual conference "Building a Resilient Europe in a Globalised World" which took place in September 2015. This workshop was aimed at identifying strategic needs and providing an outlook of future policy making actions.

This 2nd International Workshop in 2017 aimed at building on the experience gained from these previous events focusing both on the high-level strategic needs and on the current scientific advances on modelling of physical, economic and social systems. The primary goal was to explore how these are linked in order to support resilience assessment in various dimensions aiming to:

- Bring together the most up-to-date knowledge in the field of resilience across different disciplines.
- Establish the dialogue between policy and research with a two-fold scope: to provide scientific advice and support for policies that incorporate the element of resilience, and to provide guidance to the scientific community on the knowledge and tools needed to support current and future policies.

- Contribute towards establishing a coherent resilience assessment framework for communities and societies.
- Identify the constituents for measuring the resilience at various scales (local, regional, national, international) towards establishing the necessary indicators.
- Establish a long-standing partnership among the key actors in the area of resilience at global level that will support the continuous development of models that fit into the assessment framework and consequently the respective training curricula.

The following dimensions were covered:

- Resilience of technological systems (e.g. electricity, gas, water, transport) that provide essential services to citizens during normal conditions as well as during crises.
- Resilience of the built environment, thus civil engineering structures that need to guarantee a certain level of functionality both in terms of safety as well as in terms of business continuity and socioeconomic services that are supported by these buildings.
- Resilience of communities and societies to cascading effects that propagate across infrastructures and networks of infrastructures.
- Economic and societal resilience of modern societies and communities during shocks but also to longer term adaptations.
- Resilience of individuals, depending on social and economic contexts, as well as inter-dependency relationships between individuals and the rest of the society (being communities or national institutions) with respect to risk assessment, risk mitigation and post-crisis recovery.
- Resilience to changes brought about by population growth, utilization requirements, and environmental conditions.

The Organizing Committee thanks all contributors for submitted research papers, which feed into future work on resilience modelling.

JRC 2nd International workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment

Introduction

JRC Directorate E – Space, Security and Migration has organized the 2nd international workshop on Modelling of Physical, Economic and Social Systems for Resilience Assessment in Ispra that will consist in more than ten sessions for three days of full immersion into this topic. Interest in resilience has been rising rapidly during the last twenty years, both among policy makers and academia, as a response to increasing concern about the potential effect of shocks to individuals, civil infrastructure, regions, countries and social, economic and political institutions. The objective of the workshop is to bring together the scientific community and policy makers towards developing better policies and practices incorporating the element of resilience in various fields.

This workshop has been organized in close collaboration with NIST and Colorado State University who organized in Washington on 19-21 October 2016 the 1st International workshop on the same subject. This is a follow-up of several similar events in this field. The JRC already organized a higher level event, the JRC-EPSC annual conference “Building a Resilient Europe in a Globalised World” in September 2015. These workshops aimed at identifying more strategic needs and provide an outlook of future actions. In addition, the JRC organized the first plenary session during the IDRC Davos 2016 conference entitled “Implementing resilience in a world of interconnectedness and emerging challenges” in which the JRC, NIST, Rotterdam city, the Dutch authorities and researchers from Japan presented their views and best practices on resilience implementation. Such an event constitutes an excellent opportunity for positioning JRC among the top institutions in resilience modelling with the capability to influence and steer the work of this community in close collaboration with recognized institutions around the globe.

Summary

Resilience – understood as the capacity to withstand, adapt and recover from crises and shocks – emerged as a concept bridging different policy areas: economy, environment, crisis management, geopolitics, financial services, digital, food, health and many others. An important role of science in the process of building a stable, competitive and prosperous World has been confirmed.

The workshop will aim at covering the following topics:

- Resilience of technological systems (e.g. electricity, gas, water, transport) that provide essential services to citizens during normal conditions as well as during crises.
- Resilience of built environment, thus civil engineering structures that need to guarantee a certain level of functionality both in terms of safety as well as in terms of business continuity and socioeconomic services that are supported by these buildings.
- Resilience of communities and societies to cascading effects that propagate across infrastructures and networks of infrastructures.



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- Resilience of economic systems and more generally economic resilience of modern societies and communities during shocks but also to longer term adaptations.
- Resilience of individuals, depending on social and economic contexts, as well as inter-dependency relationships between individuals and the rest of the society (being communities or national institutions) with respect to risk assessment, risk mitigation and post-crisis recovery.
- Resilience to changes brought about by population growth, utilisation requirements, environmental conditions and climate change

Objectives

- a. Bring together the most up-to-date knowledge in the field of resilience across different disciplines.
- b. Establish the dialogue between policy and research with a two-fold scope: to provide scientific advice and support for policies that incorporate the element of resilience, and to provide guidance to the scientific community on the knowledge and tools needed to support current and future policies.
- c. Contribute towards establishing a coherent resilience assessment framework for communities and societies.
- d. Identify the constituents for measuring the resilience at various scales (local, regional, national, international) towards establishing the necessary indicators.
- e. Establish a long-standing partnership among the key actors in the area of resilience at global level that will support the continuous development of models that fit into the assessment framework and consequently the respective training curricula.

The building blocks of resilience

Some contributions to support the development of training curricula.

Tabajara Dias de Andrade, MD, PhD¹

¹ CLADE- Latin American Development Center

Abstract

We believe in a better world and in the responsibility of every person in making it possible.

In this paper we present the fundamentals of our practice in programs of emotional competence development, focusing on “the human side of resilience” and on the three skill groups that form resilience: personal, relational, and executive skills.

Keywords:

Resilience,
Resilience
Development,
Positive Stress
management,
Behavioral
Algorithms.

We based our work on the triple convergence promoted by advances in technological sciences, neurosciences, and training and learning development sciences.

These resources allow us to train the “behavioral algorithms” that will improve participants’ resilience.

Some practices used are artistic activities, games, mentalization, storytelling, and theatrical activities.

1. Introduction

“Humanity is complex, unpredictable, and brings together people capable of the most destructive actions. It is also capable of projecting its future and building a desirable reality.”

Resilience is a comprehensive and dynamic concept, briefly defined as the ability of people or systems to succeed in the face of change and uncertainty and to continue to develop even at critical times. It means living in a crisis and even taking advantage of it. It is the ability to transit in adversity and overcome situations of intense change or high need for adaptation.

Psychological resilience is an important factor in different contexts; its development benefits not only the individual himself but also all other instances where some level of human interaction occurs.

It is not an unusual ability. Most people have it on some level. And it is the result of multiple personal, group and community factors.

Genetic structure, biological and psychological factors, social aspects, values, personal and group histories, experiences, prior learning, and environmental resources are some of the elements that influence it.¹

Here we will address the “human side of resilience”. Or more specifically, “how to empower people and groups with the skills they need to have a high level of resilience.”

¹ Sapolsky, 2007



2. The Triple Convergence. Resources and Strategies

The triple convergence; resulting from advances in the technological sciences, neurosciences, and in the sciences of training and learning gives us a spectacular advance in the possibilities of developing people and groups in the most different capacities, like the resilience itself.

We should be concerned about the building of resilience for all mankind. Here it is not a problem of ours or of them, but of all.

We must engage in this development in all contexts and in all the stages of life; since childhood - this is one of the best times for this; but also in adulthood – when many skills, acquired naturally during life, are useful in this learning.²

Many scholars claim that this is a spontaneous and natural improving, promoted by people's own experiences. There are even those who say that the difficulties of life are good teachers. We, at the Latin American Center for Development, believe that it can be accelerated and optimized in a calm, serene and controlled environment. For 23 years, we have developed emotional and behavioral training projects, empowering leaders, groups, and individuals in the main aspects involved in the evolution of personal, group and social resilience through the training of "behavioral algorithms".

Informally speaking, an algorithm is a collection of simple instructions to accomplish some tasks. Commonplace in everyday life, algorithms are sometimes called procedures or recipes.³

Behavioral algorithms are mental schemes that direct our strategies of thoughts and actions. They are structured through our previous learning and experiences.

They can be more automated or more conscious, but we all have them, even if we do not know it.

Whenever we face a new situation we tend to use strategies that have proven appropriate in the past. But often these processes are no longer adequate, or our "old strategies" are insufficient in the face of new or critical situations.

² Sandberg, 2017

³ Sipser, 2006; Gawande, 2011

When people can improve these strategies in quality and quantity, they have a positive behavioral differential in new situations, especially in contexts that require a great deal of adaptation.

The training also aims to teach people how to identify possible future critical or risk situations and to build their own training program in order to qualify themselves for skills that may be needed.

3. Practices

Several are the practices used for these goals. Let's look at some:

3.1. Artistic Expressions

Artistic expressions are excellent means to form the essential basis for the construction and structuring of resilience.

In front of a white screen to be painted, a piece of clay to be shaped or a stone to be sculpted, the person develops autonomy, creativity and, among others, a procedural view. Once the work is finished, the self-esteem and empowerment are improved, revealing to the individual his capacity for achievement. When it is done in a group, the activities will also contribute to the development of specific collaborative skills. All of them are fundamentals of resilient behavior.

3.2. Games

Many of the situations that we live on a daily basis can be compared to games. In this context, the games help us to understand any processes of human relationships where roles, objectives, and rules are defined. We are talking about love, professional, learning games and so many others. Games can be healthy and constructive, but they can also be destructive and perverse. Rules, roles, and objectives may be well defined or not.

This perspective opens up a great field of action, allowing us to use game design elements in various contexts of development and learning. These experiences are very motivating and produce an unparalleled engagement in both intensity and duration, allowing the individual to experience a fragment of space and time, that is characteristic of real life, in a fictional and controlled context, even when addressing critical issues. When collaborative, it also promotes the optimization of group resources to overcome critical situations.⁴

3.3. Theater practice activities

Theatrical practices enable people to deal with complex and highly critical situations within a safe and controlled educational environment. They provide a good insight into the identified behaviors that can be developed or avoided according to their suitability in specific contexts. It's a great way to test and practice behaviors "before" every possible situation.

They can be performed in private groups in which all the participants take part in the scene, or with an audience, when who is watching the practice is also allowed to interact.⁵

⁴ Huizinga, 1955; Deterding-2011; Dominguez, 2013; Andrade, 2016

⁵ Spolin, 2013

3.4. Mentalization

Mentalization - if well trained - is an excellent resource for self-control, internal assessment, definition and maintenance of focus, strategic planning, personal resource recovery and construction of possible solutions and new realities. Also, it allows the visualization of the most appropriate solutions in each context.

It can also promote a feeling of freedom and peace, even in the most complex contexts. Imagining the end of the situation can increase adaptability and facilitate overcoming the situation.⁶

The practice of this “voluntary emotional adequacy” improves our ability to coping stress and finding balance, motivation and new solutions, even in critical situations.

3.5. Storytelling

Storytelling is the act of sharing stories.

Undoubtedly it is one of the teaching techniques most used by all peoples and at different times. In its various formats, it has divulged customs, thinking and life styles, strategies of conduct and values for many centuries.

This practice, of telling real or fiction stories, offers us excellent strategies for the building of learning and development programs.

Committed to ethical values and to develop skills in the population, the storytelling becomes an instrument of great value in building up resilience in individuals and groups.

These are very effective resources, with an excellent cost-benefit ratio and that do not require large structures and investments for their realization. Isolated or combined, they provide us with many possibilities for action.

4. Skills

The personal and the group resilience are better developed and trained if we break it down into its basic elements, which can be grouped into Personal, Relational and Executive skills.

4.1. Personal skills

We understand personal skills as those directly related to the person.

Among them, we mention sovereignty, self-knowledge, self-management, positive stress management⁷, personal shielding, creativity, the ability to read the environment and to perceive risk situations, capacity to identify and create opportunities, problem solving skills in critical situations, the capacity to perform and, fundamentally, the capacity for adaptation and overcoming.

4.2. Relational skills

Relational skills, like healthy leadership, the ability to establish reliable links, effective networks, and creative interdependence, determine the dynamics and effectiveness of interpersonal relationships, helping the functioning of groups and communities.

They also provide consistency, alignment, synergism, shared empowerment and reorganization to those groups, in the face of critical situations or intense need for adaptation.

⁶ Frankl, 1984

⁷ Andrade, 2010

4.3. Executive skills

Executive skills are formal or informal processes, which give us, under different circumstances, the best functioning when we deal with different types of processes that occur in our lives.

They are the competencies necessary for the conduct of processes and the execution of projects. We need them to manage our own health, our career, our financial lives and, above all, to conduct ourselves effectively, individually or collectively, during crises or intense periods of adaptation.

5. Items

The good news is that resilience is a systemic ability composed by an interacting group of items that can easily be trained one by one.

We quote here some of the items most frequently addressed.

5.1. The building blocks of resilience

They include competencies in the three groups mentioned, but also the various community resources that must be developed before being needed.

5.2. Personal and group sources of resilience

Each individual or group should develop their own strategies, driven by behavioral algorithms, in different situations. Training coordinators should facilitate the process and point out positive or negative points, stimulating the engagement and cooperation of all.

5.3. Institutions as sources of resilience

Strong, warm and humane institutions are important drivers of resilience. The commitment, especially from the authorities, in improving these institutions should be stimulated.

5.4. True values and beliefs

Values and beliefs are important pillars for structuring resilient behavior. They guide us. We live in search of meaning, and when we find it, we are more effective in dealing with critical situations. During periods of crisis, identifying a purpose in life, and feeling positive about it, can promote resilience.⁸

5.5. Bringing out the best in people

The human being is not a homogenous being.

The contradictions of society are only reflections of internal personal contradictions. We possess terrible and also very positive aspects. Redeeming the best of people is a top priority in any project that seeks the development of a resilient behavior.

5.6. Mental and emotional balance

Mental and emotional balance is one of the most important aspects of life. When we lose them in a crisis situation, we stop being part of the solution and become part of the problem.

⁸ Frankl, 1946

5.7. Self-control

Self-control is a cognitive process necessary to regulate one's behavior in order to achieve specific goals.

It is the ability to exercise control over our state in different circumstances, even the most critical ones. In other words is to have control over our feelings, emotions, thoughts, actions, and behaviors to recover from adversity or to overcome situations of intense change or high need for adaptation.⁹

5.8. Creativity and improvisation

Creativity is a partner of resilience.

Creating is the art of being, the art of building the world in which we live.

Creativity can be spontaneous or a conscious choice, but it will always be a tool for problem-solving and an indispensable strategic factor.

Improvisation is here seen as the ability to build quick solutions in unforeseen situations with limited resources.

The development of these skills can define the success or failure in critical situations.

5.9. Initiative

The ability to start something. An act or strategy designed to solve a problem or improve a situation. The readiness to engage in difficult activities.

5.10. Proactive Critical Adaptation

It is the ability to withstand undesirable situations of reality and not submit to them, but to seek a critical adaptation and develop effective strategies to overcome them.

5.11. Personal and community perspectives

Alignment of personal and group perspectives.

People feel valued by the group and value it, and defend it as themselves.

5.12. Responsibility

The duty to deal with something and the ability to act independently to make decisions without authorization, but with an obligation to respond to their actions.

5.13. The sense of community

It is not only a matter of recognizing that "my right ends when the right of the other begins" but of accepting that when the rights of anyone in the world are being disrespected, mine will also be disrespected.

5.14. Building winning teams

It is the construction of a group identity committed to the intended result.

⁹ Timpano, 2013

5.15. Shared social responsibility

Responsibility is divided and everyone feels responsible for the common good.

5.16. Synergistic and objective collaboration

It is the ability of people to act together with a common goal.

5.17. The strength of character

They are the values practiced by individuals and communities.

Ethics and other values are not characteristics of good people, but of smart people. It is much easier to live in an ethical context!

6. Final considerations

We are all responsible for enhancing everyone's resilience.

Governments, institutions, associations and individuals, all of us have this important mission.

We all dream of a better world and this means greater capacity for innovation, adaptation, coping and overcoming crises.

Training is the differential that provides the consolidation of development and essential skills for us to better conduct ourselves in different contexts.

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The Evolution of Risk Assessment for the Evolution of the Future Complex and Interconnected Physical, Economic and Social Systems

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Abstract

I consider the changing industrial, environmental and social context and address some challenges and opportunities therein, focusing on aspects of risk. Digitalization brings improvements but with them comes also the complexity of cyber-physical systems. Climate change and extreme natural events are increasingly threatening our infrastructures. Terrorist and malevolent threats are posing severe concerns.

Risk assessment must evolve for addressing these challenges. Development directions are presented, including the use of simulation for accident scenario identification and exploration, the extension of risk assessment into the framework of resilience and business continuity, the reliance on data for dynamic and condition monitoring-based risk assessment.

Keywords

Risk assessment, Simulation, Resilience, Condition monitoring-based risk assessment, Dynamic risk assessment.

1. Introduction

As the digital, physical and human worlds continue to integrate, we experience a deep transformation in industry, which far-reaches into our lives. The 4th industrial revolution, the internet of things and big data, the industrial internet, are changing the way we design, manufacture, provide products and services. This is creating a complex network of things and people that are seamlessly connected and communicating. It is providing opportunities to make productions systems more efficient and faster, and more flexible and resilient the complex supply chains and distribution networks that tie the global economy.

In this fast-pace changing environment, the attributes related to the reliability of components and systems continue to play a fundamental role for industry and those related to safety and security continue to be increasingly of concern, as a right to freedom. The innovations that are being developed have high potential of increased wellbeing and benefits, but also generate new and unknown failure mechanisms, hazards and risks, partly due also to new and unknown functional and structural dependencies. On the other hand, the advancements in knowledge, methods and techniques, the increase in information sharing, data availability and computational capabilities, and the advancements in knowledge that these can bring, offer new opportunities of development for the analysis



and assessment of risks. An evolution of risk assessment is in the making, or perhaps even a “revolution” that takes the form of new approaches to and methods for risk assessment.

In this paper, I consider the above context and point at some directions that are shaping the road of advancement of risk assessment. Some directions and challenges for risk assessment are discussed, in relation to simulation for accident scenario identification and exploration, resilience and business continuity, dynamic and condition monitoring-based risk assessment.

2. Risk Assessment

Risk assessment is a science that has been developed in the past 40 years for understanding and controlling the risk of accident events. This allows the rational management of hazardous industrial activities, through their systemic understanding. The basic idea of risk assessment is to structure, by systematic modelling, the information and knowledge available at the detailed component/basic event level to assess the accident risk at system level. As knowledge on these events and on the system responses to them is limited, the outcomes of the assessment are uncertain. The common framework used to describe the uncertainties in the assessment stands on probability theory, and particularly on the subjectivistic (Bayesian) theory of probability (Kelly and Smith; 2009, 2011). Indeed, the common term used is Probabilistic Risk Assessment (PRA), although Probabilistic Safety Assessment (PSA) and Quantitative Risk Assessment (QRA) are also widely used.

Knowledge is central to the risk assessment and should be made explicit in the definition of risk (Aven 2010):

$$Risk = (A, C, Q; K) \quad (1)$$

where A indicates the set of accident scenarios that may occur, C represents the set of consequences, Q is the metric used to quantify the associated uncertainties and K is the body of knowledge which the risk assessment (i.e., the identification of A and the quantification of C and Q) is based on.

The risk assessment outcomes are functions of the current state of knowledge, and of the related assumptions made and parameter values assigned. The methodologies and approaches for risk assessment support the structuring of knowledge in a systematic, rigorous and transparent framework.

But, it is just as important to be aware of the (incomplete) knowledge conditioning the risk assessment outcomes. Correspondingly, accident events and scenarios in a risk assessment model can be classified according to the knowledge available at the time of the assessment (Flage & Aven 2015).

Eventually, for decision making, risk assessment must provide traceable information for arguing the decisions; the risk assessment outcomes must be communicated in a way that allow the decision makers to interpret them properly for their purposes and to understand the associated uncertainty related to the available knowledge used for the assessment. It remains an open research challenge how to explicitly treat knowledge in risk assessment and management. When a risk assessment is performed to provide information that is used for making decisions, there must be a way to tell that it has been performed with adequate techniques and sufficient knowledge for making the decisions (Rae et al. 2012).

3. Simulation for Risk Assessment

The identification and characterization of hazards and accidents is a fundamental task of knowledge mining for risk assessment. This task is far from trivial in practice, given the complexity of the systems and processes: a large, combinatorial set of possible scenarios, events and conditions needs to be considered, of which only few, rare ones lead to critical, unsafe situations. This makes experimentation economically unsustainable and physically infeasible.

Simulation has long been advocated as a way to explore and understand system behavior for knowledge retrieval (Santner, Williams, & Notz 2003; Simpson, Poplinski, Koch, & Allen 2001). Thanks to the advancements in modelling techniques and the increase in computational power, the beneficial use of simulation for advancing knowledge for risk assessment has steadily increased.

Within a simulation-based accident scenario analysis, a set of simulations is run with different initial configurations of the system parameters (input), and the corresponding system states are computed (output) and evaluated with respect to specified safety conditions (critical thresholds). These states form the so called “Critical Regions” (CRs) or “Damage Domains” (DDs) (Montero-Mayorga, Queral, & Gonzalez-Cadelo 2014).

Concurrently, simulation can also be exploited to estimate the accident scenarios probabilities, or any other measure of uncertainty adopted to describe risk.

As simple and intuitive the use of simulation may seem for addressing the above two questions, in the practice of risk assessment it is actually quite demanding because the models of system behavior are:

- *High-dimensional*, i.e., with a large number of inputs and/or outputs;
- *Black box*, i.e., without an explicit Input/Output (I/O) relation;
- *Dynamic*, because the system evolves in time;
- *Computationally demanding* even for a single trial simulation, as a consequence of the above characteristics of the models and of the numerical methods employed for their solution.

Two main strategies are currently followed to address the two research questions and related challenges above presented:

- Simulation of large sets of system life histories using the increased computational power made available through parallel computing, cloud computing etc.;
- Simulation by adaptive sampling, which amounts to intelligently guiding the simulation towards the system states of interest (i.e., those belonging to the CRs). This entails that the simulation methods be capable of automatically understanding, during the simulation, which configurations are most promising to visit.

Simulation is particularly strongly advocated for the hazard analysis, and safety and resilience assessment of critical infrastructures and systems of systems (Alexander & Kelly 2013; Zio 2016). The increasing concern on the vulnerability of critical infrastructures (see Section 5 below) and the increasing role of systems of systems in safety-critical applications has raised the need for methods to analyse their hazards, and verify their safety and resilience properties. One viable way for this is simulation of the variety of scenarios that can emerge from the response of the individual system components to different perturbations and failures, sampled over space and time. The effects of the interaction between system components can, then, be observed together with the corresponding system behaviour that emerges. The challenges for the analysis of such systems come from the fact that the system boundary is not well defined and the set of components in the system can vary over time, either as part of normal operation (e.g. a new car enters the traffic scene or a new aircraft enters a controlled airspace region) or as part of evolutionary development (a traffic lane is interrupted because of construction work or a military unit receives a new air-defence system). In such an undefined and dynamic setting, conventional techniques of analysis may be inadequate for determining whether or not the failure of a given component may be hazardous for the system as a whole. Simulation, on the other hand, can provide a way of analysis of such systems made of multiple components that interact in complex and continually changing ways.

4. Business Continuity Assessment

Business continuity (BC) measures the capability of an organization to remain at or quickly recover to operational states after being affected by disruptive events. Business Continuity management (BCM) is a managerial framework that aims at ensuring that no disruptive events can lead to unexpected, unwanted interruptions of production or service activity. In this view, it lays down the vision of integrating the post-accident recovery process to the preventive view of risk assessment (Cerullo and Cerullo, 2004).

As a holistic, integrated risk management strategy, BCM offers great potential benefits but the complexity of the systems and risk problems involved is such that most currently existing BCM strategies are based on qualitative methods only, and this limits practical and effective application. No clearly defined business metrics, which impedes the quantitative analysis of BC and, therefore, limits application in practice.

To contribute to the advancement of BCM for its application in practice, Zeng and Zio (2017) have developed an integrated, quantitative framework for modeling BC, founded on the definition of four metrics that measure the potential losses caused by the disruptive events. A simulation-based method has been presented in the paper to calculate the BC metrics based on the integrated model. To demonstrate the use of the framework, the BC of an oil storage tank farm is assessed. The conceptual model that describes BC and identifies its major contributing factors refers to a performance indicator, denoted by PPIB (Process Performance Indicator-Business), whose value reflects the degree to which the objective of the system is satisfied. For example, for an oil refinery, the PPIB is its daily production yield; for a manufacturing factory, the PPIB is the products produced per day. The value of PPIB is determined by the operation state of the system: the PPIB remains at its nominal value when the system is under normal operation and drops to a degraded value when the normal operation of the system is disrupted. To reduce losses, various BC measures can be taken to guarantee the continuity of the business process in the face of disruptive events.

5. Resilience Assessment

In comparison to risk, resilience is focused also on the ability to prepare and recover quickly from threats which may be known or unknown. Managing for resilience, then, requires ensuring the system's ability to plan and prepare for a threat, and then absorb, recover, and adapt.

It is the lessons learned in recent years from some catastrophic accidents that have led to the concept of resilience to ensure the ability of systems to withstand, adapt to and rapidly recover from the effects of a disruptive event. Today's systems are not only required to be reliable but must also be able to recover from disruptions (Zio 2009, Zio 2016b).

Resilience is characterized by four properties, i.e. robustness, redundancy, resourcefulness, rapidity and four interrelated dimensions, i.e., technical, organizational, social, economic. It is considered a new paradigm for risk engineering, which proactively integrates the accident preventive tasks of anticipation (imagining what to expect) and monitoring (knowing what to look for), the in-accident tasks of responding (knowing what to do and being capable of doing it) and learning (knowing what has happened), the mitigative tasks of absorbing (damping the negative impact of the adverse effect) and the recovery tasks of adaptation (making intentional adjustment to come through a disruption), restoration (returning to the normal state) (Hollnagel et al. 2006).

Various models, methods and frameworks for analyzing and measuring resilience have been proposed in the literature (Carpenter et al. 2001; Fiksel 2003; Wreathall 2006; Jackson 2007; Madni and Jackson 2009), with focus on diverse fields of application.

For ensuring adequate protection and resilience, vulnerability and risk must be analysed and assessed in order to prepare to address them by design, operation and management. Modeling and analysis by reductionist methods are likely to fail to capture the behavior of the complex systems of interest, and new approaches are needed that consider these systems from a holistic viewpoint to provide reliable predictions of their behavior for their safe control (Kröger and Zio 2011). Furthermore, large uncertainties exist in the characterization of the failure behavior of the elements of a complex system, of their interconnections and interactions (Zio and Aven 2011).

The analysis of complex systems and CIs cannot be carried out only with classical methods of system decomposition and logic analysis; a framework is needed to integrate a number of methods capable of viewing the complexity problem from different perspectives (topological and functional, static and dynamic), under the existing uncertainties (Ouyang et al. 2009; Reed et al. 2009; Ouyang 2014).

6. Dynamic Risk Assessment

Risk assessment must account for the time-dependent variations of components and systems, as they operate, age, fail, are repaired and replaced (Villa et al. 2016). Dynamic Risk Assessment (DRA) is defined as a risk assessment that updates the estimation of the risk of a deteriorating system according to the states of its components, as knowledge on them is acquired in time (Khan et al. 2016). DRA is capable of capturing the time-dependent behaviour of the risk and provides a more realistic description of the system risk profile (Khan et al. 2015, 2016; Villa et al. 2016).

An early attempt of DRA was conducted in (Meel and Seider 2006, 2008) where Bayes theorem was used to dynamically update the estimates of accident probabilities, using near misses and incident data collected from similar systems. In Khakzad et al. (2012), Bayes theorem was combined with a Bow-Tie (BT) model for DRA: failure probabilities of the primary events and safety barriers in the BT were constantly revised over time and the updated BT model was used to estimate the updated risk profile. Paltrinieri et al. (2014) used BT to support the DRA from metal dust accidents. Abimbola et al. (2014) applied a similar method to update in real time the risk estimation of offshore drilling operations.

Most existing DRA methods only use statistical data, i.e., count data of accidents or near misses from similar systems, to update the estimated risk indexes. Additional information potentially useful for the estimation of the risk indexes may come from condition-monitoring data. The condition-monitoring data give information on the individual degradation process of the target system and of the safety barriers, and provide the opportunity to update the reliability values before actual failures occur. Therefore, introducing condition-monitoring data in DRA could be a beneficial complement to the statistical data, towards a condition monitoring-based risk assessment (CMBRA).

A method for DRA that allows the joint utilization of statistical and condition-monitoring data has been proposed in (Zeng and Zio 2017b). Consequence analysis is also considered by means of an ET.

7. Discussion

Risk assessment is a mature discipline for a structured analysis of a system, to qualitatively and quantitatively describe its risk, based on the available knowledge. The quantitative analysis is often criticized in view of the difficulty of assigning probabilities (e.g., to human errors or software failures), the difficulty of verifying the assumptions behind the models at the basis of the assessment, the inherent uncertainty involved in the phenomena of interest. However, the use of quantitative measures remains essential for rational, effective decision making combining evidential knowledge and subjective beliefs. The risk assessment must, thus, provide an argument that it must be possible to scrutinize and not a formalized demonstration of an objective truth. The argument stands on the knowledge available and the related modeling assumptions made to formalize the assessment.

Furthermore, the changes and innovations that the World is experiencing, with digitalization and the complexity of cyber-physical systems (CPSs), climate change and extreme natural events, terrorist and malevolent threats, challenge the existing methods to describe and model quantitatively risk.

In this view, the increasing modeling and computational capabilities and data availability open great opportunities for mining knowledge and improving models for use in risk assessment. In this respect, in this paper I have pointed at some research and development directions with regards to the use of simulation for accident scenario identification and exploration, and the reliance on data for condition monitoring-based, dynamic risk assessment.

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Probabilistic Modelling of Robustness and Resilience of Power Grid Systems

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Abstract

The present paper proposes a framework for the modeling and analysis of resilience of networked power grid systems. A probabilistic systems model is proposed based on the JCSS Probabilistic Model Code (JCSS, 2001) and deterministic engineering systems modeling techniques such as the DC flow model. This probabilistic systems model facilitates the propagation of the dominating uncertainties affecting the system performances, including characteristics of geo-hazard disturbances, internal flow, the resistances of the system with respect to these and effects of internal redistribution and subsequent possible cascading failure event scenarios (Nan and Sansavini, 2017). The concept of direct and indirect consequences proposed by the Joint Committee on Structural Safety (JCSS, 2008) is utilized to model the associated consequences. To facilitate a holistic modeling of robustness and resilience, and to identify how these characteristics may be optimized these characteristics, the power grid system is finally interlinked with its fundamental interdependent systems, i.e. a societal model, a regulatory system and control feedback loops.

Keywords

Power Grid Systems, Robustness, Resilience, Cascading Failures.

The proposed framework is exemplified with reference to optimal decision support for resilience management in the IEEE Reliability Test System-1996. Parameter studies are undertaken to assess the significance of decision options on the system performance characteristics. Finally, the presented framework and example results are discussed and suggestions for further developments are provided.

1. Introduction

Over the last 1-2 decades, significant progress has been achieved in research on performances of networked systems, playing critical roles in providing societal services such as energy, communication and transport. Fundamental insights on the nature and performances of systems with random characteristics are provided through the models proposed (Watts and Strogatz, 1998) and (Barabasi and Albert, 1999). Modeling and analysis of reliability and risk performances of networked systems in engineering applications is addressed in e.g. (Dueñas-Osorio and Vemuru, 2009) and (Buldyrev et al., 2010).

In pursuit of optimal decision support for sustainable and resilient societal developments, there is a need to model and analyse system performances beyond reliability and risk and with an appropriate consideration of their evolution in both time and space. Recently, a novel decision analytical framework for the representation and quantification of resilience of systems was proposed in (Faber et al., In Press). A fundamental feature of this framework is that systems performances are modelled through explicit consideration of how the services



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provided by the system contribute to the development of the systems capacities, such as social capacity, financial capacity and ecosystem capacities. Resilience failure is represented as the event that a disturbance or a combination of different disturbances lead to a capacity loss of the system beyond its accumulated reserves. This formulation facilitates the joint quantitative modelling and assessment of how systems perform with respect to robustness, resilience and also sustainability in a quantitative manner.

The present paper is organized as follows. Closely following (JCSS, 2008), (Faber, 2015) and (Faber et al., In Press), Section 2 outlines a decision analytical framework for the probabilistic modeling and analysis of robustness and resilience of networked power grid systems. In Section 3, details are provided on how we apply the deterministic systems analysis methods from (Nan and Sansavini, 2017) for the probabilistic modeling of cascading failures. In Section 4, an example is provided illustrating the application of the proposed framework and approaches on the IEEE Reliability Test System-1996. Finally, in the conclusions, the presented framework and example results are discussed and suggestions for further developments are provided.

2. Decision Support Framework and Approach

2.1. Decision support context

Consistent decision support for strategic, operational and tactical management of electricity distribution systems over all phases and instances of their service lives is crucial; only then can their reliable, robust and resilient performance be ensured.

At the strategic level, decision support typically serves to identify how the systems themselves are designed, how procedures for their normal operation and maintenance may be optimized but also how strategies and measures are optimally prepared for different types of disturbances. Operational level decision support typically concerns the efficient management of the systems in states, which might be expected as part of normal operations. This includes adaptation of system functionalities to predictable variations of demands and management of predictable needs for maintenance, repairs and renewals. Tactical level decision support on the other hand aims for efficient loss reduction and fast recovery in cases where the systems are subject to event scenarios out of the ordinary such as excessive operational demands, accidents, geo-hazard events (e.g. earthquakes, strong wind storms and floods) and malevolence.

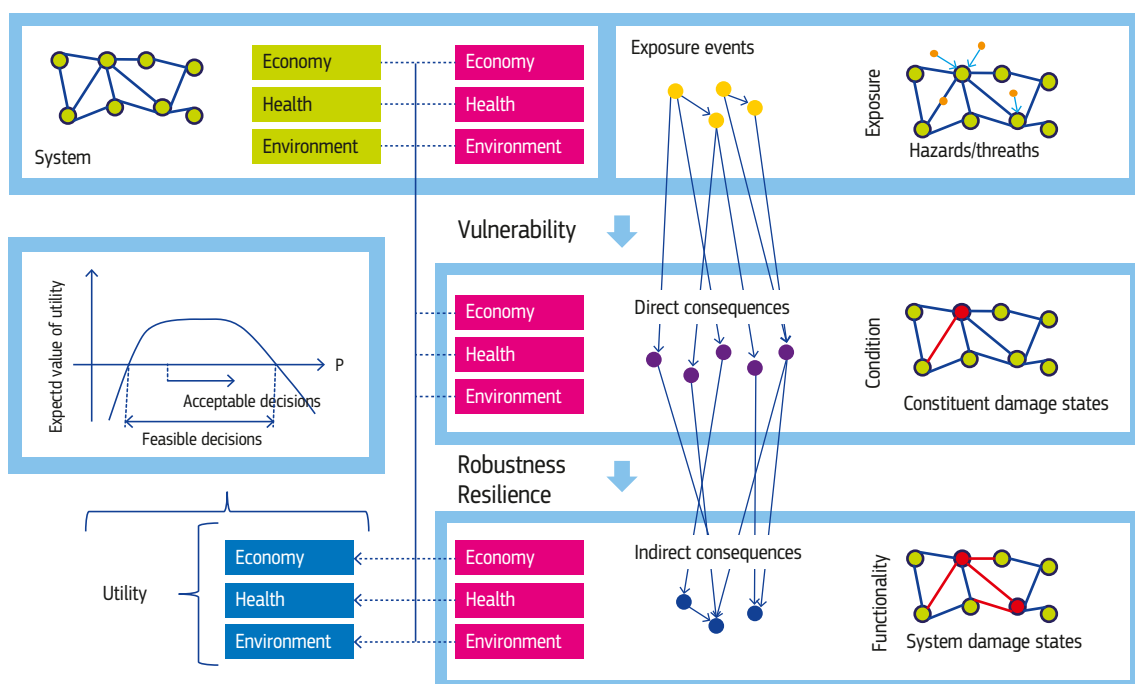
In all strategic, operational and tactical decision situations, uncertainties may significantly affect the outcomes of decisions and this must be accounted for when ranking different possible decision alternatives.

In the following, we focus on providing decision support at strategic level where as already indicated, all relevant operational and tactical level decision support situations should be accounted for. However, here we limit ourselves to address decisions on the design of the capacities of the major constituents of electricity distribution systems given that their general configurations have already been decided and given information concerning the demands the systems aims to fulfil. With this limitation due account is however given to possible disturbance events over the service lives of the systems due to extreme operational demands, geo-hazard events and acts of terrorism.

2.2. Probabilistic system performance modelling

Following (JCSS, 2008) and (Faber et al., In Press) the decision analysis framework for interconnected systems illustrated in Figure 1 is utilized. This system representation accounts for both benefits and losses generated by the interlinked systems over time, and optimal decision alternatives may be identified by a joint consideration of their effect on system performance characteristics such as robustness and resilience as introduced in sections 2.3-2.4.

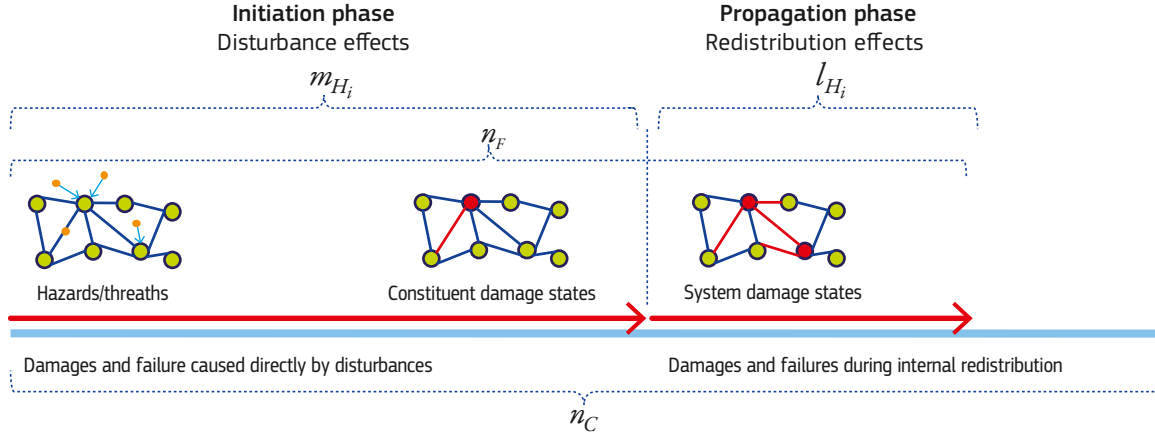
Figure 1. Generic framework for decision analysis of systems (Faber et al., In Press)



In the left side of Figure 1 the interlinked system is represented in its undisturbed configuration with associated benefits and in the right side with all possible scenarios of system damage and failure events implying losses to the system over time. It is assumed that a probabilistic system model is available (see also Section 3) which represents all relevant physical processes, engineered objects and facilities, organizational processes, human activities as well as all decision alternatives envisaged for designing and managing the performance of the system. The system modelling approach suggested by the (JCSS, 2008) is utilized to subdivide the scenarios of events leading to consequences for the system into direct consequences and indirect consequences. Direct consequences comprise all losses caused by damage and failure states of the constituents of the system except functionality related losses. Indirect consequences relate only to functionality losses.

Two phases in the evolution of consequences are explicitly considered, namely the initiation phase and the propagation phase, see also Figure 2.

Figure 2. Illustration of the two-phase scenario based failure propagation model (Faber et al., In Press)



In the initiation phase m_{H_i} constituent failures are assumed generated by the hazard event H_i . In the propagation phase l_{H_i} constituent failures are generated by the joint effect of internal redistribution of system demands and the hazard events. The two-phase failure propagation model facilitates the representation of cascading failure scenarios.

In accordance with (Faber et al., In Press) we assume in the following that a probabilistic systems model has been established comprised of all possible $i = 1, 2, \dots, n_S$ different scenarios of hazard events together with their occurrence probabilities $p(i)$, direct consequences associated with constituent failure events during the initiation phase $c_{D,i}(i)$ and propagation phases, respectively $c_{D,p}(i)$ and the associated indirect consequences $c_{ID}(i)$.

2.3. Robustness modeling and quantification

Provided the availability of the system representation outlined in the foregoing it is possible to assess the performances of the system subject to disturbance events over time. Robustness is one of the system characteristics that have attracted the most attention in this respect aiming to provide a metric for assessing the degree to which a system is able to contain or limit the immediate consequences of disturbances. In (Baker et al., 2008), risk-based formulations for the quantification of systems robustness are first provided and later in (Faber, 2015) revisited and modified accounting for a more general and consistent scenario based approach. Following (Baker et al., 2008), the idea is to relate the robustness of a system to the ratio between direct consequences and total consequences. In (Baker et al., 2008), it is suggested to assess this through the expected values of the two terms individually (equivalently through the direct and total risks). The modification introduced in (Faber, 2015) appreciates that direct and indirect consequences are generated scenario wise and thereby avoids mixing of consequences in the robustness assessment which are not generated in the same scenarios. Accordingly a scenario consistent index of systems robustness with respect to a given scenario i , i.e. $I_R(i)$ may be assessed as:

$$I_R(i) = \frac{c_D(i)}{c_T(i)} \quad (1)$$

The direct and total consequences $c_D(i)$ and $c_T(i)$ entering Equation (1) may be interpreted differently depending on the objective of the assessment. If representation and analysis of cascading failure event scenarios is in focus, Equation (1) may be rewritten as:

$$I_R(i) = \frac{c_{D,I}(i)}{c_{D,I}(i) + c_{D,P}(i)} \quad (2)$$

where $c_{D,I}(i)$, $c_{D,P}(i)$, represent the direct consequences associated with the initiation phase and the propagation phase of the failure scenario of the system, respectively.

If on the other hand the emphasis is directed on the ability of the system to contain the development of consequences from direct to indirect consequences Equation (1) may be rewritten as:

$$I_R(i) = \frac{c_{D,I}(i) + c_{D,P}(i)}{c_{D,I}(i) + c_{D,P}(i) + c_{ID}(i)} \quad (3)$$

From Equations (1)-(3), it is apparent that the robustness index is random and its assessment must be undertaken probabilistically. Robustness indexes for a given system can furthermore, straightforwardly be assessed conditional on e.g. the type and/or intensity of the hazard event as well as the magnitude of direct, indirect or total consequences. The scenario-based approach facilitates for assessing which constituent damages and failures contribute the most to inadequate robustness performance and to the total consequences.

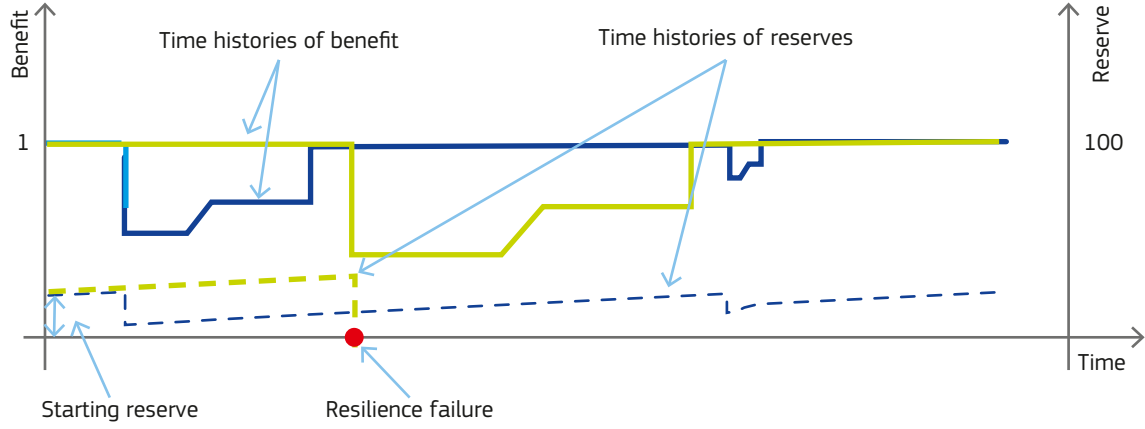
2.4. Resilience modelling and quantification

A large variety of propositions for the modelling and quantification of systems resilience is available in the literature; see e.g. (Cimellaro et al., 2010) and (Linkov et al., 2014). Most frequently, the focus is directed on the short-term representation of the ability of the system to sustain and recover from disturbances, fast and with a minimal loss of functionality. Recovery characteristics are typically accounted for through the social, organisational and adaptive capacities together with traditional characteristics of technical systems such as strength, ductility, brittleness, redundancy, segmentation, diversity and robustness (see e.g. (Derissen et al., 2011), (Pimm, 1984) and (Baker et al., 2008)).

Following (Faber et al., In Press) a service life perspective to systems resilience is taken in which scenarios of benefit generation and losses are modelled and analysed over time. Resilience failure is defined as the event of one or more of the capacities of the system (social, economical and/or environmental) are exceeded by demands/consequences of disturbances. In this manner resilience failure, similarly to systems robustness attains a random nature why requirements to resilience may only be specified meaningfully in probabilistic terms; e.g. in terms of an acceptable annual probability of resilience failure.

The idea is illustrated in Figure 3 for the case of a system for which the only explicitly considered capacity is a financial reserve collected as a fixed percentage of the annual benefit generated by the system over time.

Figure 3. Illustration of resilience model in terms of time histories of benefit generation and corresponding time histories of accumulated economic reserves (Faber et al., In Press)



In Figure 3, two scenarios of benefit generation and accumulated economic reserves are illustrated. Disturbance events may both reduce the benefit generation as well as the accumulated reserves. The time history illustrated with a green line corresponds to the event of resilience failure, i.e. the disturbance event exhausts the accumulated reserves.

Following the concept illustrated in Figure 3 and as provided in (Faber et al., In Press) the probability of resilience failure may be written as:

$$P_{RF}(t, \mathbf{a}) = 1 - P[\{r_r(\mathbf{X}(\tau), \mathbf{a}) - s_r(\mathbf{X}(\tau), \mathbf{a}) > 0, \forall \tau \in [0, t]\}] \quad (4)$$

where $r_r(\mathbf{X}(\tau), \mathbf{a})$ is a function representing a given capacity of the system at time τ and $s_r(\mathbf{X}(\tau), \mathbf{a})$ is a function representing the demand or stress on the system caused by a disturbance event at time τ , $\mathbf{X}(\tau)$ is a vector of random variables which in general depend on time and \mathbf{a} is a vector containing all decision alternatives which may affect the resilience performance of the system. Equation (4) may be realized to involve a first excursion problem.

The first immediate drop in the benefit rate after a disturbance event (as illustrated in Figure 3) may be noticed to relate directly to the systems reliability and robustness. Even with moderate assumptions concerning the contribution of indirect consequences to total consequences it is apparent that cascading failures and loss of functionality plays a significant role for the resilience of the system. From Figure 3, it is seen that a starting capital or reserve is assumed available at time $t = 0$. In the design and management of systems, sufficient resilience critically depends critically on the availability and maintenance of this reserve, as illustrated in the example presented in Section 4.

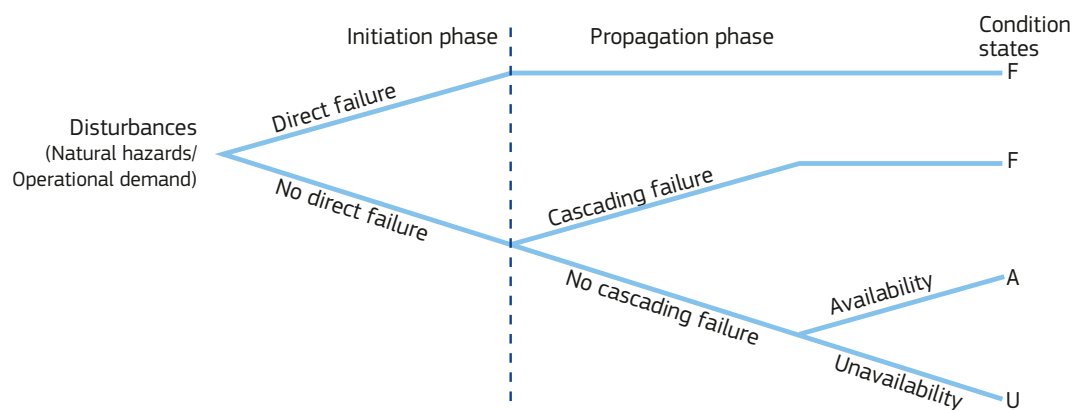
3. Probabilistic Modeling of Energy Distribution Systems

Performance of energy distribution systems is generally subject to significant uncertainties. Risk-informed decision making in general takes into account the effect of uncertainty within the framework of the Bayesian decision analysis (Raiffa and Schlaifer, 1961) and facilitates that a consistent ranking of decision alternatives may be established in coherency with the preferences and requirements of the decision maker. In (Faber, 2015), systems risk informed decision analysis is addressed and risk-based indicators for systems resilience are formulated. However, the systemic risk assessments and the quantification of performance indicator requires the probabilistic modeling of the systems characteristics and performances. The two main tasks of the probabilistic modeling are: (1) the formulation of the probabilistic modeling of the relevant variables affected by uncertainties; and (2) the probabilistic analysis of the systems states.

As illustrated in Figure 2, two phases of system performance under given hazard events are explicitly considered, during which the loads or demands on each constituent of the energy distribution system are divided into two categories, namely L_{H_j} and L_{O_j} to represent the load on the j^{th} constituent from the geo-hazard events $j = 1, 2, \dots, n_C$ and that from the operational demand respectively. Correspondingly, the resistances of the n_C constituents in the system are divided into two types, namely r_{H_j} and r_{O_j} . During the service life, the system is subjected to the joint action of the possibly interacting geo-hazards, with loads $L_{H_{ij}}, j = 1, 2, \dots, n_C$ (representing the load from the i^{th} geo-hazard H_i on the j^{th} constituent). The loads will have their own probabilistic characteristics and would in general be correlated. Also operational demands may initiate failure propagation events and cause changes in the typology of the system and corresponding alterations in internal load distribution until another equilibrium state of the system is reached. The uncertainties associated with both types of loads and the resistance, together with their dependency structure must be taken into account in the probabilistic system modeling.

In Figure 4, the potential condition states of a constituent in a energy distribution system subject to a given disturbance is illustrated. First, the constituents are affected by the disturbances, i.e. geo-hazards and/or overload by the operational demands, and they might fail (and effectively be removed from the grid system) directly. Subsequently, in the propagation phase, the topology of the system might further change in a sequence of constituent failures and the operational demands redistributed correspondingly. Even if the individual constituents survive the effects of disturbances in the first phase they still might fail due to the overload caused by other constituent failures. It should also be noted that even in the event that a given constituent survives and is in principle functional it might still loose its functionality within the system due to the possibility of loss of interconnection with the remaining system. These events are denoted as availability (A) and unavailability (U), respectively.

Figure 4. Event tree of the performance of a constituent in a energy distribution system without reorganization and rehabilitation



The probability that the j^{th} constituent is in the state F_j may be written as:

$$P(F_j) = P \left[\bigcup_{i=1}^{n_s} \bigcup_{j=1}^{n_c} (L_{H_{ij}} > r_{H_{ij}}) \bigcup_{j=1}^{n_c} (L_{O_j} > r_{O_j}) \right] \quad (5)$$

Note that the load L_{O_j} might change with the topology of the system. It is generally difficult to write the expression of the probabilities $P(A_j)$ and $P(U_j)$ explicitly. The probabilistic evaluation of the occurrence of potential condition states is challenged by the vast number of different combinations of constituent failure events which must be accounted for. In the following we use crude Monte Carlo (MC) simulation for this purpose, but highlight that more intelligent and efficient approaches are needed.

4. Example

4.1. Brief introduction

In this section, the IEEE Reliability Test System-1996 (see Figure 5 for the typology of the system) is utilized to illustrate the application of the proposed framework and approaches for assessing the robustness and resilience of a power grid system. The system is made of 24 buses and 11 buses host generators. Each bus has a capacity to withstand geo-hazard disturbances L_H , e.g. r_H , and a capacity to withstand the internal power flow L_O , i.e. r_O . The internal flow L_O is defined as the number of shortest paths passing it directed from the generators to the non-generator buses.

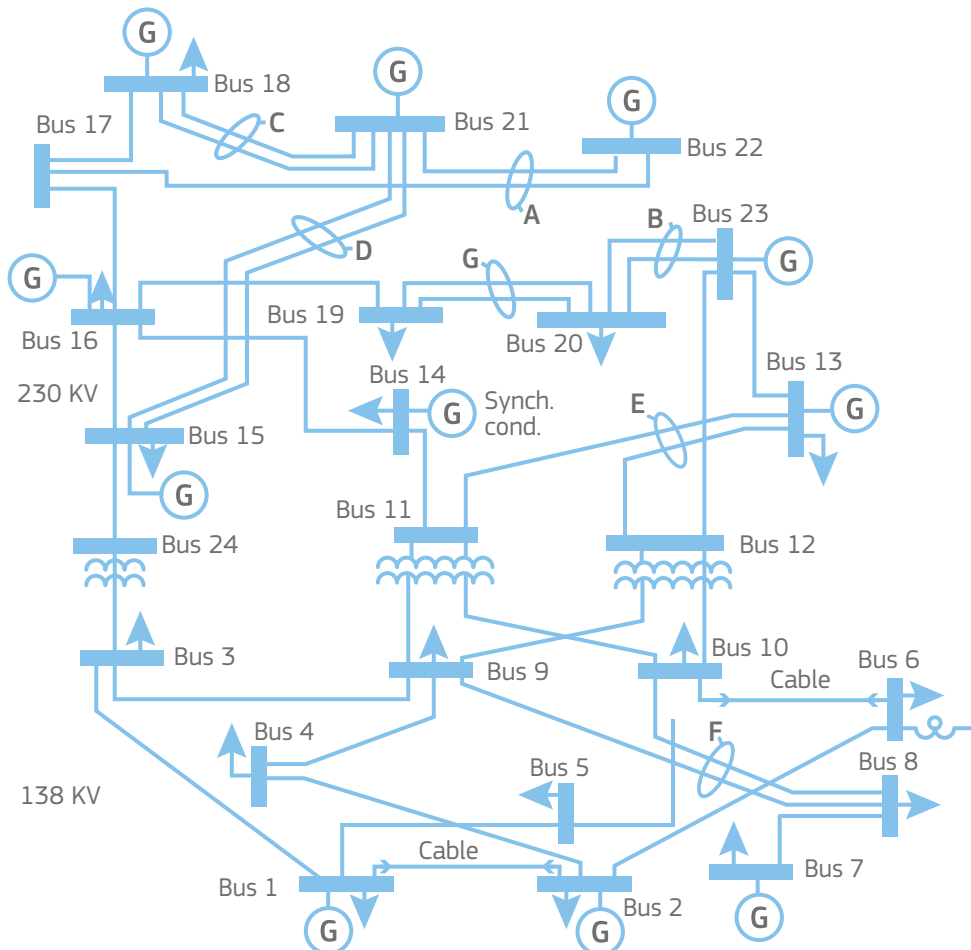
The two types of capacity r_H and r_O are modeled by Log-normal distribution random variables. The expected value and the coefficient of variation of r_H are 1 and 0.3, respectively; the expected value of r_O is defined as the initial flow of the bus, i.e. the internal flow L_O in the original system, and its coefficient of variation is 0.05.

The limit state functions representing the failure events of the individual buses with respect to the geo-hazard disturbances and the internal flows are:

$$\begin{aligned} g_H &= z_1 r_H - L_H \\ g_O &= z_2 r_O - L_O \end{aligned} \tag{6}$$

where z_1 and z_2 are design parameters which may be chosen to comply with the requirements with respect to target probabilities (reliabilities) of constituent failures.

Figure 5. Illustration of the typology of the IEEE Reliability Test System-1996 (Grigg et al., 1999)



The annual probability of individual bus failure conditional on the event of a geo-hazard disturbance is set to $p_{f|H} = 10^{-2}$ and $p_{f|H} = 5 \times 10^{-2}$ for generator and non-generator buses, respectively, and incorporated into the model through calibration of z_1 (z_1 is 4 and 3.3 for generator and non-generator buses, respectively).

The annual probability of individual bus failures with respect to operational demands (internal flow) is set to $p_{f,O} = 10^{-3}$, and incorporated into the model through calibration of z_2 ($z_2 = 1.17$).

The performance of the power grid under a given disturbance, i.e. initial constituent failure due to operational overload or geo-hazard disturbances is modelled as a two-phase process. First, the buses are impacted directly by the disturbance, and might fail and be removed from the grid system. Subsequently, in the cascading phase, the topology and the capacities of the elements might change in a sequence of consecutive failures, during which the internal flows are redistributed correspondingly. Therefore, even if the buses survive the direct effects of disturbances in the first phase, they might still fail due to overload events caused by other bus failures. The buses are assumed to fail when internal demands exceed their capacity limits (see Equation (6)). Even in the event that a constituent survives and is functional, it might still not be operational due to the possibility of loss of interconnection with the rest of the system.

The non-generator buses which are still working, distribute the power to the users, i.e. they provide system functionality (utility). It is assumed that buses are replaced upon their failure. The replacement cost and the utility of different buses are provided in Table 1.

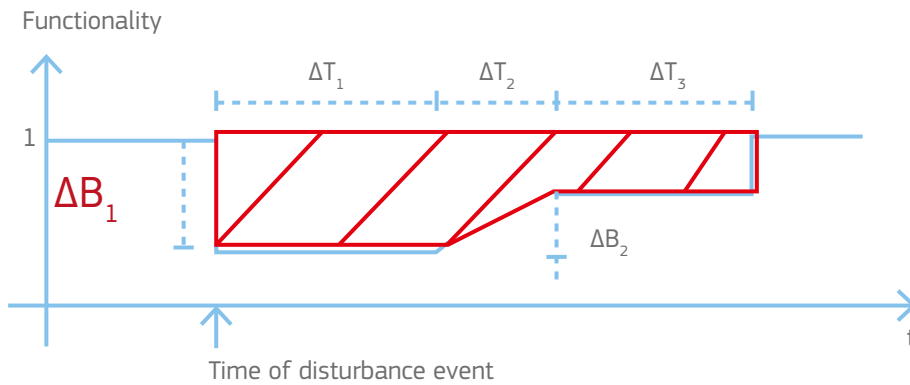
Table 1. Replacement costs and utilities of the buses.

	Generators	Non-generator buses
Replacement cost	2	1
Utility	0	5

The geo-hazard disturbance events are assumed to follow a Poisson counting process with annual occurrence rate $\lambda_H = 0.1$. The intensities of disturbance events acting on each bus is modelled by a random vector \mathbf{I}_H with constituents assumed to be log-normal distributed. The sequential realizations of \mathbf{I}_H are assumed independent but the disturbances acting on the constituents at a given time are correlated with correlation coefficient ρ_{I_H} . The expected value and the coefficient of variation of the intensity I_H , i.e. $E[I_H]$ and $COV[I_H]$, are equal to 1 and 0.4, respectively; the correlation coefficient ρ_{I_H} is 0.8.

The evolution of the system functionality (utility) illustrated in Figure 6. for a particular realization of a disturbance event shows how the functionality is reduced by ΔB_1 at the time of disturbance. ΔT_1 represents the time till the system initiates commissioning of temporary measures to re-establish functionality. The temporary measures are assumed to be fully functional after a period ΔT_2 with a resulting functionality gain equal to ΔB_2 . In parallel to and after commissioning of temporary measures, permanent measures for re-establishing functionality are also being planned and deployed. Permanent measures are commissioned after a period ΔT_3 .

Figure 6. Illustration of the reorganization and recovery of system functionality after disturbances (Faber et al., In Press)



The loss of functionality of the system ΔB_1 for a particular disturbance is considered to be the ratio of the loss of utility to the total utility of the original system. The periods $\Delta T_i, i = 1, 2, 3$ describing the principal functionality loss and recovery curve are modelled by log-normal distributed random variables. Two levels of preparedness are considered, i.e. low and high, which affect the performance of the system during recovery. The expected values $E[.]$ and coefficients of variation $COV[.]$ for the random system variables are given in Table 2.

Table 2. Definition of the probabilistic model of the system with respect to preparedness and capacity

Variable	Distribution model	Low preparedness		High preparedness	
		Expected value	COV	Expected value	COV
ΔT_1	Log-normal	$E[\Delta T_1] = \Delta B_1$	0.2	$E[\Delta T_1] = \frac{\Delta B_1}{2}$	0.1
ΔT_2	Log-normal	$E[\Delta T_2] = 5\Delta B_1$	0.2	$E[\Delta T_2] = \Delta B_1$	0.1
ΔT_3	Log-normal	$E[\Delta T_3] = 20\Delta B_1$	0.2	$E[\Delta T_3] = 10\Delta B_1$	0.1
ΔB_2	Deterministic	$0.5 \times \Delta B_1$		$0.8 \times \Delta B_1$	

Furthermore, a reserve capital is assumed available over the life-cycle of the power grid system for covering the replacement cost of buses which may fail due to disturbance events. The starting capital reserve at $t = 0$ is modelled as a percentage $\chi\%$ of the expected value of the accumulated benefits over the life-cycle of the power grid system.

4.2. Analysis results

In the following, we analyse the robustness and the resilience of considered power grid system. Robustness is quantified by the robustness index conditional on the disturbance scenarios due to the overload by internal flow or geo-hazards. The direct consequences are calculated as the replacement costs associated with buses failed due to the disturbance before internal flow redistribution. The indirect consequences are associated with replacement costs due to failures caused by internal flow redistribution, and utility loss due to the replacement and loss of connection with the generators of the non-generator buses. Figure 7 shows the CDF of the non-exceedance probability of the conditional robustness index. The probability that the robustness index I_R will be less than 0.2 for both the geo-hazard and the internal-flow disturbance is larger than 0.7, indicating that there would be great indirect consequences conditional on the disturbances. However, for the disturbance due to the overload by the internal flow, the failure probability of individual buses is small (less than 1×10^{-3}) and correspondingly, the occurrence probability of the event that two or more buses fail simultaneously is very low. That is, there generally is one bus failure at first and the subsequent cascading effect will not be significant. Therefore, the probabilities that the robustness index I_R is less than 0.2 (corresponding to the event that most damaged buses are non-generators) or greater than 0.9 (corresponding to the event that most damaged constituents are the buses host generators) are similar to each other and around 0.5.

Figure 7. CDF for the robustness index of the power grid system for operational internal flow and geo-hazard disturbances

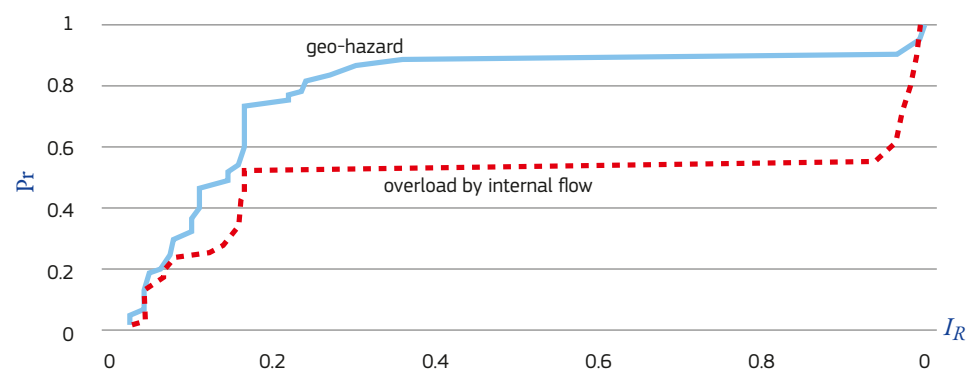
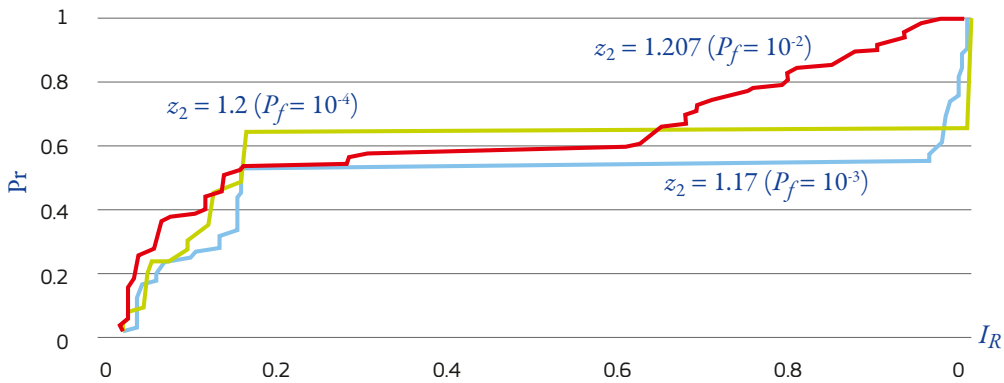


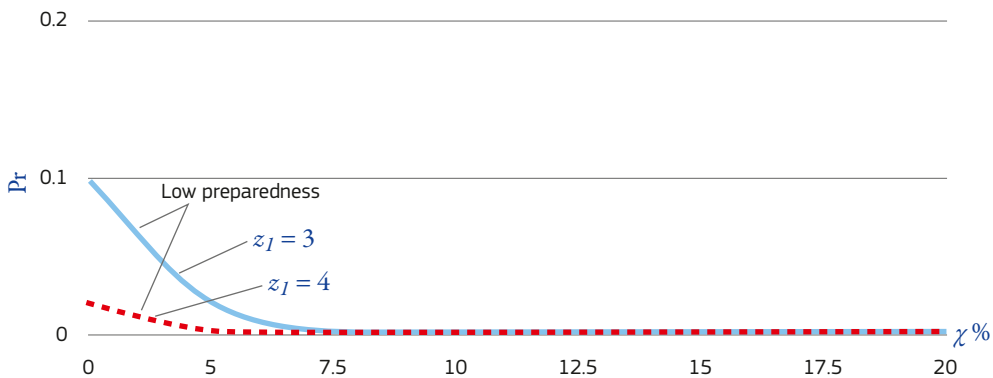
Figure 7 compares the CDFs for the robustness index of the system with different values of the design parameter z_2 for the disturbance due to the overload by the internal flow. Three values of z_2 are considered, i.e. 1.1207, 1.17 and 1.2, which correspond to the failure probability of individual buses around 1×10^{-2} , 1×10^{-3} and 1×10^{-4} , respectively. For the system with small value of z_2 , i.e. a relatively large annual failure probability of individual buses, the non-exceedance probability within the interval from 0.2 to 0.9 would have some fluctuations. That is, there would be many events captured in the simulations, in which both types of buses fail simultaneously. For the other two cases, the overall trend of the curves is similar, and the probability that the robustness index is less than 0.2 (corresponding to the event that most damaged buses are non-generators) for the system with larger value of z_2 (equal to 1.2) is a little greater than that with a small value of z_2 (equal to 1.17). The opposite occurs in the region, in which the exceedance probability is larger than 0.9 (corresponding to the event that most damaged buses are generators). Considering that the number of non-generator buses is greater than that of the buses host generators and each bus has same design failure probability, given that there is some failure due to the overload by the internal flow, the probability that some non-generator bus fails is larger than the probability that some generator fails. Such differences would be more pronounced for lower design annual failure probabilities for the individual buses.

Figure 8. CDF comparison for the robustness index of the power grid system with different values of the design parameter z_2 for the disturbance due to the overload by the operational internal flow



The resilience of the system depends on a number of factors such as the frequency and types of disturbances, the capacity and robustness of the system and the level of preparedness. The system resilience is quantified by the probability of resilience failure (the exhaustion of the capital accumulated by the system of time) in dependency of the percentage χ % within a life cycle equal to 100 years. The results are illustrated in Figure 9 for the system with low preparedness. The resilience failure for the system with high preparedness is not captured in the total 1×10^3 simulations applied in the present example. As expected, the system experiences resilience failure, if the starting reserve is limited, i.e. χ % < 7.5% in this case study, and the level of preparedness is low. Furthermore, decreasing the target annual failure probability of the constituents reduces the probability of resilience failure.

Figure 9. Probability of resilience failure of the power grid system in dependency of the percentage χ %



5. Conclusions

In the present paper, we adapt and apply a previously developed framework for modelling and assessing the robustness and resilience of systems to electricity grids. The proposed approach facilitates the representation and assessment of the systems characteristics of electricity grids, and captures the uncertainties associated with disturbance events of internal operational (e.g. demand overload) and external (e.g. geo-hazards and terrorist attacks) character as well as with the capacities of the constituents to withstand such disturbances. Moreover, the approach facilitates for representing scenarios of cascading failures and the capability of the system to recover from disturbances over time.

The approach is illustrated through its application to the IEEE Reliability Test System-1996. From the example, it is demonstrated that decisions on the target reliability of the individual constituents of the system with respect to disturbance events may be assessed and optimized to reach requirements in terms of robustness and resilience. Moreover, the framework allows decision-making on how much of the utility generated by the system should be kept in reserve to ensure sufficient capacity to recover from disturbances.

The proposed approach applies also to decision support for the optimization of grid topology and for any operational and tactical decision context, if decision alternatives are represented appropriately in the systems modelling.

Since the computational efforts associated with the representation of the system performances are substantial (in the order of minutes on a high performance PC), further research and developments on optimization of computational schemes are necessary.

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Power Systems Resilience to High-impact, Low-Probability Events: Modelling, Quantification and Adaptation Strategies

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Abstract

Electrical power systems have been historically designed and operated to deal with the so-called credible events, i.e. N-1 or N-2 outages. However, power systems are indeed exposed to much less common events caused by natural disasters and extreme weather, which can still significantly impact the electricity supply. It is thus of growing interest to design power systems that are highly resilient, in the sense that they need to first withstand high impact low probability events (HILP) and then recover as quickly as possible. Unlike the well-developed concepts associated with reliability (and security in particular), there is still no clear and universal understanding of the concept of resilience, including its modelling, quantification and adaptation measures. Hence, this paper provides the fundamentals of first distinguishing the concepts of resilience and security and then modelling and assessing power systems resilience during an extreme event through a *multi-phase resilience trapezoid*, catering for both *operational* and *infrastructure* resilience. A Sequential Monte Carlo-based simulation engine is also presented for capturing the spatiotemporal impacts of HILP events. A novel resilience metric system is introduced to capture the actual response of a power system subject to extreme events. At last, quantification of resilience during an event also allows application of different structural and operational adaptation strategies for boosting power systems resilience to such HILP events. A simplified version of the Great Britain transmission system is used for demonstration.

Keywords

Extreme weather; high-impact low-probability; natural disasters; power systems; resilience; resiliency

1. Introduction

Electrical power systems, as a critical infrastructure, are key for the sustainability and growth of modern societies, since they support several critical services and infrastructures, such as transportation, communication and health systems. Hence, given these high and complex interdependencies between these critical infrastructures, a disruption in the electricity network can have catastrophic consequences.

However, despite the efforts of keeping the power flowing and the lights on under any credible events, power systems are occasionally exposed to extreme weather and natural hazards, which as evidenced worldwide can be so intense that they can cause the collapse of power systems, leading to large and sustained power disruptions. The threats of a power system can be broadly categorized in credible or 'typical' power system outages and more extreme events, driven mainly by natural disasters and extreme weather, whose frequency and severity might increase as a direct impact of climate change [1]. Table 1 shows the distinct differences between these two categories of events [2].



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Power systems have been traditionally designed to be reliable (secure in particular) to the more typical threats. Nevertheless, recent experiences are now signifying the increasing need for power systems to also achieve high levels of *resilience* to natural disasters and extreme weather, in order to reduce the frequency and severity of power disruptions. Table 2 shows some of the key features that set the concept of resilience apart from the one of security [3].

Table 1. Comparison of typical power system outages and extreme events

Typical Power System Outage	Extreme Event
Low impact, high probability	High impact, low probability
Preventive & corrective control measures portfolio in place	No control measures in place (typically)
Random location and time of occurrence	Spatiotemporal correlation between faults and event
Supported by contingency analysis and optimization tools	Limited mathematical tools
Limited number (single or double) of faults due to component failures	Multiple simultaneous faults
Small portion of the network is damaged/collapsed	Large portion of the network is damaged/collapsed
Quick restoration	More time and resources consuming/longer restoration

Table 2. Comparison of Resilience and Security

Security	Resilience
High-probability, low-impact	Low-probability, high-impact
Based on average indicators, e.g. loss of load frequency	Based on risk profile, e.g. conditional expectation
Shorter term, typically static	Longer term, adaptive, ongoing
Evaluates the power system states	Evaluates the power systems states and the state transitions
Concerned mainly with customer interruption time	Concerned with customer interruption time and infrastructure recovery time

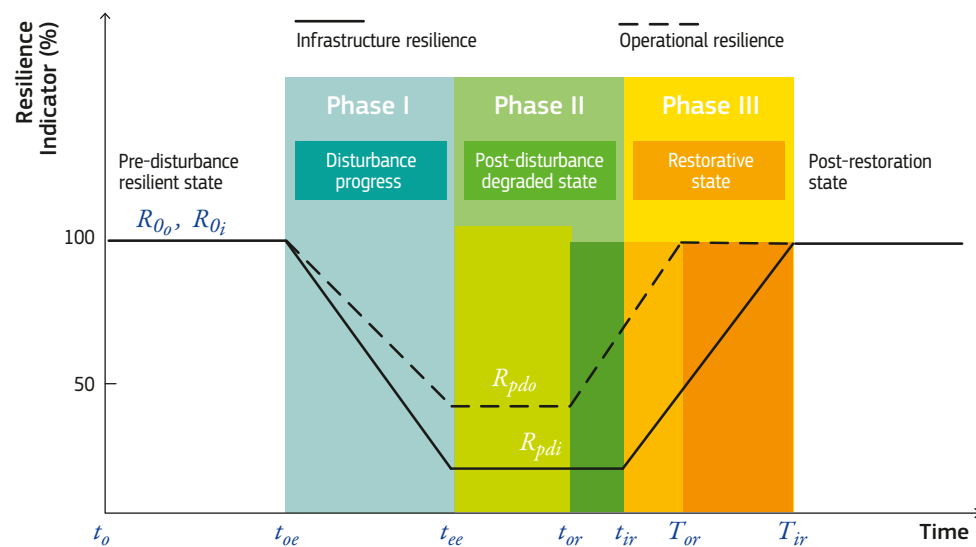
However, in the context of power systems as critical infrastructures the definition of resilience is still blur, despite the several approaches to define resilience by organizations worldwide in the last decade or so [4,5]. Further, there is currently not a systematic approach for quantifying the impact of natural disasters and extreme weather (as high-impact, low probability (HILP) events) on power systems using resilience-oriented metrics, as well as quantifying the effects of different strategies for boosting and adapting their resilience to such catastrophic events. This is also to be seen in the light of the need of defining and measuring different levels of resilience that may be achieved from an operational perspective and from an infrastructure perspective.

Based on a conceptual *multi-phase resilience trapezoid* developed in [6,7], this paper first provides insights on the concept of power systems resilience, while making indeed the distinction between *infrastructure* and *operational* resilience. This also helps understand the resilience performance of a power system during a HILP event. Next, a comprehensive approach for assessing and quantifying the fragility and resilience of power systems against HILP events is presented. Power systems resilience is quantified following the specifically developed resilience-oriented metric framework, the so-called ΦAEP resilience metric system [6]. The quantification of resilience allows the application and evaluation of different structural and operational adaptation strategies for improving the resilience of a power system to future (foreseen or never experienced before) extreme events. The concepts and techniques discussed in the paper are demonstrated using a 29-bus test version of the Great Britain (GB) transmission system.

2. Operational and Infrastructure Resilience During an HILP Event: Conceptual Multi-Phase Resilience Trapezoid

A power system might reside in different states when subject to external shocks, such as natural disaster and extreme weather. It is therefore critical to understand and define these states in order to develop techniques capable of reflecting the resilience behaviour and performance of a power system during an HILP event.

Under these premises, and beyond the so-called *resilience triangle* [8] used in the majority of existing related literature, Figure 1 shows a conceptual *multi-phase resilience trapezoid* [6,7], which clearly demonstrates the states (or phases) of a power system associated with an external disturbance. Further, the *operational* and *infrastructure resilience* are clearly depicted, which should be quantified using different indicators, as demonstrated later. The *operational resilience*, as its name suggests, refers to the characteristics that would secure operational strength for a power system, e.g., the ability to ensure the uninterrupted supply to customers or generation capacity availability in the face of a disaster. The *infrastructure resilience* refers to the physical strength of a power system for mitigating the portion of the system that is damaged, collapsed or in general becomes non-functional.

Figure 1. The conceptual multi-phase resilience trapezoid during a HILP event

Three phases (namely *Phases I, II and III*) can be clearly seen, which enable the dynamic, multi-phase resilience assessment:

- *Phase I, disturbance progress* ($t \in [t_{oe}, t_{ee}]$), between the time of the event t_{oe} and the end of the event t_{ee} ,
- *Phase II, post-disturbance degraded state* following the end of the event and before the restoration is initiated ($t \in [t_{ee}, t_{or}]$ and $t \in [t_{ee}, t_{ir}]$ for the operational and infrastructure resilience respectively), and
- *Phase III, restorative state* ($t \in [t_{or}, T_{or}]$ and $t \in [t_{ir}, T_{ir}]$ for the operational and infrastructure recovery respectively).

During *Phase I*, the resilience of the power system subject to the HILP event drops from the pre-disturbance operational and infrastructure resilience, R_{oo} and R_{oi} respectively, to the post-disturbance resilience levels R_{pdo} and R_{pdi} respectively in *Phase II*, before the restorative *Phase III* is initiated. R_{oo} and R_{oi} are assumed here to be 100%, but this may vary depending on the pre-disturbance system conditions and configuration. It also has to be noted that R_{pdo} may be lower or higher than R_{pdi} , depending on the system and on the severity of the event hitting the network, as will be demonstrated later. It is thus system- and event-specific. Further, as shown in Figure 1, *Phases II and III* can be divided in two sub-phases: the operational and infrastructure post-disturbance degraded states ($t \in [t_{ee}, t_{or}]$ and $t \in [t_{ee}, t_{ir}]$ respectively) and the operational and infrastructure recovery ($t \in [t_{or}, T_{or}]$ and $t \in [t_{ir}, T_{ir}]$), making indeed a distinguish between the two concepts. This enables the systematic modelling, quantification of the operational and infrastructure resilience during the event, and planning of optimal infrastructure that maximizes targeted *resilience metrics*.

3. Fragility and Resilience Assessment of Power Systems Subject to HILP Events

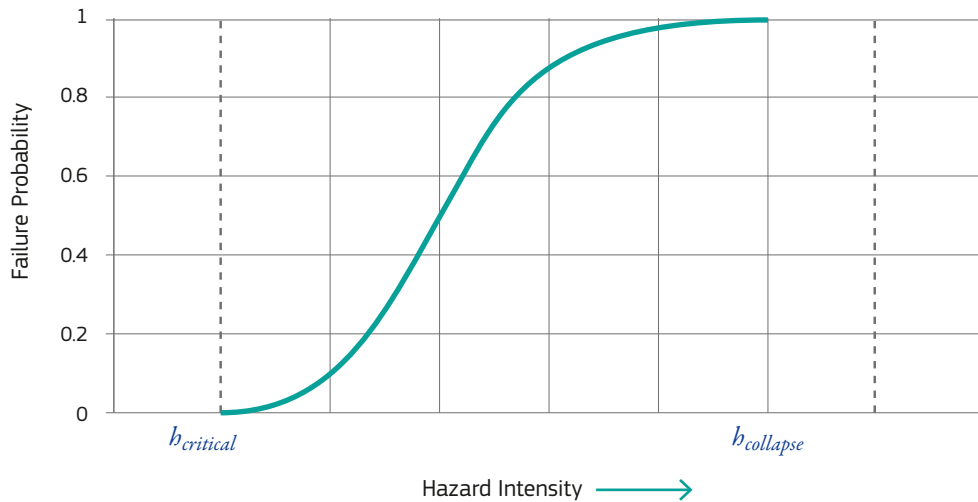
This section explains the fragility modelling of a power system exposed to an HILP event, discusses the ΦAEP resilience metric system proposed in [6] and presents the simulation procedure for assessing the resilience of power systems against HILP events.

3.1. Fragility modelling

Different approaches have been proposed in the literature for modelling the fragility of critical infrastructures to natural disasters and extreme weather. In this work, the concept of fragility curves is used for obtaining the time- and hazard-dependent failure probabilities of the power system components subject to these events. A *fragility function* relates the probability of failure of a component with the loading imposed by a hazard (e.g., wind speed or earthquake intensity). These fragility functions can be derived through different ways, such as empirically, experimentally, analytically or using expert judgment. Here, an analytical approach is used for deriving these functions [9]. A generic example of a fragility curve is shown in Figure 2, which can be expressed by the following fragility function (where P is the failure probability, h is the hazard intensity and i is the simulation step):

$$P(h_i) = \begin{cases} 0, & \text{if } h < h_{critical} \\ P(h), & \text{if } h_{critical} \leq h < h_{collapse} \\ 1, & \text{if } h \geq h_{collapse} \end{cases}$$

Figure 2. A generic fragility curve



3.2. Resilience metrics

In the light of recent rare and extreme events and given the fact that the traditional reliability indices (e.g. Loss of Load Frequency, *LOLF*, and Expected Energy Not Supplied, *EENS*) are dominated by expectation, capable of effectively dealing with events of high or known probability, they cannot be considered sufficient for characterizing the resilience of power systems. These indices need to be complemented by a set of *resilience metrics* capable of modelling the actual behaviour of a power system and quantifying its resilience performance during a HILP event. Within the context of the resilience trapezoid of Figure 1, these metrics need to be able to quantify particular features of a power system associated to an extreme

event, i.e., *how fast* (Φ) and *how low* (\mathcal{A}) resilience drops in *Phase I*, *how extensive* (E) is the post-event degraded state (*Phase II*) and *how promptly* (Π) the network recovers to its pre-event resilient state (*Phase III*), considering both operational and infrastructure resilience in each phase. This set of four metrics is defined in this work as the $\Phi\mathcal{A}E\Pi$ resilience metric system shown in Table 3 (“ $\Phi\mathcal{A}E\Pi$ ” is pronounced like “FLEP”). As suggested in [6], a linear approximation is considered for the transitions between the resilience levels/states of the resilience trapezoid, to quantify the resilience metrics.

Table 3. The $\Phi\mathcal{A}E\Pi$ resilience metric system

Phase	State	Resilience metric	Symbol
I	Disturbance progress	How <i>fast</i> resilience drops?	Φ
		How <i>low</i> resilience drops?	\mathcal{A}
II	Post-disturbance degraded	How <i>extensive</i> is the post-disturbance degraded state?	E
III	Restorative	How <i>promptly</i> does the network recover?	Π

In order to quantify the *operational* and *infrastructure* resilience during an HILP event, different resilience indicators are used in this work (focusing on the impacts of extreme events on the transmission network), as follows:

- the amount of generation capacity (MW) and load demand (MW) that are connected during the event are used as indicators for the *operational resilience*; and
- the number of online transmission lines is used as an indicator for the *infrastructure resilience*.

3.3. Modelling power systems resilience during an HILP events

In order to model the multi-temporal and multi-spatial impacts of extreme events, the time- and hazard-dependent failure probabilities obtained by the fragility curves are fed to a Sequential Monte Carlo-based probabilistic simulation tool. A component outage occurs if the failure probability of a component $P(h_i)$ is larger than a randomly generated uniformly distributed number $r \sim U(0,1)$ as follows:

$$F(h_i) = \begin{cases} 0, & \text{if } P(h_i) < r \\ 1, & \text{if } P(h_i) > r \end{cases}$$

where $F(h_i)$ is the failure function of the component.

Following a component outage, its Time to Repair (*TTR*) is randomly generated. This *TTR* mainly includes the time for the repair crew to reach the failed component and the time for the repair crew to complete the restoration of the component. It is thus dependent on the severity of the extreme event, which would affect both the accessibility to the affected areas and the damage on the components.

By systematically following this approach at every simulation step, the hazard-dependent status and resilience of the individual power system components, and in turn of the entire power system, can be determined. By applying an appropriate dispatch tool, e.g. AC OPF, the information required for calculating the resilience indicators and metrics is recorded at every simulation step. This provides useful insights on the resilience performance of the power system during the extreme event, e.g. *how low* and *how fast* resilience drops, which would support the targeted resilience enhancement (such as [10]) where it is considered critical for building highly resilient systems to both typical and unforeseen threats.

4. Case Study Application

The focus of the case study application is on assessing the impacts of severe windstorms passing across the GB transmission network. For this purpose, a 29-bus test version of the GB transmission network is used, shown in Figure 3. More details for this test system can be found in [11]. The transmission network components considered in this analysis are transmission lines and towers, whose wind fragility curves are shown in Figure 4 [9]. A simulation time of one day (24hrs) is used, with an hourly simulation step, while it is assumed that the windstorm hits the network at 50hr. The wind data are obtained by MERRA re-analysis, which are scaled-up using multiplication factors to represent extreme windstorms [9].

Figure 3. The 29-bus test version of the GB transmission network [11]

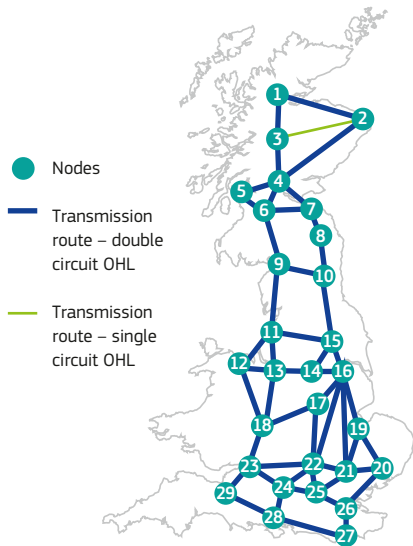
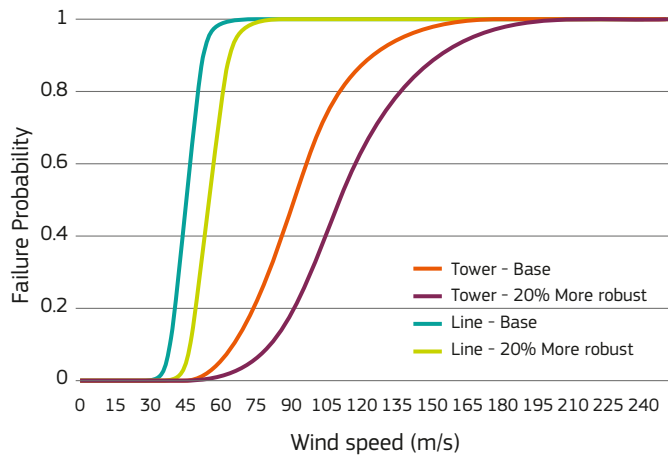


Figure 4. Wind fragility curves of transmission lines and towers (base and robust case studies) [9]



4.1. Quantifying the resilience trapezoid using the $\Phi\Delta E\eta$ metrics

Figure 5 shows the time-dependent resilience indicators for a grid-scale windstorm with a maximum wind speed (w_{max}) of 50m/s as an illustrative example (similar analysis and results can be obtained for windstorms of different severity, i.e. maximum wind speed). It can be clearly seen that the proposed methodology can effectively model the resilience trapezoid of Fig. 1, as its three phases can be clearly distinguished. It can also be observed that the operational and infrastructure resilience indicators react differently during the event, stressing the fact that it is critical to evaluate the resilience of a network from both the operational and infrastructure perspectives. Therefore, by utilizing the approach proposed in this paper, the resilience performance during a HILP event can be effectively represented using a set of resilience indicators. It is worth-noting here that any resilience indicator can be used, given the focus of the specific application.

Based on the simulation results of Figure 5, the $\Phi\Delta E\eta$ resilience metrics for $w_{max}=50\text{m/s}$ are next calculated and presented in Table 4, which enables the quantification of the resilience trapezoid of Figure 1. Critical insights on the actual behaviour and on the operational and infrastructure resilience of a power system during the different phases of a HILP event are obtained, which can drive the application of targeted resilience enhancement. It has to be noted that the Φ -metric is negative as the resilience level is decreasing in *Phase I* of the resilience trapezoid.

Figure 5. Time-dependent resilience indicators for $w_{max} = 50\text{m/s}$

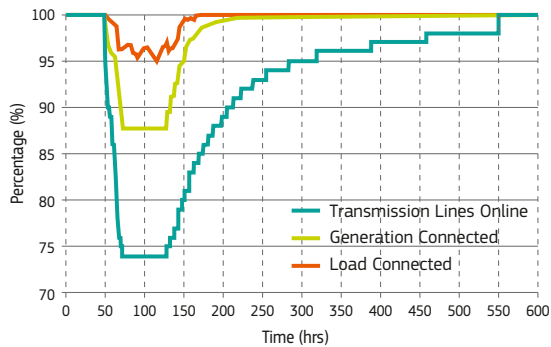


Figure 6. Transmission lines online (%) for $w_{max} = 50\text{m/s}$ for different case studies

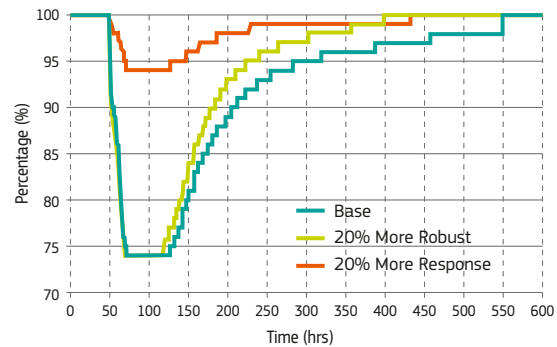


Table 4. Quantifying the time-dependent system performance of Figure 5 using the $\Phi\Lambda E\Pi$ metrics

Resilience Metric	Resilience Indicator		
	Transmission Lines	Generation Connected	Load Connected
Φ	-1.083 (% of Lines tripped/h)	-0.521 (% of MW lost/h)	-0.249 (% of MW lost/h)
Λ	26 (% of Lines tripped)	12.5 (% of MW lost)	5.99 (% of MW lost)
E	53 (hrs)	54 (hrs)	57 (hrs)
Π	0.058 (% of Lines restored/h)	0.033 (MW restored/h)	0.072 (MW restored/h)

Table 5. The $\Phi\Lambda E\Pi$ metrics for the case studies of Figure 6

Resilience Metric	Resilience Indicator		
	Base	20% More Robust	20% More Response
Φ	-1.083 (% of Lines tripped/hr)	-0.25 (% of Lines tripped/hr)	-1.083 (% of Lines tripped/hr)
Λ	26 (% of Lines tripped)	6 (% of Lines tripped)	26 (% of Lines tripped)
E	53 (hrs)	53 (hrs)	44 (hrs)
Π	0.058 (% of Lines restored/hr)	0.019 (% of Lines restored/hr)	0.092 (% of Lines restored/hr)

4.2. Quantifying the effect of operational and infrastructure strategies using the ΦAEP metrics

The effect of two resilience enhancement strategies is next evaluated using the new ΦAEP resilience metric system. In particular, the first strategy deals with making the transmission network more *robust* to the windstorm, which is modelled by modifying the wind fragility curves of the transmission lines and towers as shown in Figure 4. The second strategy refers to improving the *responsiveness* to the extreme event, which can be achieved through the application of different smart strategies, e.g. advanced monitoring and communication and advanced warning and visualization tools for achieving higher situational awareness. In this application, it is considered that a higher responsiveness means faster restoration of the faulted, damaged components. For demonstration purposes, it is assumed that the robustness and responsiveness are improved by 20% compared to the *base* case study demonstrated in the Section 4.1.

Figure 6 shows the transmission lines online (%) for these case scenarios for $w_{max}=50\text{m/s}$ and Table 5 depicts the corresponding ΦAEP metrics. It can be clearly seen that the proposed methodology can effectively graphically demonstrate the effect of these resilience enhancement strategies (Figure 6), as well as quantify this effect using the ΦAEP metrics (Table 5). Such a comprehensive resilience assessment framework can support the decision-making on the most suitable investment pathway for improving the resilience of a power system to extreme events, i.e. make the network stronger, more robust, or smarter and more responsive?

5. Conclusions

Power systems resilience is of growing interest given recent experiences with HILP events worldwide, mainly driven by natural disasters and extreme weather. Despite its criticality, there is still no clear and universal understanding of the concept of resilience, including its quantification and adaptation measures. This paper provides an overview of the fundamental concepts associated to power systems resilience, illustrates the resilience trapezoid enabling quantitative assessment of the multi-phase resilience of a system during an HILP event and evaluates the contribution of different operational and infrastructure strategies to the resilience enhancement of a power system. This altogether demonstrates the need and importance of using resilience-oriented metrics for modelling the actual response of a network, rather than relying only on the traditional reliability indices. Within this context, the ΦAEP resilience metric system is demonstrated through the case study of the GB transmission network, providing useful information to the system operator on the actual response of the system during the event. It is also demonstrated that the ΦAEP metric system can provide critical insights on the benefits of different operational and infrastructure resilience strategies, contributing to the decision-making and planning of a system operator for improving the resilience of the system through targeted investment in the most suitable strategies.

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Resilience, contagion, and vulnerability to external financial crisis in CEE countries¹⁰

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Abstract

- The recent financial crisis had serious worldwide impacts. Initial resilience and good past performances led to the illusion that the Central and Eastern European (CEE) region was able to decouple from developments in advanced economies. This initial illusion was however immediately denied by the facts that the crisis spread to that region just with a lag. The CEE region was, in fact, suddenly placed at the epicenter of the emerging market crisis. Further, the consequences of the crisis were not uniform among countries of the CEE region. Strong cross-country disparities in the resistance and recovery capacities have been observed.
- Our research project aims to analyze and disentangle the resilience performance to the financial crisis within CEE countries according to their shock isolation and absorptive capacities. We develop and estimate (by Bayesian techniques) a DSGE model for a small-open economy. Our model is individually estimated for a sample of Central and Eastern European countries. It features nominal wage and price rigidities, as well as financial frictions in the form of liquidity constrained households and limited access to deposits for the bank system. We focus on two dimensions of the regional resilience: resistance and recovery. Specifically, by using our estimation we aim to quantify the relative vulnerability or sensitivity of economies within CEE region to disturbances and disruptions (resistance) and the speed and extent of recovery from such a disruption or recession (recovery).

Keywords

resilience,
small-open
medium-scale
DSGE,
financial frictions,
CEE regions.

1. Introduction

The global financial crisis had a serious impact on mature and emerging economies. The consequences were not uniform. Europe was characterized by strong cross-country differences in the resistance and recovery capacities. The economic decline was more intense in the countries at the periphery of the European Union and in those with fragile public finances. Initially, the crisis only marginally affected the Central and Eastern European region, which had previously observed high growth rates. The past good performance and the initial resilience led to claims that the region had “decoupled” from developments in advanced economies. However, the decoupling hypothesis was an illusion, the crisis spread to the CEE region just with a lag. After the Lehman Brothers crack, in fact, the CEE region was suddenly

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placed at the epicenter of the emerging market crisis (Roaf *et al.*, 2014).¹¹

Our aim is to analyze and disentangle the resilience to the financial crisis within the CEE region. The impact of the crisis on economic activity has varied widely across countries, reflecting differences in exposure and vulnerability to the financial shocks as well as heterogeneity in policy responses. We plan to measure and explain the disparities in the resistance and recovery capacities of CEE economies by estimating and simulating medium-scale DSGE models. Specifically, our objective is to measure two dimensions of the regional resilience, namely resistance and recovery. The former is the vulnerability or sensitivity of a regional economy to disturbances and disruptions. The latter is the speed and extent of recovery from such a disruption or recession (Martin, 2012).

We built a small-open economy for distinct CEE economies and estimate it by Bayesian techniques. The model features standard nominal wage and price rigidities, and financial frictions. Financial frictions assume the forms of liquidity-constrained households and limited access to the deposits from the bank system. The financial accelerator of external shocks operates on the relationships between savers and banks featured by asymmetric information. An agency problem introduces endogenous constraints on the leverage ratios. Then, credit flows are tied to the equity capital of intermediaries. A financial crisis deteriorates intermediary capital and raises credit costs, lowering lending and borrowing (Gertler and Karadi, 2011).

Once estimated, we investigate the effects of the financial crisis by looking at the variance decomposition of CEE countries. Then we use the model to compute two measures of resilience to financial frictions. First, we look at the different stochastic structure estimated, the estimated standard deviations of the financial shocks and their auto-correlation give us a measure of the different vulnerability (or sensitivity) of CEE emerging markets. Second, we impose to all the countries within the CEE region a common stochastic structure and use simulations to derive a measure of their different recovery capacities.

Our paper is related to research that study the resilience of regional economies and the recent strand of DSGE model that introduces financial frictions into a New Keynesian framework.

¹¹ Comparing the performances of 183 economies, Didier *et al.* (2012) also claim against the decoupling hypothesis with reference to emerging economies and their resilience.

Concerning the first strand of literature, notwithstanding the growing interest among macro-economists, regional analysts, spatial economists, and economic geographers, the idea of resilience is associated to some ambiguities. Ambiguities are related to the different uses and interpretations of the term.¹² However, ambiguities should not be to rush to dismiss the concept, they vanish once that a clear definition is assumed (Martin, 2012).

A useful taxonomy of resilience is provided by Martin (2012). He summarizes resilience in four dimensions. i) Resistance as the degree of sensitivity or depth of reaction of regional economy to a recessionary shock. ii) Recovery as the speed and degree of recovery of regional economy from a recessionary shock. iii) Renewal as the extent to which regional economy renews its growth path: resumption of pre-recession path or hysteretic shift to new growth trend. iv) Re-orientation as the extent of re-orientation and adaptation of regional economy in response to recessionary shock. Our paper matches the first two dimensions, whereas is only indirectly related to the others.

An alternative related definition of resilient society is provided by Manca *et al.* (2017: 5). “A resilient society is able to cope with and react to shocks or persistent structural changes by either resisting to it (absorptive capacity) or by adopting a degree of flexibility and making small changes to the system (adaptive capacity). At the limit, when disturbances are not manageable anymore, the system needs to engineer bigger changes, which in extreme cases will lead to a transformation (transformative capacity).” We evaluate the absorptive and adaptive capacities of the CEE region and, somehow, its ex-post transformative capacity, i.e., the capacity of CEE economies to have implemented in the past crises changes that permit them to cope with the recent global turmoil.

Regarding the developments of DSGE literature in the direction of financial frictions, we borrow the specification of the banking sector from Gertler and Karadi (2011) and Gertler and Kiyotaki (2011), explicit modeling financial intermediation. An agency problem introduces endogenous constraints on the leverage ratios of intermediaries. As a result, in the financial sector, credit flows are tied to the equity capital of intermediaries. A deterioration of intermediary capital raises credit costs, lowering lending and borrowing. Their approach to model credit frictions has become quite popular (e.g., Lendvai *et al.*, 2013; Andreasen *et al.*, 2013; Beqiraj *et al.*, 2016; Rannenberg, 2016), especially to study the effectiveness of unconventional monetary policy in financial crisis (e.g., Dedola *et al.*, 2013; Gertler and Karadi, 2013, 2015).¹³

Alternative models to Gertler and Karadi (2011) and Gertler and Kiyotaki (2011) have been suggested. Other New Keynesian extensions to financial frictions are built on the external finance premium introduced by Carlstrom and Fuerst (1997), Bernanke *et al.* (1999) or collateral constraints based on Kiyotaki and Moore (1997). A discussion of DSGE extensions to financial frictions is outside the scope of the present paper, different approaches are critically surveyed by Gertler and Kiyotaki (2010), Christiano *et al.* (2014) and Brzoza-Brzezina *et al.* (2015).

The different paths of the key macroeconomic variables for the three countries taken into consideration suggest that a further study on the role and the effects of financial crises on the economic activity. Based on this starting point we will investigate the effects of the financial crisis by looking at the variance decomposition of CEE countries.

The rest of the paper is organized as follows. Section 2 briefly illustrates the impact of the global financial crisis in the CEE region. Section 3 presents our estimation results. By using our empirical outcomes, Section 4 discusses the resilience of CEE economies in a comparative perspective. Section 5 concludes. Our theoretical regional model is provided in Appendix.

¹² See Christopherson *et al.* (2010), Hudson, (2010), Pendall *et al.* (2010), Martin (2012).

¹³ Alternative models have been suggested, other New Keynesian extensions to financial frictions are built on the external finance premium introduced by Carlstrom and Fuerst (1997), Bernanke *et al.* (1999) or collateral constraints based on Kiyotaki and Moore (1997). Different approaches are critically surveyed by Gertler and Kiyotaki (2010), Christiano *et al.* (2014) and Brzoza-Brzezina *et al.* (2015).

2. CEE region and the financial crisis

Economies of the CEE region have been severally affected by recent global financial turmoil. External shocks, from Lehman Brothers' collapse to the euro-zone sovereign debt crisis, had devastating effects, hitting CEE hardest among the emerging markets regions. The weak performance of CEE region resulted from the combination of initial imbalances and external financial shocks. The imbalances that built up in the Great Moderation period left in fact the transition economies highly vulnerable. However, CEE countries were differently impacted by global financial instability according to the strength, timing and speed of the impact. For instance, the crisis was managed quite well by Poland and the Czech Republic, while the Baltic States, Bulgaria and Romania experienced huge collapse in GDP. As a result, the debate on resilience capacity, i.e., the multidimensional attitude of economic systems to isolate from, absorb shocks, adapt or transform towards new sustainable development path, emerged with stronger emphasis in the aftermath of the crisis.

The eruption of the global financial crisis triggered high risks of banking instability in CEE region. The expected unwinding of real estate booms and the potential disruptive adjustment of exchange rates, and macroeconomic imbalances were expected to wreak havoc on bank balance sheets. However, banking crises were generally avoided; portfolio losses in fact were gradually absorbed by considerable preexisting buffers and macroeconomic adjustment proceeded more smoothly than expected.¹⁴ Notable exceptions were Latvia, Ukraine, and (somehow) Slovenia.¹⁵

Anyway, the global financial crisis hard hit the CEE region through their open economy channel. The crash of property prices in some countries and distressed domestic financial markets, where financial institutions were exposed by toxic debts, triggered a massive contraction of lending (global deleveraging) and reduced the willingness of financial markets to finance sovereign debt. The recession then reduced demand for exports in Western Europe, impacting on production and employment in CEE small-open economies¹⁶ and to a less extend to larger CEE economies, as Poland and Romania. In 2009 all CEE counties faced massive reduction in their exports on GDP. The best performance was that of Romania: a reduction of 14% on previous period (in 2008 it was instead +14%); the worst country was instead Lithuania, where exports fall of 27% (in 2008 the share was 29%, but the sign was opposite).

In the aftermath of the Lehman Brothers' collapse, the most evident effect of the crisis was a decrease in GDP growth rate followed by absolute decrease in its volume. A dramatic slump happened in 2009. All CEE countries experienced a fall in GDP volumes compared to 2008, except Poland. In Baltic Republics percentage decrease was two-digit.

The impact of the recessionary shock on the growth path of CEE economies is shown in Figure 1. However, this national picture observes quite disparate—in fact, strongly divergent—GDP growth patterns among the major countries of the region. Heterogeneous trends are the product of multiple underlying forces and processes. CEE countries have differently reacted to the financial turmoil and associated recession exhibiting disparities in the degree of resilience.

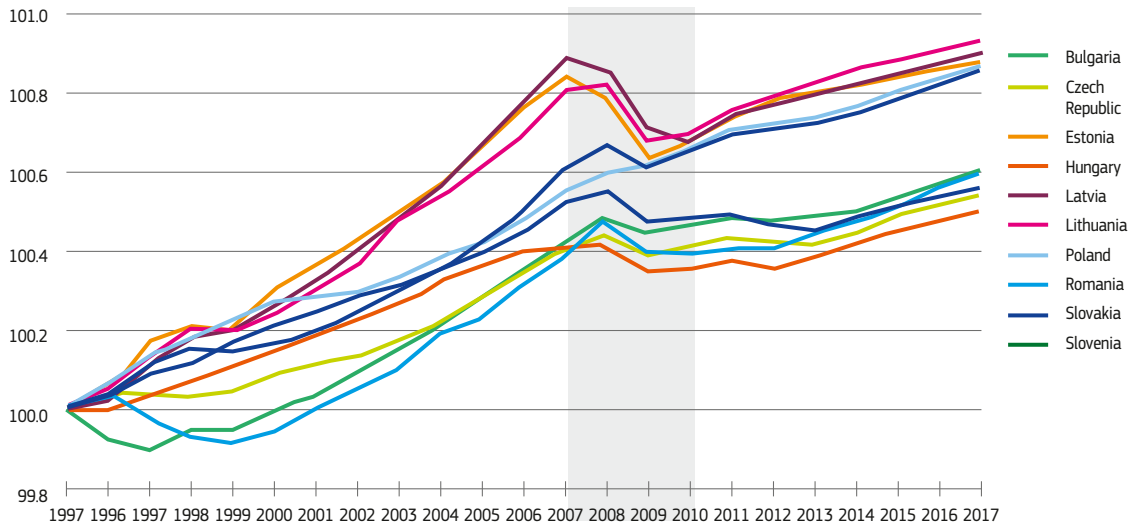
The crisis strongly affected Baltic countries, which were more lively before the Lehman Brothers' crash. A similar patter can be observed in Bulgaria, Czech Republic, Hungary, Slovenia, and Romania. Poland and Slovak Republic GDP were only moderately affected. Indeed, Poland has not experienced recession, keeping all the time positive rate of GDP growth. Already in 2009, Poland, Slovakia, and Bulgaria experienced a real GDP above its 2007 level. Other countries take much more time to recover. In Latvia, e.g., GDP decline continued in the first half of 2010.

¹⁴ Several factors prevented disruptive macroeconomic adjustments; among them, lending arrangements from IMF and other EU in member countries; EBRD, EIB, and World Bank provided funds to the banking system. Banking systems also benefited from the prevalence of parent-subsidiary relationships.

¹⁵ Latvia experienced the collapse of a large bank, Ukraine had widespread problems, and Slovenia observed relatively small and targeted recapitalization.

¹⁶ It is worth noting that exports in the Czech and Slovak Republics, Estonia and Hungary account for about 70-80% of GDP.

Figure 1. Growth and recessionary shocks in selected CEE economy
GDP [1997=100] (Source IMF)



Similar patterns can be observed in the employment dynamics. As noted by Martin (2012), movements in employment are more significant since it tends to take much longer than output to recover from recession. Moreover, regional local economies may resume output growth after a recession without recovering in employment (jobless recovery). During the recession, employment fell in all countries besides Poland, though less than proportionally to the decrease in GDP. However, in Estonia and Latvia was two-digit, whereas in the others it was less than 3 per cent. In Hungary, Lithuania and Estonia some decrease took place already in 2008. In the first half of 2010 employment was declining in all countries besides Slovenia. The highest decline was registered in Baltic Republics and Bulgaria.

3. Empirical analysis

3.1. Methodology

- The model is estimated, via Bayesian techniques, using aggregate quarterly macro data on three CEE economies namely Estonia, Hungary, Lithuania ranging from 1996:Q1 to 2016:Q4. The model is estimated by using 11 macroeconomic time-series: real GDP, consumption, investment, export, import, real wage, output deflator, consumption deflator, export deflator, import deflator and interest rate.
- Real GDP, real consumption, real investment, real import and export are obtained using the appropriate deflators. The Fed funds rate is used as a proxy for the nominal interest rate.

In order to avoid stochastic singularity eleven stochastic shocks are considered: risk premium shock on domestic and foreign bond holdings, transitory technology, domestic and foreign price mark-up, wage mark-up, investment specific, net foreign asset process worth, exchange rate process, inflation.

Data exhibiting a trend have been filtered by the Baxter-King band-pass filter. As noted by Stock and Watson (1999) and Christiano and Fitzgerald (2003), this filter should capture medium frequency fluctuations, and eliminate both the high frequency fluctuations (periods less than six quarters) associated, e.g., with measurement errors and the low frequency fluctuations (periods exceeding eight years) associated with trend growth. This implies that the gain of the ideal linear filter is unitary for frequencies of the business cycle and zero elsewhere (see Stock and Watson, 1999, for details). Data exhibiting a non-zero mean like inflation, nominal interest rate and the spread have been demeaned.

Estimates are achieved in three steps. After taking a log-linear approximation of the equilibrium conditions around the steady state, the model solution is expressed in state-space form and the likelihood function of the model is computed using a Kalman-filter recursion. By combining the prior distribution over the parameters of the model with the likelihood function, the posterior distribution of parameters is obtained via the Metropolis-Hastings algorithm.

Distributions of priors are fully specified and the estimates hinge on prior assumptions about the range of admissible values. Bayesian estimation relies on the well-known Bayes' rule:

$$p(\theta|Y_T) = \frac{p(\theta)p(Y_T|\theta)}{p(Y_T)}$$

where $p(\theta)$ is the prior assigned to parameter θ , denotes the likelihood and $p(\theta|Y_T)$ is the posterior density. Formally, one combines the prior distribution and the likelihood function to obtain the posterior distribution; however, in complex problems, this is typically not available in closed form and simulation strategies, like Markov Chain Monte Carlo, are necessary. Here we have used the Metropolis-Hastings algorithm.¹⁷

From identification analysis (Iskrev, 2010) we select the subset of identifiable parameters. The remaining are calibrated as common practice in Bayesian estimation. Several parameters are calibrated and ruled out from the estimation. Calibration is illustrated in Table 1.

Table 1. Calibration

Parameters	Description	Value
β	discount factor	0.990
κ	Kimball parameter	10.00
ε_p^d	price elasticity of demand	6.000
ε_p^m	price elasticity of demand	6.000
ε_p^x	price elasticity of demand	6.000
h	home bias	0.056
α	capital share	0.300
ω	transfer to the entering bankers	0.002
ϑ	bankers' survival probability	0.972

¹⁷ For a wider discussion on Bayesian methods applied to DSGE estimation see An and Schorfheide (2007) and Fernández-Villaverde (2010).

3.2. Estimation results

Prior distributions are elicited according to the Table 2. For the domestic Calvo parameter and the probability of being able to reset prices of the export and import retail firms a Beta distribution has been assigned; the degree of indexation to past inflation follows a Beta distribution; the exchange rate elasticity to net foreign asset, the parameters for elasticity of substitution, the inverse of the Frisch elasticity and the relative risk aversion coefficient follow a Normal distribution. A Beta distribution has been assigned to the share of non-Ricardian households.

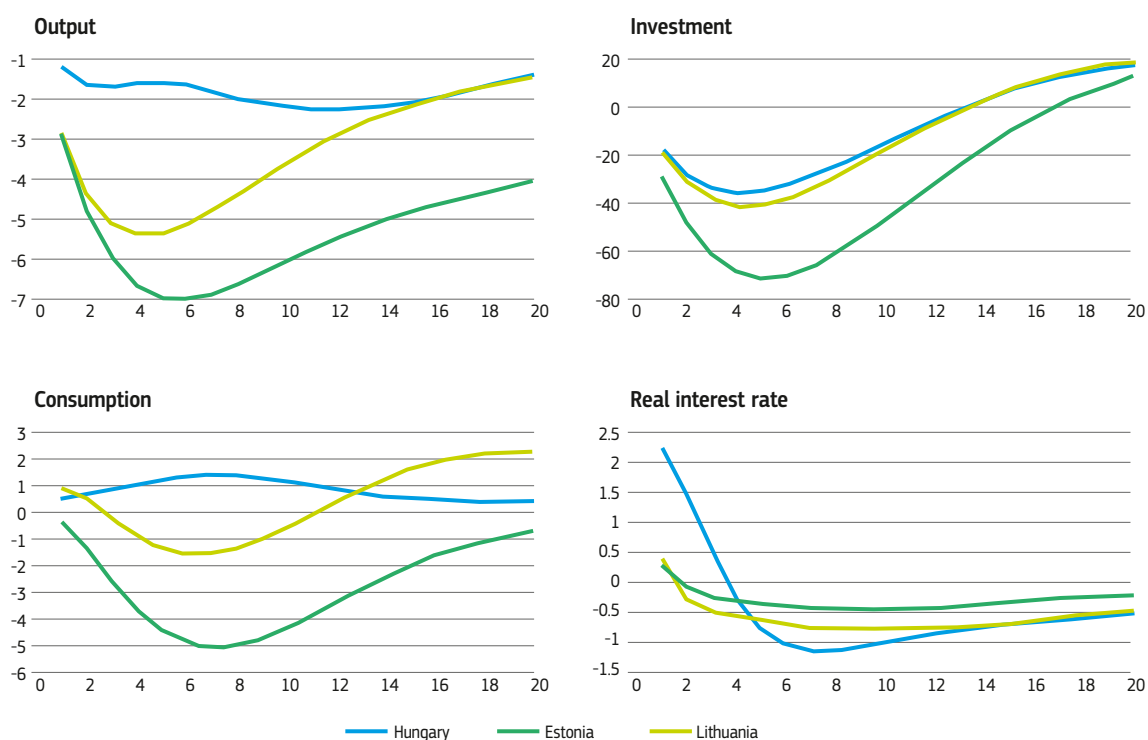
Table 2. Prior and posterior distribution for key parameters

	Density	Prior		Posterior	Posterior	Posterior
		Mean	St. dev.	(Hungary)	(Estonia)	(Lithuania)
				Mean	Mean	Mean
γ_{ind}^d	Beta	0.50	0.15	0.174	0.171	0.177
γ_{ind}^m	Beta	0.50	0.15	0.677	0.287	0.262
γ_{ind}^x	Beta	0.50	0.15	0.177	0.267	0.257
γ_w	Beta	0.66	0.1	0.793	0.889	0.853
γ_{ind}^w	Beta	0.50	0.15	0.586	0.288	0.613
λ	Beta	0.3	0.15	0.251	0.28	0.255
η	Normal	1.50	0.25	1.905	1.898	1.002
η^*	Normal	1.50	0.25	0.609	1.258	1.218
φ^a	Normal	0.01	0.005	0.009	0.001	0.009
z	Normal	7.2	2.50	6.404	8.368	7.126
σ	Normal	1.50	0.375	1.968	1.930	1.690
φ	Normal	2.00	0.75	3.294	1.963	2.495
hb	Beta	0.7	0.1	0.870	0.886	0.798
η_i	Normal	5.5	0.5	6.291	5.783	5.581
γ_p^d	Beta	0.66	0.1	0.439	0.836	0.879
γ_p^m	Beta	0.66	0.1	0.793	0.447	0.313
γ_p^x	Beta	0.66	0.1	0.734	0.652	0.454

4. Resilience in CEE countries: A comparison

As expected, a negative shock to the net worth in $t=1$ implies a fall in investment and output as well due to the increase in the risk premium and volatility. Hours worked decrease and the real wages go up immediately after the shock with some positive effects on the consumption due to the non-Ricardian households. The positive effect on consumption due to the limited constrained households is not sufficient, given the share of the latter, to obtain positive responses of total consumption in which the interest rate plays a crucial role. Figure 1 illustrates the response of macro variables to a negative financial shock in the three estimated countries namely Estonia (red), Hungary (blue), Lithuania (yellow). The impact of the crisis was smoothed and less permanent in Hungary compared to Lithuania and Estonia which both experienced sharp decline in real GDP and consumption. The collapse of real investment was particularly marked in Estonia.

Figure 2. Impulse response of key macro variables in selected CEE countries



5. Conclusions

The different paths of the key macroeconomic variables for the three countries taken into consideration suggest a further study on the role and the effects of financial crises on the economic activity. Based on this starting point we will investigate the effects of the financial crisis by looking at the variance decomposition of CEE countries. Then we will use the model to compute two measures of resilience to financial frictions. First, we look at the different stochastic structure estimated, the estimated standard deviations of the financial shocks and their autocorrelation give us a measure of the different vulnerability (or sensitivity) of CEE emerging markets.

Second, we impose to all the countries within the CEE region a common stochastic structure and use simulations to derive a measure of their different recovery capacities.

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Appendix – A small open-economy model with financial imperfections

We consider a simple small-open medium-scale New Keynesian economy characterized by nominal price and wage rigidities, consumption habits and investment adjustment costs. The economy is augmented with an imperfect banking sector by assuming that firms borrow indirectly from households through the banking sector that operates in an imperfect financial market. Financial frictions are twofold: i) Only a fraction of the households can access the credit market by financial intermediaries (limited-asset market participation assumption, LAMP henceforth).¹⁸ ii) An agency problem between banks and their depositors implies that financial intermediaries are subject to endogenously determined balance sheet constraints that could limit the ability of non-financial firms to obtain investment funds (Gertler and Karadi, 2011).

Production

The supply side of the economy is characterized by a retail competitive sector that combine intermediate goods produced by labor and capital to obtain the final consumption good. The final sector operates under imperfect competition and is subject to price stickiness. By contrast, intermediate goods and capital producing firms operate in competitive markets. Intermediate firms borrow from the banks to acquire physical capital.

The intermediate goods sector is composed by a continuum of competitive producers. The typical firm uses labor inputs and capital to produce an intermediate goods Y_t sold to retail firms, according to the following Cobb–Douglas technology:

$$Y_t = A_t L_t^\alpha (u_t^k K_t)^{1-\alpha}$$

where $\alpha \in$ is the labor share, A_t represents the total factor productivity, L_t denotes labor inputs hired, K_t is the capital stock and u_t^k is the utilization rate of the capital. Capital acquisition is financed by borrowing from a financial intermediary.

Denoting the real wage by W_t , the real marginal cost by MC_t , the capital depreciation function by $\delta(u_t^k)$, and the market value of a unit of capital by Q_t , the firm's first-order conditions are:

$$\begin{aligned} W_t &= \alpha MC_t \frac{Y_t}{L_t} \\ u_t^k &= MC_t (1 - \alpha) \frac{Y_t}{\delta'(u_t^k) K_t} \\ R_{t+1}^R &= \frac{MC_{t+1} (1 - \alpha) Y_{t+1} / K_{t+1} + Q_{t+1} - \delta(u_{t+1}^k)}{Q_t} \end{aligned}$$

which implicitly define a labor and capital demand (utilization rate of the physical capital).

¹⁸ See Galí *et al.* (2007).

Capital producing firms act in an environment characterized by perfect competition. At the end of period t , they buy capital from the intermediate sector repairing the depreciated capital and building new capital stock. Both the repaired and the new capital are then sold. A typical capital producing firm maximizes discounted profits, i.e.,

$$\max E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} \Lambda_{t,\tau} \left\{ (Q_{\tau} - 1) I_{N\tau}^O - \mathcal{F} \left(\frac{I_{N\tau}^O + I_{SS}^O}{I_{N\tau-1}^O + I_{SS}^O} \right) (I_{N\tau}^O + I_{SS}^O) \right\}$$

where $F(1) = F'(1) = 0$ and $F''(1) > 0$, $\beta \in (0,1)$ is the discount factor, $\Lambda_{t,\tau}$ denotes the stochastic discount factor between t and τ , $I_{Nt}^O \equiv I_t^O - \delta(u_t^k) K_t^O$ is the net capital created (I_t^O and I_{SS}^O are gross capital and its steady state) and Q_t should be interpreted as the Tobin's Q . As we will explain in the next section, we denote capital and investment by a superscript "O" to take account for the limited-asset market participation assumption. Then, $K_t = (1 - \lambda) K_t^O$ and $I_t = (1 - \lambda) I_t^O$ where λ is the fraction of agents who are not allowed to access to the financial markets (recall that these agents do not own neither assets nor firms equity capital).

The first-order condition for investment is then

$$Q_t = 1 + \mathcal{F} \left(\frac{I_{Nt}^O + I_{SS}^O}{I_{Nt-1}^O + I_{SS}^O} \right) + \left(\frac{I_{Nt}^O + I_{SS}^O}{I_{Nt-1}^O + I_{SS}^O} \right) \mathcal{F}' \left(\frac{I_{Nt}^O + I_{SS}^O}{I_{Nt-1}^O + I_{SS}^O} \right) - \beta E_t \Lambda_{t,t+1} \left(\frac{I_{Nt+1}^O + I_{SS}^O}{I_{Nt}^O + I_{SS}^O} \right)^2 \mathcal{F}' \left(\frac{I_{Nt}^O + I_{SS}^O}{I_{Nt-1}^O + I_{SS}^O} \right)$$

which describes the Q relation for net investments.

The domestic retail firms operate in an imperfect competition environment. Aggregation is obtained as follows

$$Y_t = \left[\int_0^1 Y_t(j)^{(\varepsilon_p^d - 1)/\varepsilon_p^d} dj \right]^{\varepsilon_p^d / (\varepsilon_p^d - 1)}$$

where $Y_t(j)$ is the domestic output by the domestic retailer j and ε_p^d is the elasticity of substitution between differentiated domestic goods.

In this setup, prices are sticky according to a Calvo mechanism (we denote by $1 - \gamma_p^d$ the probability of being able to reset prices). The corresponding optimal domestic price adjustment and aggregate domestic inflation are then described by the following expressions:¹⁹

$$\pi_t^{d,*} = \frac{\varepsilon_p^d}{\varepsilon_p^d - 1} \frac{Y_t^{d,p}}{\Xi_t^{d,p}} \pi_t^d$$

$$\pi_t^d = \left[\gamma_p^d (\pi_{t-1}^d)^{\gamma_{ind}^d (1 - \varepsilon_p^d)} + (1 - \gamma_p^d) (\pi_t^{d,*})^{1 - \varepsilon_p^d} \right]^{1/(1 - \varepsilon_p^d)}$$

where γ_{ind}^d indicates the domestic degree of indexation to past inflation.

The domestic auxiliary variables $Y_t^{d,p}$ and $\Xi_t^{d,p}$ evolve as:

$$Y_t^{d,p} = Y_t M C_t + \beta \gamma_p^d E_t \Lambda_{t,t+1} (\pi_{t+1}^d)^{\varepsilon_p^d} (\pi_t^d)^{-\gamma_{ind}^d \varepsilon_p^d} Y_{t+1}^{d,p}$$

¹⁹ The price inflation is $\pi_t^d = P_t/P_{t-1}$; $\pi_t^{d,*}$ is the price inflation of the adjusting firm.

$$\Xi_t^{d,p} = Y_t + \beta \gamma_p^d E_t \Lambda_{t,t+1} (\pi_{t+1})^{\varepsilon_p^d - 1} (\pi_t^d)^{\gamma_{ind}^d (1 - \varepsilon_p^d)} \Xi_{t+1}^{d,p}$$

The export and import retail firms also face sticky prices (we denote by $1 - \gamma_p^x$ and $1 - \gamma_p^m$ the probability of being able to reset prices of the export and import retail firms, respectively). Each of them faces the foreign demand for the domestic goods, $X_t(j) = \left[\frac{P_t^x(j)}{P_t^x} \right]^{-\varepsilon_p^x} X_t$ or the domestic demand for the foreign consumption, C_t^m ,

and investment, I_t^m , goods, i.e., $\Gamma_t(j) = \left[\frac{P_t^m(j)}{P_t^m} \right]^{-\varepsilon_p^m} \Gamma_t$, $\forall \Gamma_t = \{C_t^m, I_t^m\}$. In analogy with the domestic retail firms, optimal price adjustments and aggregate inflation rates for the export, $l = x$, and import, $l = m$, retail firms are described by the following expressions:²⁰

$$\pi_t^{l,*} = \frac{\varepsilon_p^l}{\varepsilon_p^l - 1} \frac{Y_t^{l,p}}{\Xi_t^{l,p}} \pi_t^l, \quad \forall l = \{x, m\}$$

$$\pi_t^l = \left[\gamma_p^l (\pi_{t-1}^l)^{\gamma_{ind}^l (1 - \varepsilon_p^l)} + (1 - \gamma_p^l) (\pi_t^{l,*})^{1 - \varepsilon_p^l} \right]^{\frac{1}{1 - \varepsilon_p^l}} \quad \forall l = \{x, m\}$$

where ε_p^l is the elasticity of substitution between differentiated l -type goods' and γ_{ind}^l indicates the l -type goods' degree of indexation to past inflation.

The export and import auxiliary variables $\gamma_t^{l,p}$ and $\Xi_t^{l,p}$ evolve as:

$$Y_t^{l,p} = Y_t M C_t^l + \beta \gamma_p^l E_t \Lambda_{t,t+1} (\pi_{t+1})^{\varepsilon_p^l} (\pi_t^l)^{-\gamma_{ind}^l \varepsilon_p^l} Y_{t+1}^{l,p} \quad \forall = \{x, m\}$$

$$\Xi_t^{l,p} = Y_t + \beta \gamma_p^l E_t \Lambda_{t,t+1} (\pi_{t+1})^{\varepsilon_p^l - 1} (\pi_t^l)^{\gamma_{ind}^l (1 - \varepsilon_p^l)} \Xi_{t+1}^{l,p} \quad \forall = \{x, m\}$$

where $M C_t^x = P_t^d / e_t P_t^x$ and $M C_t^m = P_t^* e_t / P_t^m$ are the export and import marginal costs, respectively, with e_t defining the nominal exchange rate.

Financial market

Limited-asset market participation

Households can be either liquidity constrained or not. However, apart from their ability to access to the financial market they share the same kind of preferences. Formally, there is a continuum of households in the space $[0, 1]$. The household's period preferences are defined as:

$$u_t = \frac{(C_{t+i} - h C_{t+i-1})^{1-\sigma}}{1-\sigma} - \chi \frac{L_{t+i}^{1+\varphi}}{1+\varphi}$$

where C_t is the aggregate consumption, $h \in [0, 1)$ denotes the habits in consumption parameter, χ measures the relative weight of the labor disutility, φ is the inverse Frisch elasticity of labor supply and σ is the relative risk-aversion coefficient.

²⁰ The price inflation is $\pi_t^l = P_t / P_{t-1}$; $\pi_t^{l,*}$ is the price inflation of the adjusting firm.

Non-liquidity constrained households (“dynamic optimizer households” from now on) solve the following intertemporal optimization problem

$$\begin{aligned} \max \mathcal{W}_t^O &_{C_{t+i}^O, L_{t+i}, B_{t+i}, B_{t+i}^*} \\ &= E_t \sum_{i=0}^{\infty} \beta^i \left[\frac{(C_{t+i}^O - hC_{t+i-1}^O)^{1-\sigma}}{1-\sigma} - \chi \frac{L_{t+i}^{1+\varphi}}{1+\varphi} \right] \end{aligned}$$

$$s. t. \quad C_t^O + B_{t+1} + e_t B_{t+1}^* = W_t L_t + \Pi_t + T_t + R_t B_t + e_t \Phi_t R_t^* B_t^*$$

where C_t^O is the consumption of the dynamic optimizer households, R_t and R_t^* are the gross real domestic and foreign return of one period real domestic and foreign bonds, respectively, B_t and B_t^* are the total quantity of short term domestic and foreign debt that the household acquires, respectively, Π_t are the net payouts to the household from ownership of both non-financial and financial firms and T_t is a lump sum net transfer. Finally, Φ_t denotes the risk premium on foreign bond holdings given by

$$\Phi_t = \exp[(R_t - R_t^*) - \phi_a A_t + u_t^\phi],$$

where $A_t = e_t B_{t+1}^*$ denotes the net foreign assets (NFA) position, ϕ_a denotes the risk premium elasticity to the NFA position and u_t^ϕ is the risk premium shock on foreign bond holdings, which is assumed to follow a first order autoregressive stochastic process $u_t^\phi = u_{uip,t-1}^{\rho_{uip}} e^{\epsilon_{uip,t}}$.

From the non-liquidity constraint household's optimization problem, the first-order conditions for consumption, C_t^O , domestic and foreign bond holdings, B_t and B_t^* respectively, are:

$$\rho_t^O = (C_t^O - hC_{t-1}^O)^{-\sigma} - \beta h E_t (C_{t+1}^O - hC_t^O)^{-\sigma}$$

$$E_t \beta \Lambda_{t,t+1} R_{t+1} = 1$$

$$e_t E_t R_{t+1} = E_t e_{t+1} \Phi_{t+1} R_{t+1}^*$$

where $\Lambda_{t,t+1} = \rho_{t+1}^O / \rho_t^O$ denotes the stochastic discount rate.

Instead, LAMP households solve:

$$\max \mathcal{W}_t^L &_{C_{t+i}^L, L_{t+i}} = E_t \sum_{i=0}^{\infty} \beta^i \left[\frac{(C_{t+i}^L - hC_{t+i-1}^L)^{1-\sigma}}{1-\sigma} - \chi \frac{L_{t+i}^{1+\varphi}}{1+\varphi} \right]$$

$$s. t. \quad C_t^L = W_t L_t + T_t$$

According to the budget constraint, their optimal consumption is equal to

$$C_t^L = W_t L_t + T_t$$

and their marginal utility of consumption is

$$\rho_t^L = (C_t^L - hC_{t-1}^L)^{-\sigma} - \beta h E_t (C_{t+1}^L - hC_t^L)^{-\sigma}$$

The aggregate demand for consumption goods is obtained using a CES aggregator of domestically produced and imported consumption, C_t , and investment, I_t , i.e.,

$$C_t = \left[(1-v)^{\frac{1}{\eta}} (C_t^d)^{\frac{\eta-1}{\eta}} + v^{\frac{1}{\eta}} (C_t^m)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

$$I_t = \left[(1-v)^{\frac{1}{\eta}} (I_t^d)^{\frac{\eta-1}{\eta}} + v^{\frac{1}{\eta}} (I_t^m)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

where, from households' cost minimization problem, the demand for domestic and foreign produced consumption and investment goods are given by

$C_t^d = (1 - \nu)[P_t^d/P_t]^{-\eta} C_t$, $I_t^d = (1 - \nu)[P_t^d/P_t]^{-\eta} I_t$, $C_t^m = \nu[P_t^m/P_t]^{-\eta} C_t$ and $I_t^m = \nu[P_t^m/P_t]^{-\eta} I_t$ respectively, where ν denotes the home bias parameter and η is the elasticity of substitution between domestic and imported goods. P_t^d and P_t^m denote the price indexes of domestic and imported goods, respectively, such that:

$$P_t = \left[(1 - \nu)(P_t^d)^{1-\eta} + \nu(P_t^m)^{1-\eta} \right]^{\frac{1}{1-\eta}}.$$

The banks' balance sheet constraints

Each dynamic optimizer household is composed by workers and bankers. The workers supply labor and redistribute their labor income within their household. Each banker manages a financial intermediary and returns its earnings back to its family. Banks are owned by the fraction of households that are dynamic optimizers as well. Each period a fraction θ of bankers survives while a fraction $1 - \theta$ exits and is replaced.

Each banker can divert a fraction ζ of funds to its family. Diverting assets can be profitable for a banker who can then default on his debt and shut down, and correspondingly represent a loss for creditors who could reclaim the fraction $1 - \zeta$ of assets, at most.

Financial intermediaries obtain B_{jt+1} funds from the dynamic optimizer households (short-term liabilities) and lend them to non-financial firms (holding long-term assets). Each bank faces a quantity of financial claims S_{jt} by the non-financial firms and owns an amount of net worth denoted by N_{jt} . Thus, the balance sheet of an intermediary is:

$$Q_t S_{jt} = N_{jt} + B_{jt+1}$$

where Q_t is the relative price of a financial claim.

The bank pays back a real gross return R_{t+1} on the funds obtained from the household and earns the stochastic return R_{kt+1} on the loans to non-financial firms. N_{jt} can be thought as the intermediaries' equity capital and it is obtained as the difference between the earnings on assets ($R_{kt+1}Q_t S_{jt}$) and interest payments on liabilities ($R_{t+1}B_{jt+1}$). Hence:

$$N_{jt+1} = (R_{kt+1} - R_{t+1})Q_t S_{jt} + R_{t+1}N_{jt}$$

The term $(R_{kt+1} - R_{t+1})$ represents the premium that the banker earns on his assets.

Each banker's objective is to maximize the expected discounted present value of its future flows of net worth N_t , that is:

$$V_t = E_t \sum_{i=0}^{\infty} (1 - \theta)\theta^i \beta^{i+1} \Lambda_{t,t+1+i} N_{jt+i}$$

Following Gertler and Karadi (2011), in order to avoid that in presence of positive premium the bankers will expand its loans indefinitely, it is assumed that there is a limit to do this represented by the presence of a moral hazard problem.

As a consequence, depositors would restrict their credit to banks as they realize that the following incentive constraint must hold for the banks in order to prevent them from diverting funds:

$$V_{jt} \geq \zeta Q_t S_{jt}$$

i.e., the potential loss of diverting assets (l.h.s. of the above equation) should be greater than the gain from doing so (r.h.s. of the above expression). Moreover, V_{jt} can be expressed as

$$V_{jt} = v_t Q_t S_{jt} + \eta_t N_{jt}$$

where η_t is a variable representing the expected discounted value of having an additional unit of net worth and v_t must be interpreted as the expected discounted marginal gain to the banker of expanding assets $Q_t S_{jt}$ by a unit.²¹

In this framework, the financial intermediary can acquire assets accordingly to his equity capital:

$$Q_t S_{jt} = \frac{\eta_t}{\zeta - v_t} N_{jt} = \phi_t N_{jt}$$

where ϕ_t is the private leverage ratio, i.e., the ratio of privately intermediated assets to equity.

Labor market

Labor markets are imperfect: sticky wages are set by monopolistic unions, who represent differentiated labor inputs provided by both dynamic optimizers and LAMP agents. Labor unions set the nominal wages facing nominal rigidities *à la* Calvo. Labor is aggregated by a Dixit–Stiglitz function, where we indicate the elasticity of substitution between labor inputs by ε_w .

Formally, a typical union chooses the optimal nominal wage W_t^* to maximize a weighted utility function:

$$\max_{W_t^*} \sum_{j=0}^{\infty} (\gamma_w \beta)^j \left\{ W_t^* \left(\frac{W_t^*}{W_{t+j}} \right)^{-\varepsilon_w} L_{t+j} [\lambda \varrho_{t+j}^L + (1 - \lambda) \varrho_{t+j}^O] - \frac{\chi}{1 + \varphi} \left[\left(\frac{W_t^*}{W_{t+j}} \right)^{-\varepsilon_w} L_{t+j} \right]^{1+\varphi} \right\}$$

where γ_w is the probability to keep the wage unchanged in the future.

Solving the above problem we obtain the adjustment dynamics for wage inflation²²

$$\pi_t^{w^*} = \frac{\varepsilon_w}{\varepsilon_w - 1} \frac{Y_t^w}{\Xi_t^w} \pi_t^w$$

$$\pi_t^w = \left[\gamma_w (\pi_{t-1}^w)^{1-\varepsilon_w} + (1 - \gamma_w) (\pi_t^{w^*})^{1-\varepsilon_w} \right]^{\frac{1}{1-\varepsilon_w}}$$

Auxiliary variables γ_t^w and Ξ_t^w evolve according to:

$$Y_t^w = U_{L,t} L_t + \gamma_w \beta E_t (\pi_{t+1}^w)^{\varepsilon_w} Y_{t+1}^w$$

$$\Xi_t^w = W_t L_t [\lambda \varrho_t^L + (1 - \lambda) \varrho_t^O] + \gamma_w \beta E_t (\pi_{t+1}^w)^{\varepsilon_w - 1} \Xi_{t+1}^w$$

²¹ See Gertler and Karadi (2011) for the evolution of v_t and η_t and a wider discussion about the agency problem.

²² The wage inflation is ; $\pi_t^w = W_t / W_{t-1}$; $\pi_t^{w^*} = W_t^* / W_{t-1}$ is the wage inflation of the adjusting union.

Aggregation, resource constraint, and government policies

The economy-wide resource constraint is given by

$$Y_t = C_t^d + C_t^x + I_t^d + I_t^x + G_t + \frac{\psi}{2} \left(\frac{I_t^N + I_{SS}}{I_{t-1}^N + I_{SS}} - 1 \right)^2 (I_t^N + I_{SS})$$

where ψ indicates the elasticity of investment adjustment cost.

The market clearing condition in the foreign bond market requires that, at the equilibrium, the equation for NFA evolution is satisfied:

$$e_t B_{t+1}^* = e_t P_t^x (C_t^x + I_t^x) - e_t P_t^* (C_t^m + I_t^m) + e_t \Phi_t R_t^* B_t^*$$

As in Galí *et al.* (2007), the aggregate consumption is

$$C_t = (1 - \lambda) C_t^O + \lambda C_t^L$$

The total value of intermediated assets is:

$$Q_t S_t = \phi_t N_t$$

The law of motion of capital is

$$K_{t+1}^O = K_t^O + I_{Nt}^O$$

Government expenditures G_t are financed by lump sum taxes

$$G_t = T_t$$

Finally, the nominal interest rate i_t follows a simple Taylor rule

$$i_t = \rho i_{t-1} + (1 - \rho) \kappa_\pi \pi_t$$

where ρ denotes the degree of interest rate smoothing, K_π measures the response of the monetary authority to inflation and $\pi_t = P_t / P_{t-1}$ denotes the CPI inflation gross rate.

A composite policy tool to measure territorial resilience capacity

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Abstract

The recent global recession and consequent slow recovery have revealed considerable heterogeneity in economic performance across countries, regions and local actors. This study aims at constructing a simple composite indicator to measure and monitor economic system resilience at regional level in order to facilitate a common easily understanding of this complex and dynamic process for decision makers and for the general public.

Keywords

regional resilience,
composite indicator,
resilience life cycle,
slow burning and
dynamic processes.

1. Introduction

In the last years the European Union (EU) has been probably hit by the worst crisis in its history. The roots of this crisis are the combination of a loss of competitiveness and high indebtedness²³ especially of periphery countries in the European Monetary Union (EMU) (EC, 2010; Crescenzi *et al.*, 2016). The consequent instability, which has led to unprecedented turbulence on financial markets, has put a great challenge to the EU and to the rest of the world.

In response to the crisis, EU has agreed upon a common strategy within the 2008 European Economic Recovery Plan (EERP) (EC, 2008) that essentially proposes a number of measures to direct short-term actions to reinforce Europe's competitiveness²⁴ in the long term, i.e., smart investment for capacity building in order to promote efficiency and innovation. These measures have been included in the EU2020 framework with respect to which Cohesion Policy has been shaped. In view of EU2020 strategy, the capacity of the European regions to react to external shocks is of particular interest because it has a direct implication on the outcomes of European Economic Policy (Milio *et al.*, 2014).

The crisis spread asymmetrically in time, strength, and speed across EU regions (ECB, 2010). Not all regions experienced economic decline and the territorial impact of the crisis has varied greatly also within the same country (European Commission, 2013; Martin, 2010). Similarly, while some regions experienced a swift return to pre-crisis levels of employment and output, the process of recovery has proved much more protracted for many regions entering a period of sustained stagnation.

²³ The government budget position, measured by debt-to-GDP ratio index, is the result of fiscal policy, which is, combined with monetary policy, one the main policy instruments. A healthy fiscal position would allow adjustments to taxation and expenditure policies to offset adverse shocks. High level of external indebtedness would also limit the ability to mobilize resources in the face of external shocks.

²⁴ Competitiveness is generally agreed as the capacity of countries or regions to produce goods and services that meet the test of foreign competition which can be reflected in a sustainable balance of payments, while simultaneously maintaining and expanding domestic real income and jobs creation. The most commonly used measure of competitiveness is productivity (Camagni, 2002; Kitson *et al.*, 2004).



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In this context, a composite policy tool is becoming key in order to identify resilience and design territorial development strategies (Martin, 2016). To the best of our knowledge, economic resilience has been conceptualized (Martin, 2012; Briguglio et al., 2009) as a multidimensional complex concept, but it has not been translated into a synthetic regional indicator. In the frame of the activities of the LUISA²⁵ Territorial Modelling Platform, our research aims to: i) setup a simple indicator of regional economic resilience, ii) identify the resilience degree of EU regions, iii) suggest a potential instrument to draw policy implications.

The paper is structured as follows. The theoretical framework is introduced in Section 2. Section 3 discusses data and methodological issues concerning the weighting and aggregation procedures of the composite indicator. Our results are reported in Section 4 and, finally, Section 5 concludes.

2. The resilience framework

Recently, much work has been done to identify the drivers of crisis recovery and investigate the structural characteristics of the regions and determinants of resilience.

Briguglio *et al.* (2009) distinguish between economic vulnerability and economic resilience. The former is defined as the exposure of an economy to exogenous shocks, which depends on permanent or quasi-permanent inherent structural characteristic over which policy makers can exercise limited control while the latter is defined as the policy-induced capacity of an economy to withstand or recover from the effects of such negative shocks.

Martin (2012) analyses the concept of resilience identifying four main dimensions: (i) resistance, which identifies the sensitivity of regional output and employment to exogenous shock and determine the demand for public policies; (ii) recovery, which measures how fast the region bounces back from a negative shock; (iii) reorientation, which concerns the extent to which a region changes after a shock by switching for example its economic sectoral composition; and (iv) renewal, which is the ability of a regional economy to renew its growth path.

²⁵ LUISA Territorial Modelling Platform is implemented by the Joint Research Centre for the evaluation of EC policies that have a direct or indirect territorial impact.

More recent literature, among others e.g., Martin and Sunley (2014), Diodato and Weterings (2015) and Manca *et al.* (2017), following Martin (2012), defines resilience as the multidimensional capacity of regional and local economy to absorb shocks, adapt or transit to new sustainable development path.

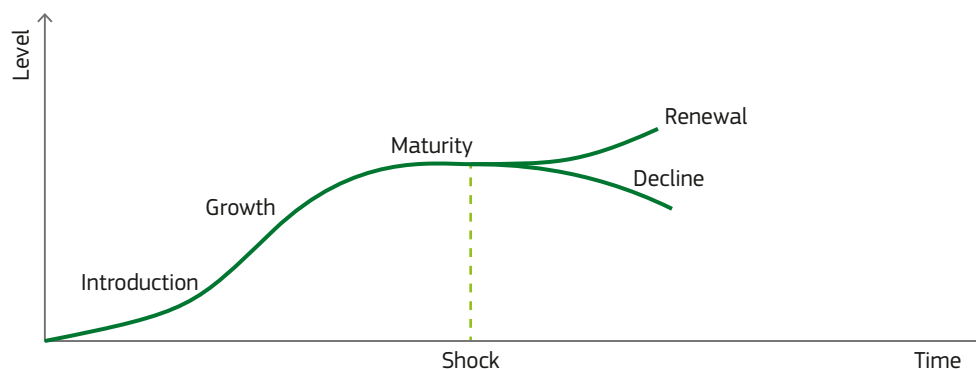
2.1. The life cycle of resilience

Our approach to resilience extends the previous conceptualizations characterising it as a complex process with a well-defined life cycle. We borrowed the product life cycle theory that was first developed by Raymond Vernon in 1966 in order to conceptualize our framework.

This theory identified four stages, each with its own characteristics crucial for business that are trying to manage the life cycle of their particular products. In Figure 1, we identify and characterize the different steps of a resilience capacity building process following the product life cycle theory's four stages:

- **Introduction Stage** – This stage of the cycle is characterized by a process of learning-by-doing that entails increasing returns to scale for the economy: a proportionate increase in the usual production inputs (labour and capital) gives rise to more than proportionate gains in output (Arrow, 1962; Romer, 1986, 1993; Lucas, 1988). It requires an active participation of different actors to earn enough in terms of capital accumulation and capacity building to escape from the spiralling mechanism of the so-called poverty trap and accumulate resilience capacity. According to Sachs (2005), many factors can contribute to stagnate into a poverty trap, including a limited access to credit and capital markets, poor infrastructure, lack of public services and corrupt governance, extreme environmental degradation, etc. Public interventions can help to reverse the vicious cycle.
- **Growth Stage** – The growth stage is typically characterized by a strong growth that benefits from economies of scale. Innovation processes and spill-overs that increase over time, enhancing skill and productivity levels throughout the economy, determine the speed of the growth process and then the slope of our curve of the resilience capacity-building process (Krugman and Obstfeld, 1997). During this phase, catching up and falling behind mechanisms act leading to different levels of development and resilience.
- **Maturity Stage** – During the maturity stage, the growth and capacity building process is close to its steady-state value, and the aim for regional and local authorities is now to maintain the adaptive and coping capacities they have contributed to build up. This stage potentially identifies specific regions with a competitive advantage over others.
- **Decline/Renewal Stage** – Eventually, if a shock hits the economy two opposite options might occur. The resilience capacity can start to shrink, and this is what we refer to as the decline stage. This shrinkage could be due to the saturation or inadequacy of that capacity. The alternative can concern the extent to which a regional economy reacts after a shock and renews its growth path leading to a renewal stage. The capacity to recover built over the first three stages can determine the decline, renewal or eventually a scalloped pattern.

Figure 1. The life cycle of Resilience



2.2. An empirical overview

The first three stages identified in the previous paragraph refer to the so-called *slow burning process* (Manca *et al.*, 2017), which measures the capacity built over time of a region to cope with a shock. During these phases, policy-induced changes can strengthen the resilience capacity of a region. The last stage, referred to as *shock wave* or *dynamic process*, is based on the immediate exposure to an unexpected shock over which a region can exercise limited control.

A recent empirical exercise proposed by Crescenzi *et al.* (2016), split the time period analysis in pre-2008 crisis (*slow burning process*) and post-2008 crisis (*shock wave*) and apply a regression approach to explore the relation between post-2008 crisis regional performance indicators and pre-2008 national macroeconomic conditions and regional resistance factors.

In order to get a first understanding of the EU NUTS2 regions' pre and post-crisis performance, we explored the linkage between the growth trend before and after the crisis of some key economic variables i.e., GDP per capita, employment rate and productivity, defined as GDP per employee.²⁶ These variables have been chosen because i) they are the best indicator able to synthesize economic conditions at regional level, and ii) they react quickly to shocks. Furthermore, GDP per capita is derived from the multiplication between employment rate and productivity. A lasting GDP per capita growth is sustained by productivity growth. At the reverse, a rising employment rate might hamper GDP per capita growth if not followed by productivity growth.

We classify the 271 NUTS2 regions according if they placed above or below the EU average for the three variables.²⁷ Thus, each of the points in Figure 2 represents a combination of performances' value measured before (x-axis) and after the crisis (y-axis). The x- and y-axes divide the scatterplot into four quadrants (anticlockwise from top right): in the first and third (high-high, HH, and low-low, LL, respectively) a region exhibits a high (low) value of both pre and post-crisis indicators. In the second and fourth quadrants (low-high, LH, and high-low, HL, respectively) a region reveals a low (high) value of the variable before the crisis and a high (low) value of the post-crisis variable.

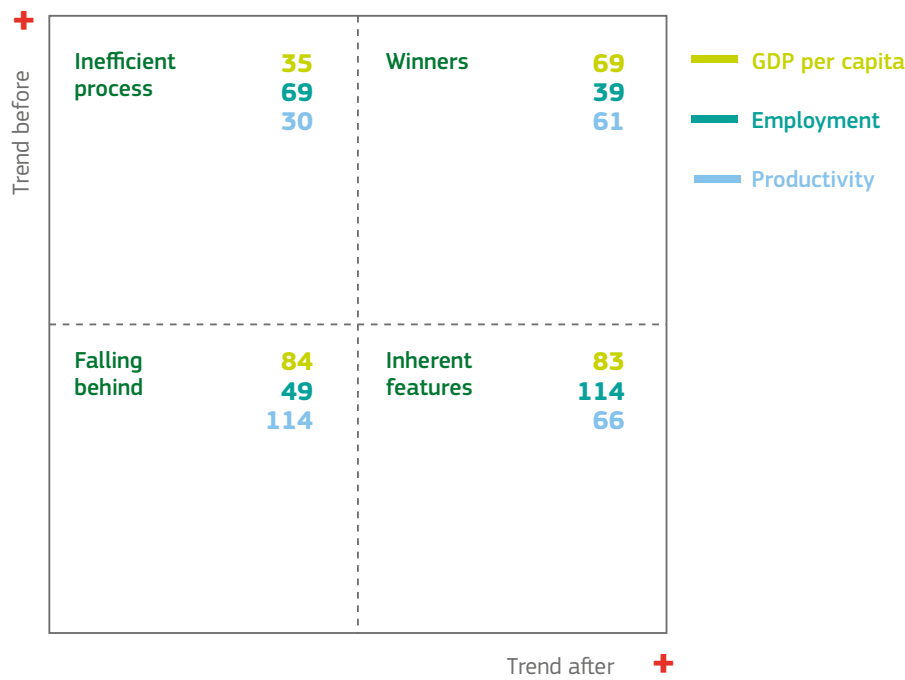
In order to derive a classification of EU NUTS2 regions with respect to their economic behaviour before and after the 2008 financial and economic crises and the consequent potential for resilience, four different clusters of regions were identified. These quadrants, in anticlockwise, correspond to:

- **Winners (top right)** – Regions belonging to this group performed better than the European average before and after the crisis. The crisis hits them but the economic stability and resilience capacity reached before the shock occurred helped them to recover fast.
- **Inefficient process (top left)** – The group classifies regions that were not able to recover even if they were experienced a pre-crisis growth trend above the EU average. Many factors can contribute to negatively change the growth trend e.g., among others inefficient policies, lack of public services, etc. The growth and resilience capacity building process has not reached in the pre-crisis period such a critical mass necessary to recover from a negative shock.
- **Falling behind (bottom left)** – Starting from a position below the European average, these regions have been strongly affected by the negative shock and failed to recover.
- **Inherent features (bottom right)** – Regions in this quadrant were below the European average before the crises while they were able to efficiently react to the crisis revealing a post-crisis trend above the European average. We attribute this capacity to recover to some inherent structural characteristics that contributed to change past trend.

²⁶ The time period of the analysis is 2000-2015. We consider the 2000-2008 interval to compute the trend before the crisis while the 2009-2015 interval is chosen for the trend after the crisis.

²⁷ We choose the arithmetic mean as a threshold to split the sample of regions and not the median because outliers were not strongly affecting the distribution so that the arithmetic mean can be used as an adequate position index.

Figure 2. Classification of EU NUTS2 over the period 2000-2015



In terms of GDP per capita, regions are equally distributed in the third and fourth quadrants, *losers* and *falling behind* regions, respectively. This means that, of the 167 regions that were declining before the crisis, half of them continued to decline, while half of them experienced a renewal process. Furthermore, 25% of regions well performing before the crisis continued to perform positively after. The pattern of employment rate shows that around 42% of regions are placed in the fourth quadrant, showing that the employment trend after the crisis is above the average, while it was below before the crisis. Furthermore, 25% of regions show that the rise of employment before the crisis was not sustainable. Finally, regarding productivity it can be observed that 42% of regions fall in the third quadrant, highlighting strong problems related to their business structure. Anyway, around 25% of regions improve the productivity, and 22% of them continue to have trend above the average.

3. The Regional Resilience Indicator

Since the resilience of EU regions is a multidimensional complex concept, we propose a composite synthetic regional economic resilience indicator that considers the three variables above described.

To the best of our knowledge, this approach to resilience capacity is innovative since it assesses in a unique indicator all the phases of the resilience life cycle.

Weighting and aggregation approaches in composite index construction have been in detail surveyed by the OECD (2008). The regional resilience indicator is constructed through a normalization and weight elicitation based on principal component analysis that can be applied as a means to reduce dimensionality by transforming the multiple dimensions into a set of few uncorrelated dimensions. For a robustness check, equal weighting has also been applied. This technique is the most commonly applied approach, mainly due to the simplicity of the concept, computation and interpretation of selected indicators.

The composite 'Regional Resilience Indicator' to external shocks is defined by two dimensions. The first measures the intrinsic capacity of a region registered over time along its resilient evolutionary path from a base line target point taken as a reference to the measurement

period to cope with a crisis and figures out its so-called slow burning process. The second, to whom we refer as shock wave or dynamic process, allows us to analyse the immediate exposure and reaction capacity to an unexpected shock.

A three-step approach was followed for the identification of regional disparities in the resilience capacity to the crisis:

- (i) data collection and indicators selection;
- (ii) weighting and aggregation;
- (iii) pattern and clusters analysis.

3.1. Data collection and indicators selection

This study employs annual data in 2005 constant price euros over the period 2000-2015 from Cambridge Econometrics' European Regional Database (GDP per capita, employment rate and productivity, defined as GDP per employee).

Then, our slow burning and shock wave indicators have been selected and built for each variable. The slow burning indicators are:

- mean over the period 2000-2008 indicates the level over a particular period of time or in the steady-state behaviour of the system;
- trend over the period before (2000-2008) and after (2009-2015) the crisis:²⁸ is the average sustainable rate of growth over a period of time. It is the slope of the line connecting the two points before and after the crisis and measures the steepness of that line and so the speed of the growth rate. The trend over the pre-crisis period is assumed to be the long run growth trend that a region would have had if the crisis did not occur. The trend over the post-crisis period is a proxy of the long run growth trend after the shock.

The shock dynamic indicators considered are:

- the maximum hit of the crisis between 2009 and 2010 compared to 2008 pre-crisis year is conceived as the immediate reaction to an unexpected shock;
- the relative change between 2015 and 2008 pre-crisis year is assumed as the capacity to recover.

The following step consists in the aggregation of the measures created for each variable, GDP per capita, employment level and productivity.

3.2. Weighting and aggregation

Two different weighting and aggregation methodologies have been used. The first approach relies mainly on Goletsis and Chletsos, (2011), while the second proposed methodology is based on equally weighting and used, for example to construct the Regional Competitiveness Index (Annoni *et al.* 2013).²⁹

The first approach consists of two stages: (a) normalization and (b) weight elicitation.

²⁸ The trend has been computed as follows: i) we regress the time period on the log of the selected variables, and ii) we keep the coefficient associated with the log of the selected variables. If it is positive (negative) and significant, it means that the slope rises up (falls). If the coefficient is zero or not significant, the trend is not statistically different from zero.

²⁹ RCI aggregates indicators and sub-indices through weighted arithmetic mean.

(a) The normalisation of the data helps to i) remove the different scale of each variable, and ii) identify indicators may be positively correlated with the phenomenon to be measured, whereas others may be negatively correlated with it³⁰ There are different methods of normalization, such as ranking, re-scaling (or min-max transformation), standardization (or z-scores) and indicization. As suggested by Goletsis and Chletsos, (2011), we made use of the min-max transformation. Consider the *i-th* indicator for region *j*, I_{ij} is transformed to I_{ij}^{adj} taking values within the interval [0,1] according to the following equation:

$$I_{ij}^{adj} = \frac{I_{ij} - \min_j(I_{ij})}{\max_j(I_{ij}) - \min_j(I_{ij})} \quad (1)$$

(b) A multivariate method usually applied for space reduction, namely the Principal Component Analysis (PCA) has been used for weight elicitation.

PCA aggregates sub-indicators that are collinear into new ones named components, which are able to capture as much of common information of those sub-indicators as possible. PCA determines the set of weights, which explains the largest variation in the original data. Different criteria can be applied on the selection of number of components in order to keep the maximum of information. We keep the components cumulatively contribute to the explanation of the total variance of the data by more than 70%. The selected components are then used for the aggregating procedure to ensure that the variables used are not correlated.

Weights are estimated as normalized squared loadings (implying the portion of variance of each component explained by each variable). We apply the approach, which uses highest loading per variable weighted according to the relative contribution of the respective component to the explanation of the overall variance. The indicator is aggregated through the following weighted additive function:

$$CRI_j = \sum_i w_i I_{ij}^{adj} \quad (2)$$

where CRI_j , is the Composite Resilience Index for region *j*, w_i is the weight of indicator *i* and I_{ij}^{adj} is the adjusted value of indicator I_i for region *j*.

The second approach shares with the first above explained the normalization procedure while differs for the weight elicitation since it is based on weighting equally the selected indicators through arithmetic mean.³¹

3.3. Pattern and cluster analysis

The overall objective of clustering is to identify regions sharing common resilience features and, therefore, strategic geographical and thematic areas of intervention for policy makers.

We use a decile method in order to split up our ranked data into 10 equally large subsections and be able to capture the regional disparities in the resilient capacities to the crisis. An Anselin global Moran's I and Local Moran analysis is also performed to investigate how clusters and outliers behave.

To analyze space dependence, the most recognized indicator is the Moran's I (MI) (Moran, 1950). This statistics has been widely used in the literature to describe economic phenomena whose distribution in the space is not random (Le Gallo and Ertur, 2003; Ertur *et al.*, 2006; Dall'Erba, 2005; Gregory and Patuelli, 2015).

³⁰ This step is required in order to ensure that an increase in the normalized indicators corresponds to increase in the composite index

³¹ The weighting scheme of the EU RCI is more complex because it is based on z-scores normalization procedure and weighted arithmetic mean where the weights are the region's stages of development.

The MI relates the value of a selected variable with the values of the same variable in the neighbor areas, namely its spatial lag. The intuition behind is that socio-economic phenomena might be not isolated in space and what is happening in a certain location might be correlated to what is happening in the neighbor locations. The formal definition of this relation is as follows:

$$MI = \frac{N}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i w_{ij} (x_i - \bar{x})} \quad (3)$$

where N is the number of regions indexed by i and j , x is the variable of interest; \bar{x} is its mean, and W_{ij} is an element of the spatial weights matrix \mathbf{W} , which is defined as a queen contiguity matrix, i.e. regions are considered as neighbor if they touch themselves for at least a point.³² Then, as customary, the matrix is standardized by row.

The calculated MI for global autocorrelation, in the case of \mathbf{W} standardized by row, varies between -1 and 1. A positive coefficient points to positive spatial autocorrelation, i.e., clusters of similar values can be identified. The reverse represents regimes of negative association, i.e., dissimilar values clustered together in a map. A value close to zero indicates a random spatial pattern.

One of the advantages of this statistics is that it can be visualized in a scatterplot, the so-called Moran scatterplot, in which the spatial lag of the (standardized) variable is on the vertical axis and the original (standardized) variable is on the horizontal axis. Thus, each of the points in the scatterplot represents a combination of a locations' value and its corresponding values in the surrounding regions, i.e., the spatial lag. The x- and y-axes divide the scatterplot into four quadrants (anticlockwise from top right): in the first and third (high-high, HH, and low-low, LL, respectively) a location that exhibits a high (low) value of the variable is surrounded by locations with a high (low) value of the variable as well. In the second and fourth (low-high, LH, and high-low, HL, respectively) a location with a low (high) value of the variable is surrounded by locations with a high (low) value of the variable. A concentration of points in the first and third quadrants means that there is a positive spatial dependence (nearby locations will have similar values), while the concentration of points in the second and fourth quadrants reveals the presence of negative spatial dependence (that is, nearby locations will have dissimilar values).

A precise evaluation and identification of the levels of local spatial autocorrelation are achieved by Local Moran, which is a Local Indicators of Spatial Association (LISA). The Local Moran allows identifying the clusters of "spatial outlier regions", i.e., the statistical hotspots and coldspots, the areas with a concentration of regions with high levels and low levels of turnout, respectively. This is possible because the Local Moran is able to identify for each region an indication of significant spatial clustering of similar values around that observation. Furthermore, the sum of the Local Moran for all observations corresponds to the global indicator of spatial association, the Moran's I (Cochrane and Poot, 2008, p. 71; Le Gallo and Kamarianakis, 2011, p. 129).

The local version of Moran's I statistic is a LISA and expressed as follows:

$$I_i = (x_i - \bar{x}) \sum_j w_{ij} (x_j - \bar{x}) \sum_i \sum_j w_{ij} \quad (4)$$

Finally, given that the local Moran I_i is not approximately normally distributed, a conditional randomisation or permutation approach is used to yield empirical pseudo significance levels.

³² The islands have been connected to the nearest region.

4. Results

The composite index for resilience for 271 NUTS-2 regions has been constructed considering to the two different aggregation procedures above illustrated. Since the correlation between the two approaches is very high, we reported only the results based on the first approach. PCA estimated the weight values for the 15 selected indices. Three components were extracted. The identified components account for approximately 77.1% of total variance. Figure 3 illustrates the resilient capacity of NUTS2 regions to the financial crisis. The Regional Resilience indicator varies between 0 and 1, where the smaller values (lighter) represent the less resilient regions, and the higher (darker) the most resilient.

As expected, the consequences of the crisis were not uniform among EU regions.

Well-identified territorial patterns can be observed:

- National trends are prevalent: Mediterranean countries were characterized by slow growth of the selected indicators before and after the crisis, while Germany and Northern countries experienced strong growth and coping and adaptive capacities. Baltic countries were experiencing fast growth in the pre-crisis period and, in spite of the economic collapse, they were able to recover;
- Within some countries there is a north-south regional divide that often depends on historical origins. These countries are Italy, Spain and Belgium;
- In the countries where NUTS2 regions have a more fine resolution, i.e., Germany, Great Britain, Belgium, Hungary and Austria, cities show a higher resilience than the surrounding regions.

Figure 3. Regional Resilience Indicator over the period 2000–2015 by NUTS2

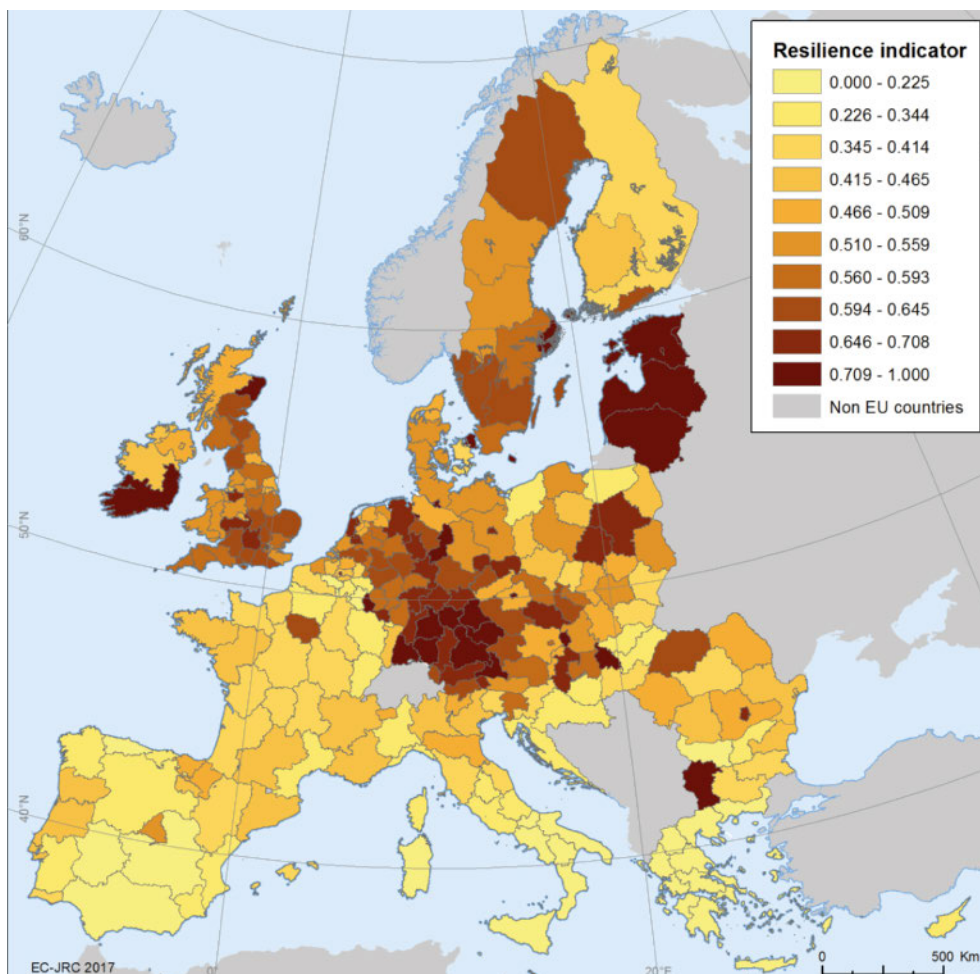
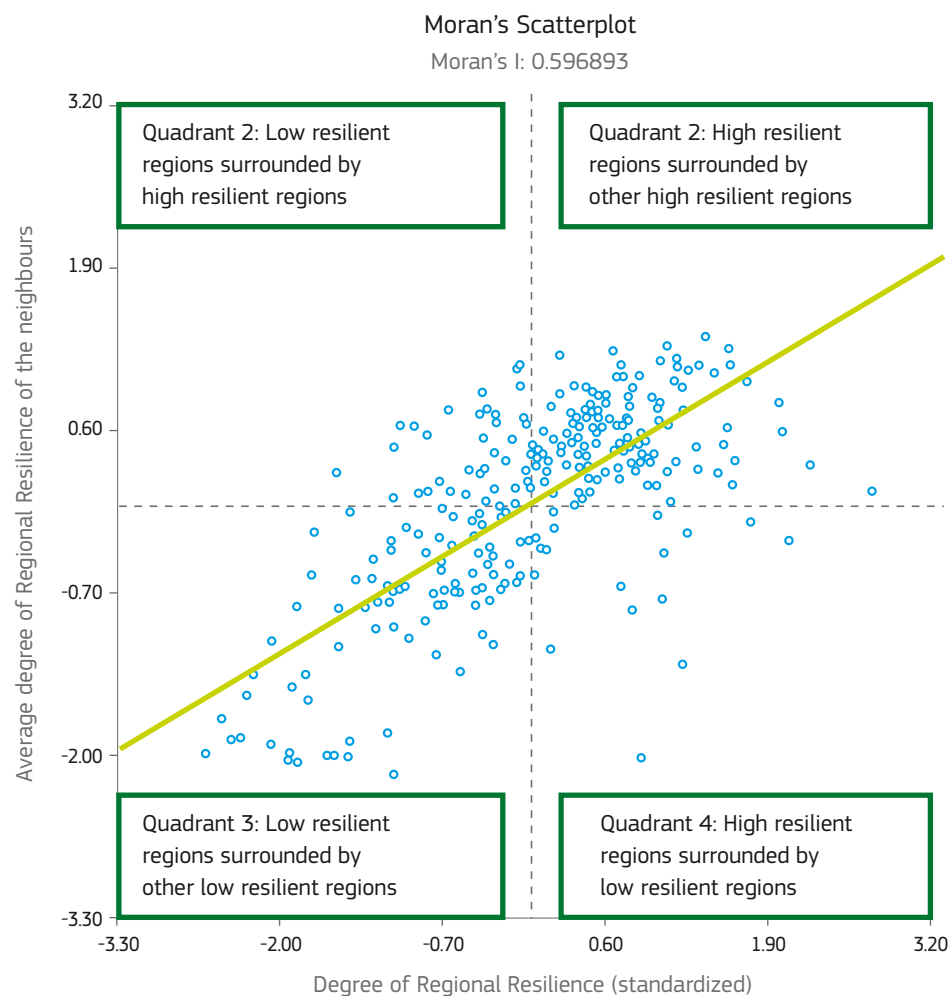


Figure 4 shows the Moran scatterplot, which accounts for spatial autocorrelation, which is a measure of the presence of spatial clusters of regions sharing a similar value of resilience. Spatial autocorrelation is due to externalities that consist in the influence that a region has on the neighbors as a consequence of different factors such as commuting, share of technology, trade, migration, and a set of intangible assets. A region can take advantage or disadvantage of the externality if i) it is surrounded by resilient or not resilient regions and ii) it has the capacity to be permeable to positive environment and impermeable to negative environment. It is worth mentioning that Moran's I is equal to 0.60 and about 82% of regions are located in the first and third quadrant. This means that there are statistically significant well-defined and generally homogeneous regional patterns: high (low) resilient regions are surrounded by high (low) resilient regions. Among the remaining ones (18%), the majority is concentrated in the second quadrant, i.e., low resilient regions are surrounded by other regions with high resilient capacity.

Figure 4. Moran's Scatterplot



One limit of the global measure of spatial autocorrelation is that it is not able to give us information regarding the presence of local significant clusters, the so called 'hot-spots' and 'cold-spots' that deviate from the overall pattern.

The local Moran's I shown in Figure 5 identifies the statistically significant spatial clusters of resilient and non-resilient regions. The divide within countries detected in Figure 3 is only partially confirmed, highlighting the importance of using statistical tools to identify clusters.

Southern regions of Italy, Spain and Portugal and Greece belong to group of ‘cold-spot’ regions. The statistically significant spatial cluster of resilient regions is located in Latvia, Southern Denmark, center and south Germany, the northern region of Sweden, and around London.

Figure 5. Statistically significant spatial clusters of resilient and not resilient regions

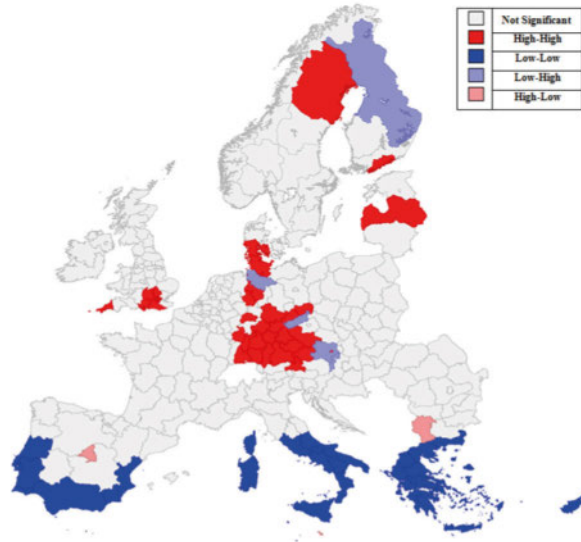
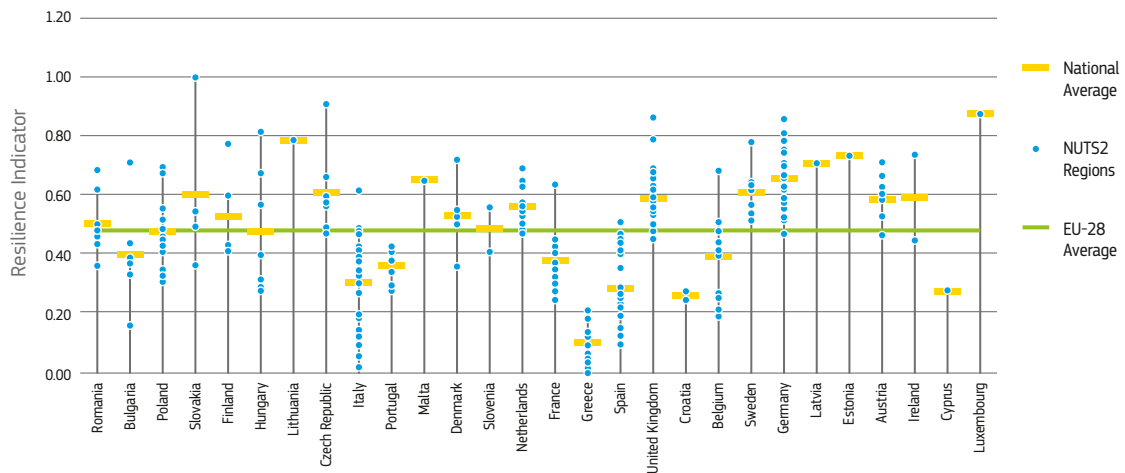


Figure 6 shows the regional degree of resilience by country. With some exceptions, regions tend to be centered on national averages. If the country average is below the EU-28 average, the regions belonging to that country are below the EU-28 average, and vice versa. This means that there is a limited variability within countries, but there are strong differences among countries. Romania, Poland, Hungary and Slovakia, despite this general trend, demonstrate a quite high variability. The most resilient countries are the Baltic countries, which experienced a huge growth before the 2008 and, despite the collapse of the economy due to the crisis, had the capacity to recover faster than other counties. These results show that the degree of regional resilience varies significantly only within some countries, while the majority of regions tend to follow the national trend.

Figure 6. Regional Resilience Indicator by country



Conclusions

The Regional Resilience Indicator is a tool that accounts for several components of economy related resilient capacity and combines them into a comparable, synthetic and easily understandable measure. The analysis shows that the resilience capacity of a region is heavily co-related to that of the surrounding regions. However, some countries reveal a certain degree of heterogeneity due to rooted historical gaps.

As suggested by Martin and Sunley (2015), an analysis of the economic resilience should consider, after the identification of the regionally differentiated effects of the shocks, the explanation of the results in terms of their determinants, including social, institutional and political aspects to understand the forms of assistance and governance that can help to recover and protect regional economies from future crises (Bristow and Healy, 2014).

The national dimension still plays a strong role, because regions tend to be affected by common institutional and legal frameworks, structural policies, etc. Lack of competitiveness, huge debt, heavily borrowing and large exposure to financial markets had plunged Greece into a recession deeper than in many other European countries. Similar factors affected with a more smoothed strength Italy, Portugal and Spain's economy but the effects were not uniform across regions, with some that have shown a much lower resilience. A combination of strong economic activity, more stable public finances and favourable political environment helped Germany to recover faster. In particular, western regions are the most resilient. Recent literature explains the different degrees of regional resilience through several channels, among which the most important are: the sectoral composition of the economy, the export-oriented enterprises and their capacity to innovate, the skills of the workforce and some institutional aspects (Martin, 2011; Fingleton *et al.*, 2012; ESPON, 2014). The last point, originally not considered a completely satisfactory explanation for the existence of regional disparities (Overman and Puga, 2002), recently turned into one of the key explanatory factors (Boschma, 2014).

Our results, on the other hand, tend to support the position of Boschma for countries with historical well-grounded territorial development gaps such as Italy, Spain, Portugal and Germany. Regions belonging to other European countries do not show a so high deviation from the national average, highlighting that the major determinants of regional resilience mainly identify with the national macroeconomic conditions.

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CIRP: A Multi-Hazard Impact Assessment Software for Critical Infrastructures

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Abstract

In this work we present the design and development of the Critical Infrastructure Resilience Platform (CIRP) in the frame of the EU Research project EU-CIRCLE. The project's scope is to derive an innovative framework supporting resilience of the interconnected European Critical Infrastructure (CI) to climate pressures.

CIRP's primary goal is to provide a multi-user web accessible software that will be able to analyse the CI's vulnerabilities and impacts due to climate change in the form not only of physical damages but also service impacts, interdependencies, societal costs, environmental effects, and economic costs due to suspended activities.

Keywords

Climate Change, Critical Infrastructure, Impact Assessment, Natural Hazards

The CIRP is intended to be a user-friendly environment that will provide its users with the ability to analyse what-if scenarios: leveraging model selection, climate data repositories and CI inventories in order to calculate impact for any kind of climate hazard and CI. In this way, end users will be able to understand the impact of various adaptation strategies or quantify the potential impact of a catastrophic event on society.

1. Introduction

It is acknowledged that climate related hazards have the potential to substantially affect the lifespan and effectiveness or even destroy European Critical Infrastructures (CI), particularly the energy, transportation sectors, buildings, marine and water management infrastructure with devastating societal and economic impacts. In this context, modeling the impact of climate change to CIs is of vital importance. Many risk assessment tools and platforms exist today. Most, however, lack the flexibility to easily add new algorithms or to extend their base features. This is typically due to a combination of architectural approach and closed-source licensing policies. Such software does not allow the community to actively contribute new algorithms and capabilities and, therefore, allow the software to evolve with the advancements of science.



The Climate Infrastructure Resilience Platform (CIRP) is a collaborative software environment that aims to create new capabilities for CI policy-makers, decision makers, and scientists by allowing them to use different and diverse modelling and risk assessment solutions, to develop risk reduction strategies and implement mitigation actions that help minimise the impact of climate change on CIs. This can help improve the understanding of system interdependencies by providing decision makers with the latest tools, based on the best scientific and engineering principles, as they emerge. From the policy and decision maker perspective, the platform capabilities is offered as a toolbox that consists of a collection of diverse Risk and Resilience analyses of Critical Infrastructures that are exposed to the direct and indirect effects of climate change.

From the technical point of view, CIRP is primarily based on the Eclipse Rich Client Platform (RCP) technology and two distinct frameworks each compliant with RCP: the ERGO-CORE of the ERGO consortium and the Chameleon Enterprise Foundation (CEF) of Satways Ltd. Both frameworks are a collection of OSGi plugins (or bundles) and are briefly described in subsequent sections. Being modular and extensible, CIRP is able to accommodate different types of datasets (e.g. hazard, assets, interconnections, fragilities), file formats, and risk analysis algorithms and provide an intuitive user interface for scenario and data repository management, analysis workflows setup, intuitive results (2D/3D) visualisation and reporting.

CIRP's essential elements for impact assessment are hazard, inventory, and fragility. Hazard is considered as the descriptive parameter quantifying the possible phenomenon within a region of interest. The assets in a region exposed to hazards are defined by inventory. Finally, fragility is the sensitivity of certain types of inventory items when subjected to a given hazard. Assuring that the science and engineering principles behind the forecasting of damage probability of Critical Infrastructures (buildings, bridges, networks, pipelines, and other inventory items) from anticipated events is both pragmatic and state-of-the-art is therefore critical to minimising the impact of climate change events, reducing losses to economic resources, and the development of more stable communities.

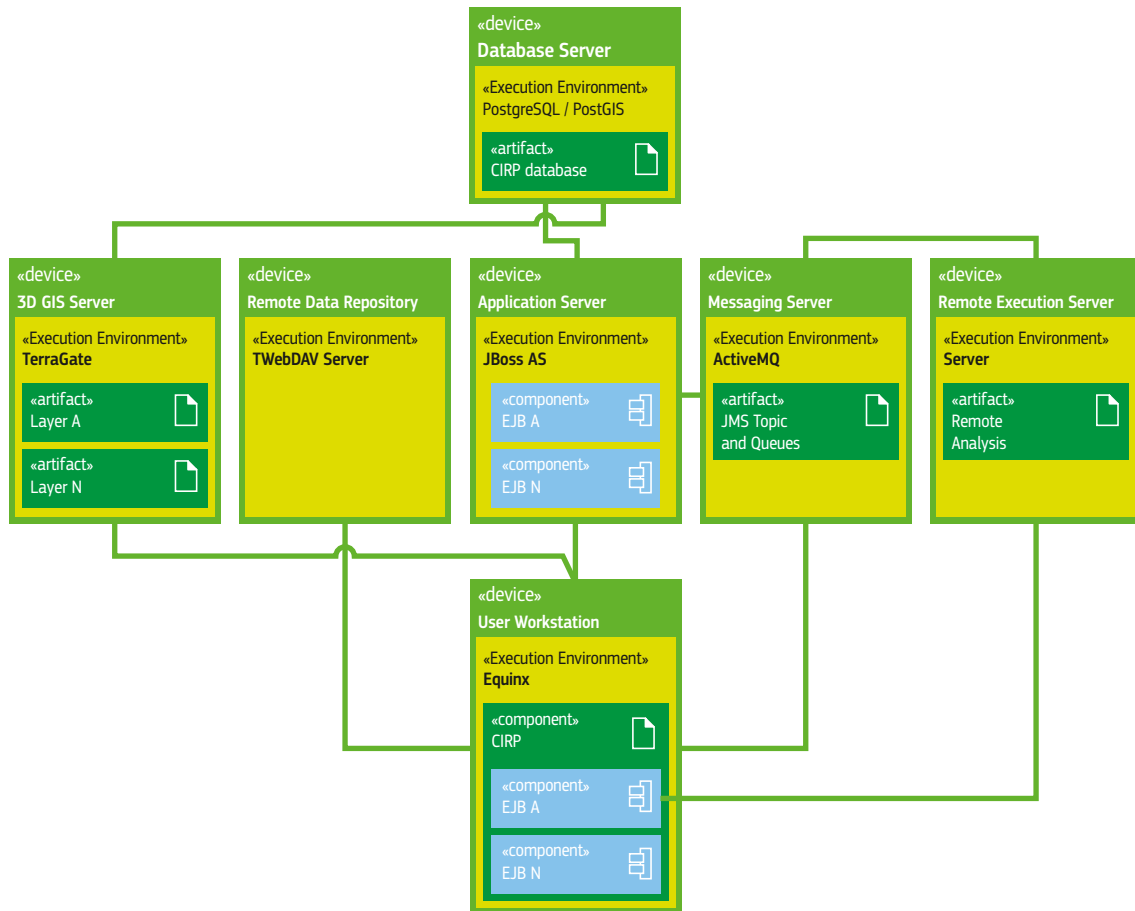
Overall, the intention is for Risk management professionals to become familiar with identifying vulnerabilities, assessing loss reduction strategies, guiding resource allocation before disasters, identifying vulnerable areas during disasters, guiding recovery efforts, and providing information to decision-makers throughout the process.

2. Design and Architecture

CIRP has been designed and developed as a fully modular, extensible, multi-user geospatial N-tier software system according to the design considerations and strategies presented in Deliverable 5.1 (EU-Circle, D5.1). The CIRP server is based on the Java Enterprise Edition specification while the CIRP client architecture is based on the ERGO-CORE and CEF RCP frameworks. Each of the two core frameworks provides a set of discrete functionalities that may be exploited independently or in a collaborative manner. The ERGO-CORE is the base IT infrastructure of the ERGO (ERGO, 2017) an open-source project that was originally developed under the name Maeviz to perform seismic risk assessment. The ERGO-Core OSGi bundles provide the functionality related to inventory, data and metadata management, and the ability to wrap new analysis types and execute them on a workflow engine. The CEF framework on the other hand provides the User Management & Roles and Access Rights modules, and the 3D GIS viewer and editor modules.

From the Risk assessment point of view, CIRP follows the Consequence – based Risk Management (CRM) generic approach which has been selected and extensively described in Deliverable 3.4 (EU-Circle, D3.4). CRM has been used in climate/disaster risk reduction assessments allowing for the identification of uncertainty of climate risk modeling and quantify the risk to societal systems and functions. It also enables relevant stakeholders to develop risk reduction and adaptation strategies and implement mitigation actions. The CIRP end user application (client) is delivered via Java Web Start. CIRP users are able to create and store scenarios by means of selection of a chain of analysis tools. Each analysis tool is associated with input and output parameters and relevant datasets that conform to the platform supported types. It will be possible to chain analysis tools to form analysis workflows and each individual analysis in the workflow will be monitored as provided for by the analysis type, the geographical span of the scenario, and the number of CI elements analysed. An analysis will be able to be executed in seconds, minutes or even hours. The design of the CIRP provides a uniform user experience for the user input of values and selection of input datasets. Each analysis tool within the CIRP is described in the Extensible Markup Language (XML) and transformed at runtime into suitable widgets and user interface controls.

The following UML Deployment Diagram depicts the physical layout of the various hardware components (nodes) of the CIRP system as well as the distribution of executable environments and software components on that hardware. The diagram depicts the actual devices (workstations, servers), along with the inter-connections, and provides an effective system topology. In that topology, as illustrated below, the location of executable components and objects illustrates where the software units are deployed and executed.

Figure 1. CIRP UML deployment diagram

3. Main Functionalities and User Interface

CIRP's UI consists of one or more (in case of using multiple workstation monitors) main application windows. As typical Eclipse RCP application, each window includes a menu, toolbars, the perspective area and the main toolbar where the users will be able to navigate between the different perspectives. A perspective groups a number of views and supporting widgets and menus as well as shortcuts to relevant content creation wizards, other related views, and other related perspectives. The most important views of the CIRP User interface are:

- **Scenario Manager:** shows each scenario a user is working with. A scenario is a user defined case that consists of one or more selected analysis tools from the CIRP toolbox and the associated datasets (input and output). Each scenario can be expanded to show its contents (input/output datasets and map layers as well as analysis workflows). An analysis View is launched upon double clicking a Saved Analysis workflow from the Scenario Manager or upon selection of an analysis from the "Execute Analysis" wizard.
- **Catalog:** provides access to the local and remote file caches. A cache is a location where CIRP looks for and stores all of the data that it uses and produces. A cache can be located locally, as a file on the local machine drive, or be remote. By default, CIRP creates a local cache on the user's system, where any remote data that is accessed is cached for local use.
- **Loss Curves and Mappings Editor:** The Loss Curve editor provides a set of tools for creating and editing Damage Curves consisting of a set of X, Y pairs and linear interpolation as well as rules associating a loss curve with an inventory (shapefile) based on DBF attribute values. The Curve editor is capable of manipulating curves ingested in CIRP's repository (XML files), as well as files located in user's local filesystem. By loading a Curve

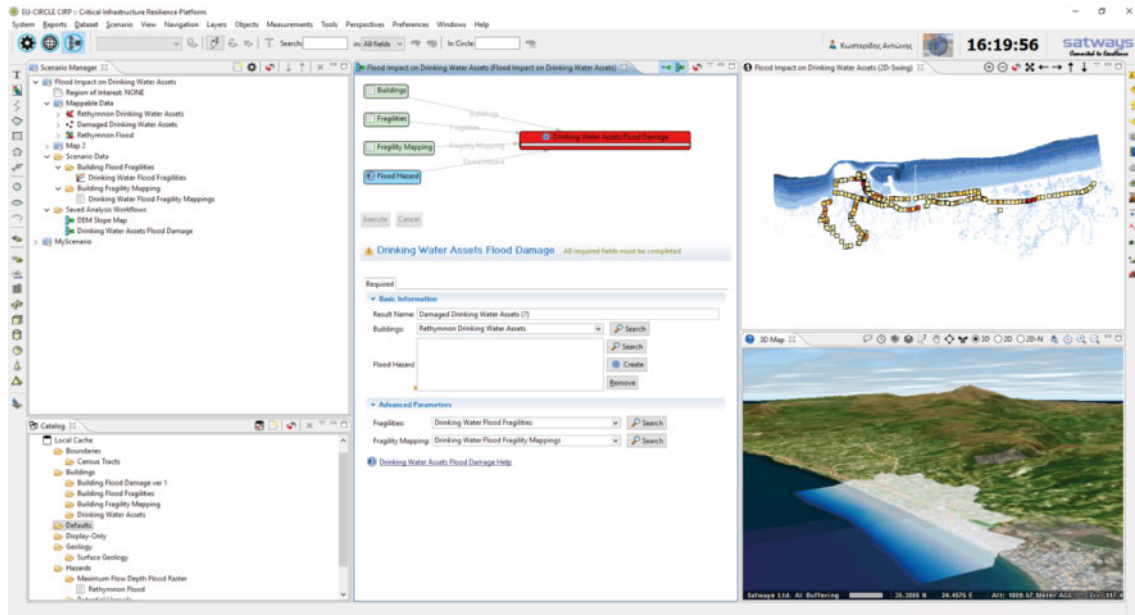
dataset or creating a new one, user has the capability to add or edit curve's points either from a raw table view or from a chart view using drag-n-drop features. This functionality complements other supported curve function types supported by ERGO-Core.

- **2D Map Viewer:** allows the visualization of raster and vector datasets in a layered approach and according to the defined styles applied via the Style Editor View. The underlying map engine is based on the open source library (Geotools, 2017).
- **3D Map Viewer and Editor:** allows view is created by fusing aerial and satellite photography, terrain elevation data and other 3D and 2D information sources including geospatial dataset layers. A basic difference from the 2D Map is the fact that feature and imagery layers can be streamed from the 3D GIS servers and that the underlying map engine (TerraExplorer, 2017) is using Graphics Card acceleration (DirectX) providing maximum performance. Additionally it provides tools for editing the spatial characteristics and attributes of shapefiles datasets (e.g. inventories) without requiring the usage of external GIS tools.

CIRP currently provides support for five (5) different plugin types as platform extensions.

- **Type Definition Plugins:** Type definition OSGi plugins make use of the extension points of the underlying analysis framework and can register dataset and metadata schemas. Even if data definitions can be included in the execution plugins described below it is a good practise to separate them in order not to repeat the definition in multiple execution plugins that require and/or produce these dataset types.
- **Local Execution Java Plugin:** Local OSGi plugins make use of the extension points of the underlying analysis framework and register analysis descriptions according to a predefined XML schema and a Task class which extends one of the base Task classes. The task is the one executed by the underlying workflow engine of the analysis framework. The base Task classes generally provide the means to iterate over vector or raster input datasets to perform calculations.
- **Local Execution Hybrid Plugin:** The local execution hybrid plugin has no difference than the previous type apart from the fact that the Task class is a wrapper over executables written in other languages or closed source java codes and controls their input and output. The executable is either bundled in the hybrid plugin or installed in the client machine. An example of such a plugin is presented in Section 0.
- **Remote Execution Plugin:** In this type of plugin the Task class submits a job to the CIRP Message Bus according to a predefined protocol. A remote analysis service is subscribed in the Message Bus and executes the job. Messages exchanged in certain time intervals allow the indication of the analysis progress in the CIRP analysis workflow window.
- **Local Scripting Plugin:** The last plugin type provides the ability to wrap scripts instead of executables. Currently the R language is supported. This allows even editing of the parameters and logic of the script at runtime without the need to recompile the plugin.

Figure 2. The CIRP user interface and main views



4. Flood Risk Assessment Example

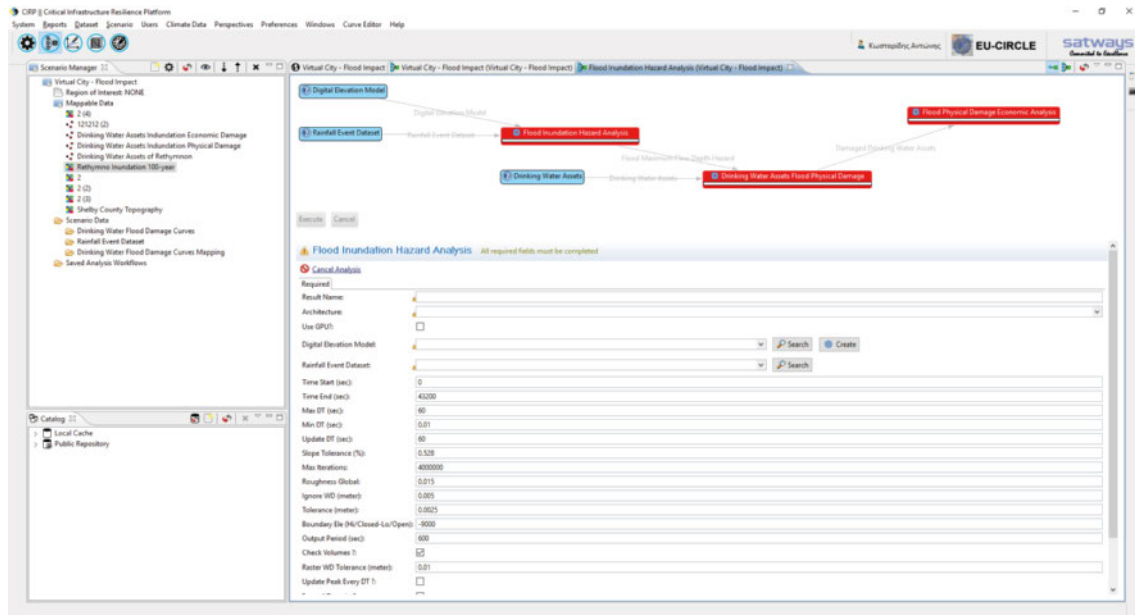
In this section we demonstrate the usage of CIRP to estimate flood impact on Drinking and Waste water assets in the Virtual City of EU-Circle. There are various hydrological attributes that affect damage levels of Critical Infrastructures such as flood duration, flow velocity, speed of water rise, flood duration, content of water. Hydrodynamic models, along with detailed spatial data, are necessary for a good indication of the impact of flooding on Critical Infrastructure. It is generally assumed that inundation level is the most important factor contributing to flood damage and a useful indicator on which to base the damage levels (Kreibich, 2010). Thus the following models will use inundation level as the only indicator on which to base the damage levels.

The CIRP scenario will make use of a set of chained analysis available from the CIRP analysis toolbox that estimate damage, losses and functionality for selected vulnerable components of the drinking and waste water systems namely treatment plants, control vaults and control stations and pumping stations.

The assessment of direct economic damage by flooding is generally done by setting a replacement value on assets and using loss curves as estimations of their susceptibility to flood damage (Jonkman, 2008). Such curves represent the monetary damage received by level of inundation, expressed as a fraction of the replacement value, which represents maximum possible damage.

The following Figure shows the different analysis (hazard, damage and economic impact) chained as a workflow in CIRP. Each analysis box (in red color) requires a number of input datasets (light blue color) and a set of parameters all set by the user. The output of one or more analysis can be used as input in subsequent ones. The execution of the workflow is handled by the underlying ogrscript workflow engine and monitored via the user interface with progress bars per analysis box.

Figure 3. Flood impact chained analysis workflow



4.1. The Flood Inundation Hazard Plugin

The Flood inundation hazard plugin is a “Local Execution Hybrid Plugin”. It acts as a wrapper by preparing the required analysis input from datasets and parameters chosen by the CIRR user to an external flood simulation application. Within the project EU-CIRCLE, this application is CADDIES (Guidolin, 2016), a 2D pluvial flood inundation simulator using cellular automata (CA) techniques instead of solving the classic shallow water equations (SWEs). The CA technique offers a versatile method for modelling complex physical systems using simple operations (Wolfram 1984).

In CA, the change of cell status is determined by transition rules, which depend on the status of each cell and its neighbourhoods. This simplification dramatically reduces the computational load of a CA model in comparison to a physically based model. On top of this, the latest parallel computing techniques, including GPU processing and OpenMP, are implemented in CADDIES to accelerate the computational performance. Experiments showed that CADDIES can perform at an order of magnitude faster than a traditional hydraulic modelling approach (Guidolin, 2016).

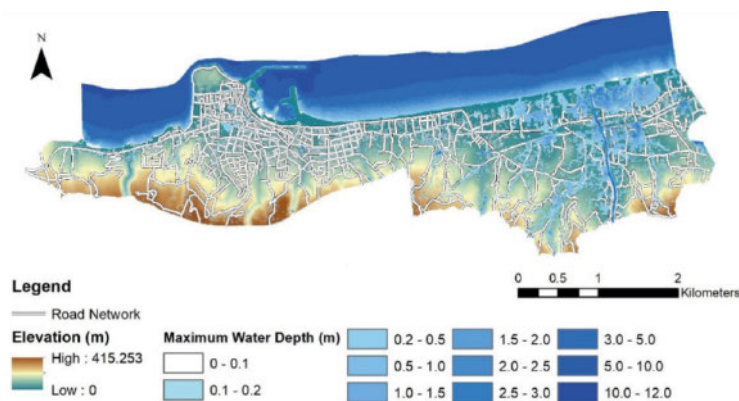
The Flood Inundation Hazard Analysis in CIRR requires as input an elevation model, a rainfall event dataset and set of parameters. The elevation model and rainfall events can be selected from the local or public repository while the rest of the parameters can set by clicking in the Flood Inundation Hazard Analysis red box (see Figure 3).

4.2. Using External Flood Simulators

As each analysis in CIRR can be executed in standalone mode a user is able to execute a flood impact analysis using datasets produced by external simulation software packages that solve part or full Saint-Venant continuity and momentum depth-averaged equations in the longitudinal directions (1D models) or both longitudinal and lateral direction (quasi-2D or 2D models) as stated in (Dimitriadis, 2016). Such software packages are the HEC-RAS, the LISFLOOD-FP, the FLO-2D, SOBEK, SWMM, MIKE Models, etc. In this work MIKE models have been applied and used for hydraulic simulations for the city of Rethymno (Makropoulos, 2015), the outcomes of which were utilised in flood risk assessment processes fulfilled within CIRR.

A combination of 1D-2D MIKE models (MIKE 11, MIKE 21FM and MIKE Urban) has been setup and coupled through MIKE Flood for the simulation of flood events and their propagation in space and time. The domain of models' set up is the urban area where the flood impact is important due to city's services and functions, but all river catchments that cross the city of Rethymno have been taken into consideration for the calculation of the total water volumes that drain through the city. MIKE 11 has been used for 1D hydraulic simulations of open channel flows, MIKE URBAN has been used for flows in closed cross sections and MIKE 21FM, the 2D model, was used for the simulation of surface runoff. All three models have been coupled with MIKE Flood, through 4 types of links, enabling combined 1D-2D simulation of flood phenomena (PEARL, D3.4). Several outputs are being produced for each simulation based on which flood risk assessment can be implemented e.g. maximum water depth and maximum current speed which was recorded for the whole area under study for all the simulated time steps, time when the maximum values were reached, duration while the water depth was above a defined threshold, as well as, "actual" water depths/surfaces and velocities values and how those values change in space and time. For the purposes of the current study, maximum water depth results have been used and fed into CIRP platform for further analysis.

Figure 4. Maximum water depth map



4.3. Impact on Drinking Water and Waste Water Assets

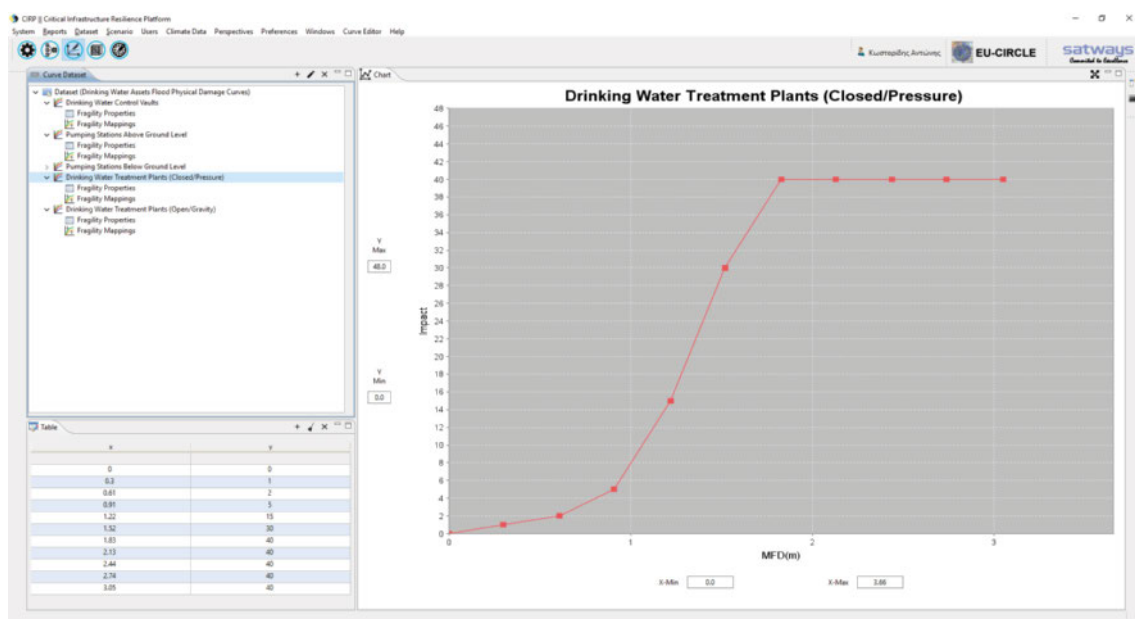
The impact model estimates damage for selected vulnerable components of the drinking water and waste water systems. For the drinking water network these include treatment plants, control vaults and stations, and pumping stations. For the waste water system these are pipelines, wastewater treatment plants, control vaults and stations, and lift stations.

For the impact analysis the inventory data have been prepared as four (4) different shapefiles, two for each system. A polyline GIS layer contains the geographical location and classification of the pipelines and a point layer for facilities. The classification includes the type of each asset, the need for electricity connection, the underground or above ground position of the asset, whether the asset is part of a pressurized system, the floor elevation, its size (small, medium, large), the year of construction of the asset, its estimated lifetime and the replacement cost for facilities and the repair cost for pipelines. The classification of the inventory follows the HAZUS-MH method (FEMA, 2010). There are two general scenarios for inundation damage, diked/protected and unprotected/undiked. Using the CIRP GIS editor (refer to Section 0) perspective a user is able to edit the attributes of assets and set for instance the floor elevation. In some facilities e.g. the treatment plants, there may be different structures with different floor slab elevations. In this case the user is required to select the elevation that best represents the vulnerability of the overall facility.

4.3.1 Loss Curves

Loss curves used in this example have been developed in HAZUS-MH for the aforementioned inventory classes. The operational vulnerabilities, damage and restoration times can be considered a function of the fragility of electrical equipment, mechanical equipment and building damage. In many situations the operation of these facilities will be terminated on a management decision to shut down the facility at some threshold floodwater elevation. For instance a water treatment plant commonly has multiple structure on its terrain, which may be situated on different elevations. The functionality of a water treatment plant is dependent on electrical circuits and components. When determining a treatment plant's vulnerability to inundation, the elevation of the buildings which house the key electrical controls can be set to represent the vulnerability of the entire treatment plant. Damage to electrical equipment is expected if inundation depth reaches 1 meter (FEMA, 2010). Nevertheless, within CIRP point assets, like treatment plants and pumping stations, are assessed as a whole and not as system of systems. In accordance with HAZUS-MH method (FEMA, 2010) there are several characteristics that affect flood vulnerability, such as size and type of the asset. CIRP chooses loss curves depending on the characteristics of the assets. These characteristics are available through the assets' classification. Drinking water plants and pumping plants are expected to receive high levels of damage at low depths of inundation due to their commonly low elevation locations and basements. The HAZUS-MH method provides data for setting up a damage curve for water treatment plants. The loss curves and mapping files can be created with the Loss Curve Editor of CIRP as depicted in the following figure. The user can assign a different damage function to each facility class within their study region.

Figure 5. Editing the curve for closed/pressure drinking water treatment plants



4.3.2 The Impact Analyses

This analysis uses the maximum water depth results from the inundation analysis and calculates the percentage of damage expected for each facility used as the inventory dataset using the loss functions described in the previous section.

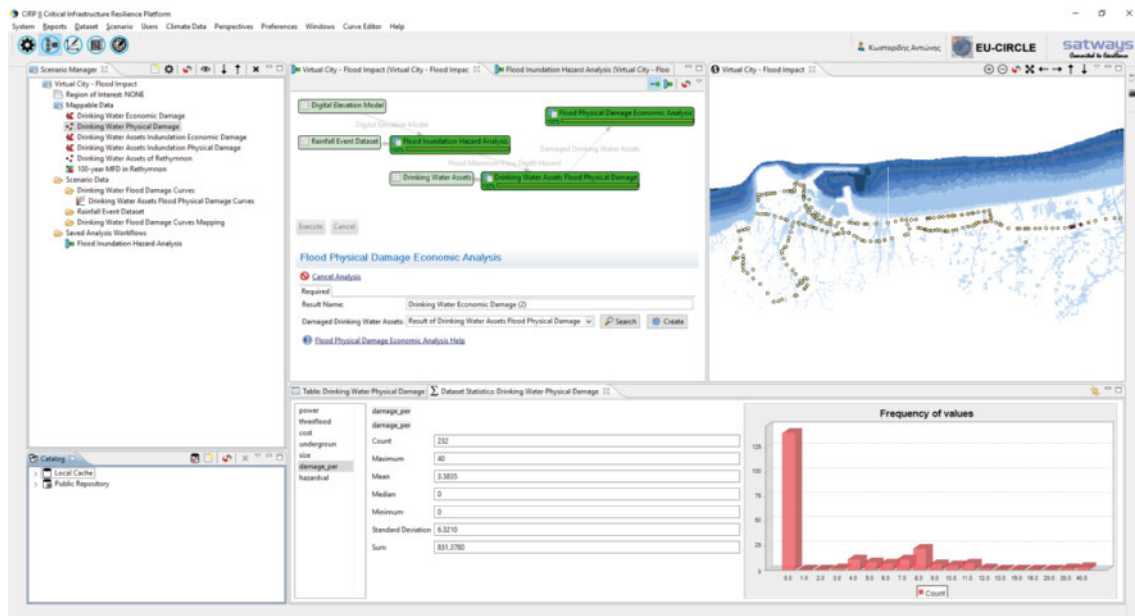
$$(\% \text{ damage}) = \text{damage at (depth of water - asset height)}$$

Which is read directly from the table of depth damage values using the internal API of the platform. Once the expected amount of damage is known (percent %), it is necessary to multiply this with the replacement value to determine the amount of loss.

$$(\text{€ Loss}) = (\text{\% Damage}) * (\text{Inventory € value})$$

The following Figure depicts impact results statistics via the embedded Chart engine (JFreeChart, 2017).

Figure 6. Result statistics for the physical damage analysis



Conclusions

The CIRP has been designed and developed as a collaborative modelling environment where new risk assessment and geospatial analyses can extend the analysis workflow and where multiple scientific disciplines can work together to understand interdependencies, validate results, and present findings in a unified manner.

CIRP offers an environment for what-if scenario analyses with the selection of model chains, climate data, and CI inventories in order to calculate damages and assess the resulting risk. The CIRP platform as designed provides a user friendly environment to enable the intuitive design and analysis of modelling scenarios created for any combination of climate hazard and CI assets. In this way, users are able to understand the impact of various adaptation strategies or to quantify the potential impact of a catastrophic event on society. This provides an efficient, pragmatic, and effective solution that integrates existing modelling tools and data into a holistic resilience model in a standardised fashion.

The CIRP extensible modular architecture can be shared across multiple communities to enable CI policy maker, owners, and scientists to leverage existing software analysis types and algorithms, inventory types, and fragilities while not binding the underlying platform to a particular scientific domain. This pluggable, open architecture is what will allow CIRP to support a wide variety of domain specific functionality isolated in plugins; to repackage different functionalities as a starting point for new applications, and to be extended to add new analytical capabilities in the future.

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Understanding the Physical, Environmental, Economic, and Social Factors that Contribute to Environmentally Driven Migration

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Abstract

In countries around the world, leaders and planners are addressing the issues associated with potential climate change impacts. In the majority of the discussions, the focus is on developing mitigation strategies. However, there are locations around the world, including in the United States, where engineering solutions are impractical and the only plausible long-term mitigation strategy may be to relocate to more resilient locales.

We examine the various physical, environmental, economic, and social factors that contribute to developing climate impact response strategies, including the choice of migration. We present a brief review of historical instances of environmentally driven migrations and the realized consequences. We then summarize the factors that drove migrations, their destination, and if they were ever able to return to their original locations.

We also present a conceptual model for a system-of-systems approach for how climate mitigation strategies can be evaluated, including the factors and decisions required to evaluate migration as a plausible and implementable outcome. We discuss data sources that could be used with “big data” analytic approaches to ascertain potential emerging events that could be precursors to migratory pressures with potential disruptive consequences.

Keywords

Climate change, environmental disruption, migration, mitigation

1. Introduction

The effects of climate change, including heavier rainfall, more intense drought, and rising sea levels, will likely be an impetus for widespread migration in the coming years (IPCC 2014). A recent analysis of populations at risk due to sea level rise in the United States points to potentially significant demographic shifts, with significant population losses in the coastal areas of Virginia, New Jersey, Louisiana, and Florida and population gains in Texas (Hauer 2017). In the Middle East and North Africa, maximum summer temperatures could increase by 3°C by 2050 and 7°C by 2100, which could also lead to significant migration as people try to escape heat extremes (Lelieveld et al. 2016).



However, because of the numerous factors that contribute to one's decision to migrate, attributing migration to a specific environmental "push" factor can be very difficult. In social-ecological systems, where human and environmental systems interact, environmental changes may create or exacerbate social, political, or economic hardships.

In addition, societal factors may contribute to environmental degradation such that the ecosystem services that were formerly provided by the environment are no longer available (Renaud et al. 2011). Thus, it is rarely straightforward to categorize a person as an environmental migrant or to establish a cause-effect relationship between a specific environmental hazard and a migration event, since environmental factors typically interact with social, political, economic, and demographic factors to influence a person's decision to migrate (Black et al. 2011; Warner et al. 2010; Renaud et al. 2011).

Planning for the impacts of sea level rise has already begun at various locations around the world. While planning efforts in most areas focus on mitigation and adaptation strategies that will allow communities to remain in their current locations, some countries are already considering relocation as the most viable option. For example, in 2014 the island country of Kiribati purchased a 5,460-acre portion of the island of Vanua Levu in Fiji as a potential site for relocation (Tong 2014).

2. Environmental Migration Factors

2.1. Rapidity of Onset

The rapidity of onset of an environmental hazard has major implications for migration (Renaud et al. 2011). Previous research has shown that the migration response to short-term events, such as hurricanes and earthquakes, is much different than migration that results from less-rapid, long-term environmental degradation. In the case of hurricanes or floods, residents are often forced to leave their homes, either due to evacuation requirements prior to an event or in order to escape dangerous conditions and a lack of basic services after an event. In these cases, migration is much easier to attribute to environmental concerns (Warner et al. 2010). The speed of recovery after a natural disaster and the financial resources of the residents affected are important factors in determining whether people will return to their homes and rebuild or permanently relocate (Smith et al. 2011; Gutmann and

Field 2010). Fast recovery and rebuilding often leads to higher rates of return, while slower recovery efforts may dissuade residents from returning and lead to permanent out-migration (Gutmann and Field 2010). In addition, poorer residents may find it more difficult to rebuild and may be permanently displaced (Gutmann and Field 2010).

The frequency and intensity of natural disasters can also affect the choice to return and rebuild or to migrate elsewhere. Warner et al. (2010) observed that people living in the Zambezi River Valley in Mozambique moved temporarily during seasonal flood events before returning to their homes. However, after a series of severe flood events in 2001, many residents chose the move to resettlement areas (Warner et al. 2010). As climate change causes environmental hazards, such as flooding and drought, to become more frequent and severe, a similar pattern may be seen in other areas, where residents who had previously lived with hazards are no longer able to adapt to the increased frequency and intensity of these disruptions.

In contrast to rapid-onset disasters, residents often have more time to weigh social, political, and economic considerations when faced with gradual environmental change or degradation. As a result, the decision to migrate is rarely based solely on environmental conditions (Carr 2005). For example, Carr (2005) describes the migration of residents in a village in Ghana due to a decline in the timber market. The migration was spread over several decades and was influenced not just by a decline in rainfall and loss of soil quality due to logging, but also by social and political conditions in the village. Similarly, the abandonment of Holland Island in Chesapeake Bay due to rising sea levels occurred over a period of approximately 20 years and was completed long before the island became completely uninhabitable, largely because residents who remained on the island were not numerous enough to support community services, such as a school or church, and thus chose to leave as well (Gibbons and Nicholls 2006). While the original decision to migrate may have been primarily due to environmental factors, the final residents who left the island did so mainly due to social circumstances (Gibbons and Nicholls 2006). Some authors suggest that migration in response to gradual change comes only after a certain threshold is exceeded, perhaps marking the occasion when residents can no longer adapt to their surroundings and must leave (Doos 1997; Warner et al. 2010; Renaud et al. 2011).

2.2. Characteristics of Environmental Migrants

Renaud et al. (2011) propose a new framework to describe people who migrate solely or in part as a response to environmental change, taking into account both the temporal evolution of the event and the primary push factors that ultimately lead to migration (see **Table 1**). These include “environmental emergency migrants,” “environmentally forced migrants,” and “environmentally motivated migrants.” Environmental emergency migrants move in response to short-term extreme events to ensure their personal safety and often leave only temporarily, returning when the event has passed and basic services have been restored. For these migrants, the main push factor is clearly environmental, and other considerations play only a minor role in the decision to migrate. In cases where environmental degradation is much more gradual, those who decide to migrate are known either as environmentally forced migrants or environmentally motivated migrants. For environmentally forced migrants, the main push factor is environmental, such as complete inundation of land due to sea level rise, loss of groundwater resources due to salinity intrusion, etc. These migrants cannot return to their former homes unless some sort of adaptation or change in livelihood is available. In contrast to those forced to migrate due to loss of land or environmental services, environmentally motivated migrants choose to move in response to a deteriorating environment, but do not experience an immediate need to relocate (Renaud et al. 2011). For example, a homeowner in Miami may decide to relocate because of frequent sunny-day flooding (flooding not associated with storm events) of his property, even though the property is still inhabitable. Socio-economics play a much larger role for this category of migrants, and those who are wealthier or have stronger social connections may be better able to migrate than those whose resources or social networks are tied to their current homes (McLeman and Smit 2006).

Table 1. Type of Environmental Migrants (adapted from Renaud et al., 2011)

Type of Migrant	Catalyst	Push factor(s)	Type of migration
Environmental emergency	Short term extreme events (i.e. hurricane)	Environmental	Temporary; return when basic services are restored
Environmentally forced	Long term environmental change (i.e. complete floodinundation)	Environmental; socio-economic	Temporary or permanent depending on adaptation measures and economic means
Environmentally motivated	Long term environmental degradation (i.e. nuisance flooding)	Socio-economic; environmental	Permanent

Vulnerability to environmental hazards plays a major role in determining whether residents will stay in their current location and live with a lower quality of life, stay and attempt to adapt to changing conditions, or migrate elsewhere (McLeman and Smit 2006; Warner et al. 2010). Because vulnerability is highly dependent not only on exposure to environmental hazards but also on one's adaptive capacity, responses to environmental change will vary, even among people who experience the same level of exposure (McLeman and Smit 2006). For example, McLeman and Smit (2006) found that tenant farmers who migrated out of Eastern Oklahoma during the Dust Bowl in the 1930s had modest economic means and more extensive social networks that allowed them to find opportunities elsewhere, as compared to poorer residents who lacked widespread social connections and thus had little choice but to stay. In other cases, wealth may help residents to remain in their homes and eliminate or delay the need for migration (Willekens et al. 2016). For example, many adaptation strategies related to sea level rise, such as elevating or waterproofing homes and access to insurance are very costly and are not a viable option for low-income residents. However, wealthier families have the ability to implement these adaptation strategies and may be able to remain in their homes longer. Thus, economic status and social connections play an important role in determining migration behaviour (McLeman and Smit 2006; Smith et al. 2011).

Findlay (2011) suggests that migrants prefer to remain as close to their place of origin as possible, mainly due to social and cultural connections, particularly for international migration as a result of environmental stresses. Therefore, cities in the southern hemisphere are predicted to be the most common destinations for migrants who face environmental degradation in rural parts of the southern hemisphere (Findlay 2011). Hugo (2011) compared predictions for demographic and environmental changes and found that developing countries that are expected to experience the greatest population increases in the coming years are also highly susceptible to environmental hazards and climate change. In addition, poverty is a major concern in many of these countries, which may make residents more vulnerable and less resilient to environmental hazards (Hugo 2011). Thus, the interactions between demographic and environmental change could have significant implications for global migration patterns in the future.

3. Migration Modelling Approaches

A variety of modelling approaches have been used to predict migration behaviour, although fewer studies have attempted to incorporate environmental change as a component of the process. Piguet (2010) outlined several types of analyses that have been used: ecological analyses, which consider group rather than individual behaviour; surveys of individuals; and methods that attempt to incorporate both individual and ecological aspects, including time-series analysis, multilevel analysis, and agent-based modelling. Time-series analysis attempts to discern correlations between historical migration behaviour and other variables, such as rainfall amount and timing, crop yields, etc. These correlations can then be used to

predict future patterns of migration (Kniveton et al. 2008). Multi-level approaches combine individual and ecological approaches with time-series analysis, but have not yet been widely applied in the migration literature (Piguet 2010). Agent-based modelling methods simulate migration behaviour at the level of the individual or family and allow agents to form relationships with each other and to make migration decisions based on a variety of variables. This type of approach can be very valuable because it not only allows for an analysis of individual behaviour, but also can lead to emergent behaviours at the group- or community-scale that would not be discernible otherwise. However, more research into the decision functions embedded within the models is needed to ensure that they can accurately capture real-world migration responses to climate change (Kniveton et al. 2008).

Kniveton et al. (2008) applied the time-series approach to analyse Mexican migration to the U.S. based on rainfall patterns and found a positive correlation between migration and total rainfall in Durango. However, they emphasized that the lack of available data on past migration behaviour and the uncertainty in extending historical correlations into the future are major limitations to this approach. Hauer (2017) used historical time series data and migration systems theory, which considers all possible origins and destinations for migrants, to predict where coastal populations would relocate in the U.S. as a result of sea level rise. The analysis indicated that all states, even those without a coastline, will be impacted by migration due to sea level rise. Some inland areas, such as Austin, TX, Atlanta, GA, and Phoenix, AZ, could receive more than 250,000 in-migrants. This demonstrates that sea level rise will have impacts beyond the coastal communities that experience direct inundation. Other environmental stressors, such as drought, could have similar impacts in terms of changing the population distribution across the U.S.

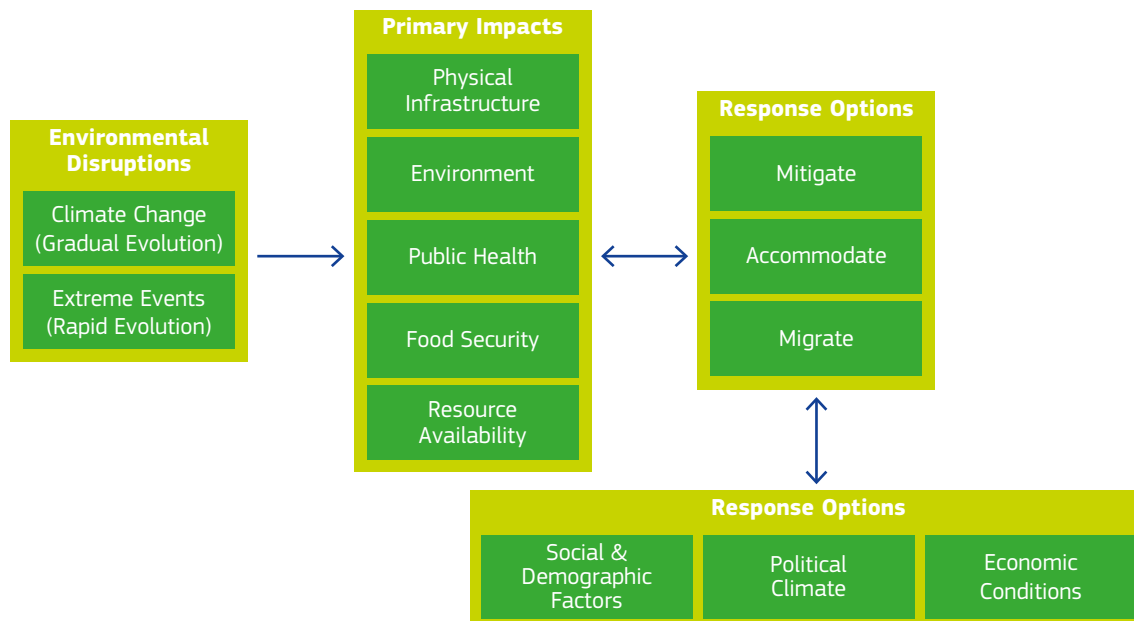
Entwisle et al. (2016) used an agent-based model to simulate migration dynamics in Thailand as a result of drought and flooding. Their analysis only considered the indirect impact of climate change on crop yield and the resulting implications for household incomes, and thus did not directly model residents' responses to droughts or heavy rainfall. While a regression analysis of the data showed a significant migration response to adverse environmental conditions, the results of the agent-based model showed only a small response, suggesting that incorporating socio-economic factors into the analysis, as was done with the agent-based model, may reduce the climate change signal. The authors suggest that the weak signal due to climate change may be a result of the already high migration rates in the area, which suggest that most people who are eligible to migrate are already doing so, regardless of environmental conditions (Entwisle et al. 2016).

4. Developing a Model for the Drivers of Migration

Developing a model of how environmental factors may become drivers for migration will require a system of systems approach to how physical, environmental, economic, and social factors impact the migration process. In order to understand how these interactions may play out, we have developed a high-level conceptual model, which is shown in Figure 1, of how environmental disruptions may impact migration.

Environmental disruptions can come from climate change, which evolve slowly, or can come from punctuated, extreme weather events. These disruptions can result in direct impacts on factors such as physical infrastructure, the environment, public health, food security, and resource availability. The response options to the impacts can involve mitigation, accommodation, or migration and can involve feedback relationships to the primary impacts. The response options can also result in secondary impacts, such as, changes to social and demographic characteristics, the political climate, and the economy.

Figure 1. High-level conceptual model of how environmental disruptions can generate response options that can include migration.



The decision process for migration is a linked two-phase process: (1) “we must go”, and “where shall we go?” As in our introductory example with the government of Kiribati, the goal is to find a location that would be able to support a similar standard of living and similar environmental conditions. However, if the decision to migrate is based on immediate and extreme disruptions, the question often becomes “where can we get to?”, rather than a preferred migration locale. Environmental disruptions do not recognize political boundaries and the need to move away from an extreme event may also necessitate ignoring boundaries, as well as moving to non-optimal locales. This can then result in trading of one migration pressure for another, simply as a reaction to the most pressing factor at the time, and successive moves as migrants react to variable pressures. These evolving situations are not unlike the original crisis that caused the initial move, and are a complex interplay of external forces, met by individual and group capability and bounded by the available set of options.

The following steps can provide a foundation for a phased approach where modelling can inform policy and collective action.

4.1. Determine Locales Likely to Experience Migration Pressures

Numerous studies (e.g. IPCC 2014) have analysed where climate change impacts, such as sea level rise or increased occurrences of extreme events, could be a threat to people. S&P has analysed 116 sovereign countries in terms of their vulnerabilities to climate change. Of the 10 most vulnerable countries evaluated by S&P (S&P 2014), only one country, Fiji, was rated as having high human development based on the United Nations Human Development Index (HDI) (UNDP 2016), with the remaining nine rated with medium to low human development.

Since migration may not honour nor even recognize international governmental boundaries or policies, the ability to predict pressures and strategically shape migration policies or response would support effective mitigation and response. Modelling the interplay between evolving pressures and the capability of impacted persons and groups is the foundation of this targeted effort.

4.2. Assess the Range of Options for Pressured Locales before a Crisis Hits

Through understanding of these pressured locales, options driving the move(s) and both mitigation and response efforts can then be explored and possibly ranked based upon ease and efficacy. This will inform discussions for governments, policy makers, agencies, and residents. Since these decisions are difficult and are often socially impactful and resource intense, a shared understanding assists communities in moving forward (sometimes literally) in the face of unwanted circumstances.

4.3. Develop an Informed Crisis Planning Process

No agency, government, or locality ever has an unlimited pool of resources. Therefore, responses must not only follow an immediacy orientation, but also a longer-term approach toward sustainable communities that are resilient to the ever-changing threats to living standards. It is often in the shift from immediate response to long-term rebuilding of community that efforts experience roadblocks, as the overall goal expands and efficacy of the effort becomes less definitive (e.g., applying a bandage versus improving the overall health of the system). As an example, the City of Miami is investing in a re-engineering of a number of coastal city blocks by raising the roadbeds several feet and installing more advanced drainage systems.

5. Conclusions

Modelling of migration is an important tool in the international policy arsenal, as it creates information for governments, policymakers, and communities to make informed choices and target resources most effectively. Understanding the triggers of migration can help prepare communities for potential migration events and the requirements needed to facilitate easy transitions, both temporarily and permanently.

The circumstances surrounding an environmental migration are linked to not only the severity of environmental events, but also to a plethora of physical, socio-economic, and cultural stimuli that influence individual decision-making. In this paper, we have presented a conceptual model of how environmental disruptions can operate on these stimuli to generate different response options, including the decision to migrate. We are continuing to expand the conceptual model, define the relevant processes that would be represented at the algorithmic level, and outline how to implement them at the computational level. One of the challenges that exists in developing a simulation of this kind of system is that the required physical, environmental, socio-economic, and cultural processes operate at different physical and temporal scales. The ultimate goal of the effort is to provide communities with a better understanding of the potential impacts surrounding an environmental event, so they will be able to prioritize response and recovery actions that might include the permanent relocation of displaced populations more effectively.

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The Resilient Bow-tie and Decision-Making under Uncertainty

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Abstract

The Dutch National Institute for Public Health and the Environment (RIVM) uses bow-ties for evaluating major hazard and occupational risk. The bow-tie is a well-known model in risk assessment for quantifying risk and prioritising risk reduction. Outcomes are linked to causes and the approach is to identify ways to eliminate or reduce causes that result in the realization of the risk e.g. the release of a hazardous chemical and its subsequent effects on workers, the public and the environment. It has been argued that risk assessment is a reactive approach that fails to address the positive aspects of the human resource. Humans are necessary for supporting the flexibility required in complex changing environments typified by interactions, variability in conditions and weak signals of potentially important events. In a European SAFERA project “*Success in the face of uncertainty: human resilience and the accident risk bow-tie*” a start was made on developing the success components of the risk bow-tie. This served as a basis for understanding and developing approaches to resilient performance in recovering from situations that could otherwise have been disastrous. Disasters are frequently triggered by a surprise, something unforeseen. In the success bow-tie resilience was incorporated as an aspect of interventions in response to such unexpected events. This aspect reduces the uncertainty associated with achieving a successful outcome, thereby increasing the chance of success. The results of this SAFERA project were further developed for the purpose of bringing resilience into practice with the use of workshops and tools. One approach that is being developed with the help of safety professionals in the Netherlands is a serious game that can be applied to situations of decision-making under uncertainty and limited time.

Keywords

Bow-tie, safety, resilience, uncertainty, serious game

1. Introduction

1.1. Risk assessment and failure

For industrial hazards which threaten workers, the public and the environment a certain level of protection is expected to be in place. There are regulatory requirements for prevention and for dealing with events that could arise if prevention fails. Risk assessment is one way in which failure scenarios can be understood and managed. In the Netherlands a prescribed method for quantitative risk assessment (QRA) of chemical plants is used for land use planning. The method groups possible scenarios into a limited number of categories covering the foreseen risks (Uijt de Haag et al, 2013). There is also an occupational risk assessment tool, WebORCA (RIVM, 2008) and a set of bow-ties (36 occupational hazards & 1 major hazard loss of containment bow-tie). Together these databases currently contain around



30,000 accident scenarios (event sequences) developed from detailed reportable accident investigations by the Dutch Labour Inspectorate. The bow-tie models are constructed from safety barriers in a tool called Storybuilder™ (Bellamy et al, 2008, 2013). The data enable detailed qualitative and quantitative analyses to be made of barrier failures, failures in human tasks that directly relate to the barriers and underlying management factors which deliver resources to these tasks. Identification of hazards and risks are needed in order to be able to prioritise risk reduction and manage the remaining risks. As the European Agency for Safety & Health at Work state – “Risk assessment is the cornerstone of the European approach to prevent occupational accidents and ill health”.³³

1.2. Resilience, uncertainty and success

Recently risk assessment and the approach to addressing safety through analysis and avoidance of failure has been criticised by technical and human engineers working in the safety field for focussing solely on failure avoidance and not also addressing successful responding in the normal functioning of socio-technical systems (Hollnagel et al, 2011). Resilience Engineering (RE) defines (safety) success as “the ability to succeed under varying conditions” and concentrates on how adjustments to changes and disturbances sustain operations. RE is particularly popular in areas like transportation (aviation and railways) and healthcare (patient safety) sectors. Systems, like Air Traffic Control, are considered to be too complex and dynamic to be sufficiently addressed by classical risk assessment (Hollnagel *et al*, 2013).

Risk assessment uses historical (and in its absence also expert judgement) data, which do not exist with new and emerging risks and with increasing uncertainties like those in these dynamic and complex systems. Leveson (2017) explains that systems can fail without component failures due to emergent phenomena of complex interactions. With unpredictable futures, and ones that could even be made worse by risk-based actions, Ramírez and Ravetz (2011) suggest that “scenario planning” (Wack, 1985a, 1985b) is needed to address the hitherto unthinkable. Scenario thinking, simulation to support decision-making and signal watching for early detection are approaches to uncertain futures suggested by a number of authors (Brooker, 2010; Dinh et al, 2012; Paltrinieri et al, 2012). When considering safety strategies, the heart of resilience from the perspective of the human component

³³ <https://oiraproject.eu/en/what-risk-assessment>

of the system is to understand as much as possible the complexities and uncertainties and to be prepared for what that may deliver in order to maximise the chance of success. Mountaineers, for example, might be considered to be very reliant on resilience. This can be contrasted with normative management systems like the major hazard (petro)chemical processing industry where the human component largely follows procedures in a standardised technical environment with automated supervisory systems. However, even when replaced by automation humans still have a role in adjustment and recovery, except that it can get even more complex. This is the irony discussed in the timeless paper by Bainbridge (1983) – the more advanced the control system the more crucial the contribution of the human operator.

Resilience and uncertainty from a human perspective was addressed in a SAFERA (European ERA-NET) project which continues its aims to provide a research coordinating network in the area of industrial safety³⁴. **Success In The Face Of Uncertainty: Human Resilience and the Accident risk Bow-tie** (Resilience Success Consortium, 2015), or “SITFOU”, was one of the first coordinated projects to be undertaken, starting in 2014, and had a multidisciplinary research team³⁵ with expertise in risk assessment, human factors, crisis management, and in the areas of modelling occupational and major hazard risk.

Using the “four cornerstones of resilience” as a basis (Hollnagel, 2009) - anticipating, monitoring, learning and responding - common human and organisational Factors (HOFs) were identified from 350 pages of transcribed interviews from top professionals working in major hazards, dangerous maintenance, and mountaineering and coming from the Netherlands, Belgium, France, UK, and Denmark (Van Galen & Bellamy, 2015). Amongst these were production and process managers, HSE professionals, and process safety specialists from installations falling under the Seveso Directive (EC Council 2012). They provided their perspectives on handling uncertainties in relation to unforeseen and uncertain circumstances, in their case concerning the possible release of major hazard (petro)chemical substances. In the different circumstances of mountaineering and dangerous maintenance (using rope access in difficult locations) similar HOFs could be identified from the case studies as the positive shapers of uncertainty-reducing interventions for unforeseen changes and deviations.

In SITFOU, resilience was considered as *the ability to increase the chance of a successful recovery or adjustment to deviations through uncertainty reduction*. The SITFOU project pioneered a success bow-tie which could be used to evaluate successes under different levels of uncertainty and where the centre event of the bow-tie is successful intervention. Like the failure bow-tie, this can be used to collect scenarios but with the purpose to improve the monitoring of success and the understanding of recovery under uncertainty. The difference between a failure and a success bow-tie is explained in section 2 of this paper.

Section 3 then describes the implementation in practice of the results of SITFOU by involving users from Dutch industry. Implementation was facilitated through the development of simple practical tools as well as networking events, initiated and managed by the Centre for Safety of the Dutch National Institute for Public Health and Environment (RIVM). The key aim was to bring the exploratory results into practice in response to the interest in resilience shown by Dutch safety professionals and the perceived lack of tools. The tool of interest in this paper is a serious game which can be used to help train people to understand uncertainty and analyse situations to support decision-making and to better understand the nature of near miss type successes.

³⁴ <http://www.safera.industrialsafety-tp.org/>

³⁵ White Queen Safety Strategies, NL (coordinator); NCSR Demokritos, GR; Technical University of Denmark, DK; Anne van Galen Consultancy, FR

2. The bow-tie as a model for both normative and resilient safety

The understanding and representation of risk has many different models of which the bow-tie is one (see Figure 1). This is a graphical model which is not only important for understanding and improving the control of risk but also for communicating about risk. The bow-tie has been used since the 1970s to represent causes and effects of critical failure events in risk analysis, particularly in high hazard industry such as at Shell's Pernis refinery (Zuiderdijn, 1999). Bow-tie models may specifically incorporate the failure of safety barriers as a way of modelling accidents (Duijm, 2009; Papazoglou et al, 2017) and for analysing near misses (Ansaldi et al, 2016). The centre event of a bow-tie might be quite specific or quite general. That event is the release of some kind of hazard-agent with various possible consequences.

Figure 1. Failure bow-tie

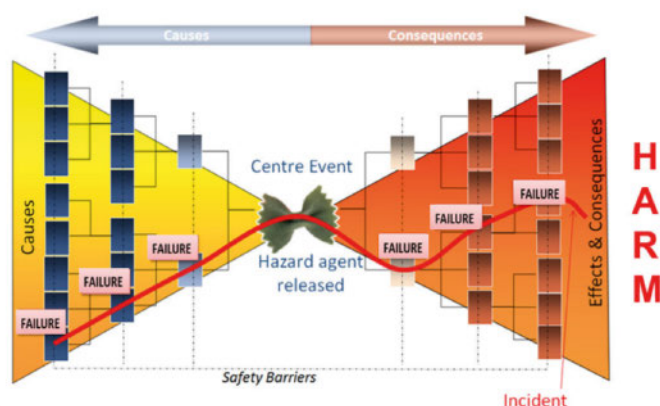
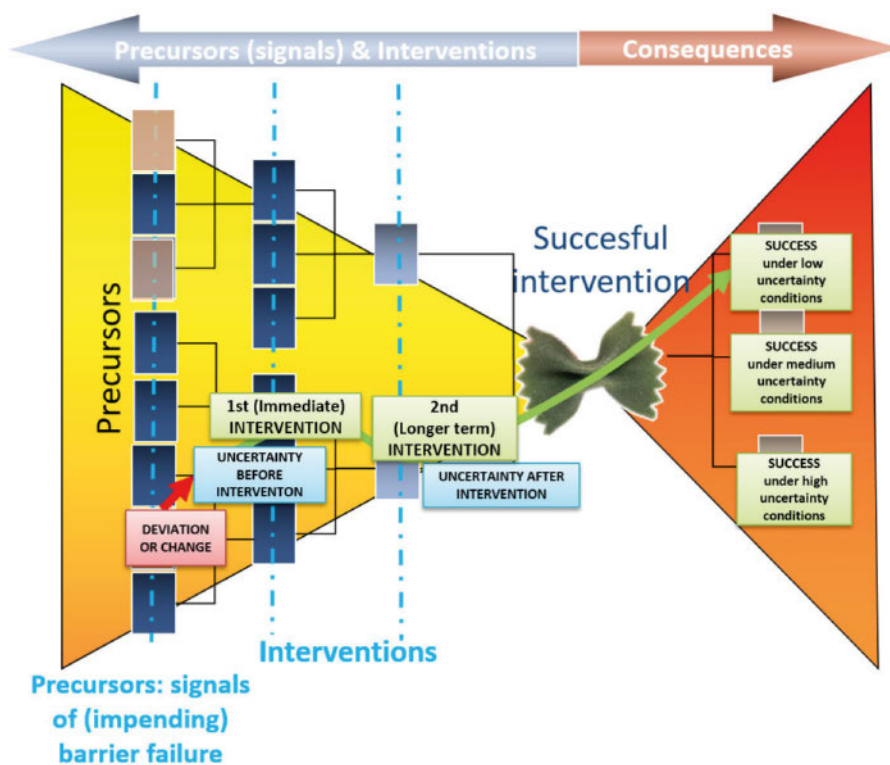


Figure 2. Success bow-tie



The underlying model for successful intervention is also a bow-tie, initially developed in the SITFOU project, where it was used to analyse a near miss database (Resilience Success Consortium, 2015). The broad framework of the success bow-tie is shown in Figure 2. The centre event is not a failure but a successful intervention leading to success under different levels of uncertainty conditions. It is intended to capture reported sequences of events that occur in so-called near miss or recovery scenarios triggered by a deviation or failure event (precursor) that ends in success (no harm and continued functioning of the system). In the success bow-tie pure luck would be represented by an outcome of success under a very high level of uncertainty. A success outcome is considered more likely the more the uncertainty is actively reduced in the process of intervention. The bow-tie structure captures the nature of the detection of the deviation or change, the evaluation of options and the selected response, including identification of any resilient components in the process which contribute to uncertainty reduction. A successful outcome under conditions where uncertainty has been reduced to low or medium is distinct from a success where there were large uncertainties but no attempt or possibility to reduce them. In practice the different types of success may be indistinguishable, which renders success particularly dangerous because it gives the message to go on doing the same.

The difficulty of distinguishing resilience from luck is well illustrated in the report of the ditching of a plane on the Hudson River where “the investigation revealed that the success of this ditching mostly resulted from a series of fortuitous circumstances” (NTSB, 2010 p.79) whereas the pilot acquired hero status for his miraculous recovery after the loss of both engines.

3. Resilience implementation project

3.1. Cards and strategy

The identified HOFs from the SITFOU study were developed as a set of cards containing pictures and short text descriptions for use in a serious game (see Figure 3). The game simulates a decision dilemma with a group of people who play different roles in the team. The aim is to reduce the uncertainty in the process of deciding on a response and how that will be monitored during its implementation. The players talk about intervention scenarios in uncertain situations (case studies) and use the cards as descriptors for properties of the decision process as subtitles to the steps taken to decrease time pressure and reduce the uncertainty. Time and uncertainty cards are numbered 1-6, which are coupled to the model described in the next section and shown in Figure 5. Decision dilemma cases are provided by the safety professionals, taken from their own experience, but could also be developed from bow-tie data. The *Resilience Card Game* contains 57 cards and is used together with a storyboard which takes the players through the five steps shown in Figure 4 and provides a structure for laying out the cards.

Figure 3. Examples of cards in the Resilience Card Game (by permission RIVM)



Figure 4. The five steps (by permission RIVM)

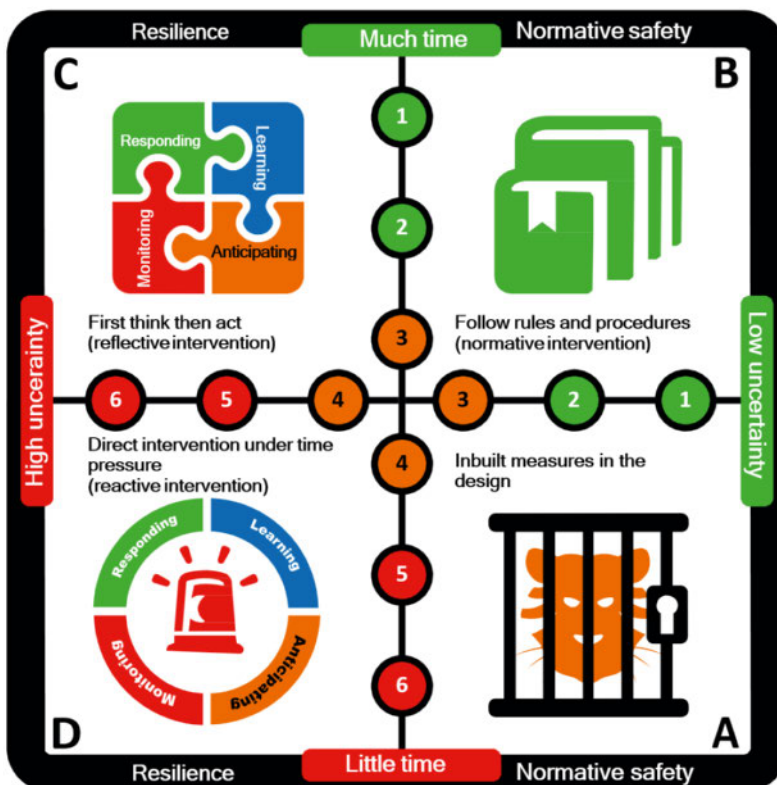


3.2. Resilience versus normative strategy

For the serious game, the model in Figure 5 was elaborated from SITFOU. The traditional approach to safety is to learn from failure and then to implement that learning through rules and regulation, technical and management standards and inspections, and the updating of models with new data and understanding. This normative approach is about controlling foreseen risks. Here signals indicate to a person what rule applies (IF-THEN). New signals (change) or surprise outcomes can suggest that a different form of responding is needed. Decision-making dilemmas may arise or signals may be ignored. Phenomena may be encountered that have never been seen before or not predicted by models. The decision-making process in the serious game is intended to focus on these kinds of uncertain situations where the normative approach does not apply. For example, when a petrol storage tank overflowed at the Buncefield oil storage depot in the UK in 2005, a massive explosion generating unexpectedly high overpressures resulted (Health & Safety Executive, 2008). The accident illustrated how humans are very good at ignoring signals of change and not resolving uncertainties. Operators treated the multiple persistent failures of the level gauge in the tank in a normative way. In a low uncertainty (foreseen) situation responses can be specified by procedures. However, under high uncertainty (in this case the unknowns of the repeated level failure) resilience may be required to find the best intervention option. These two situations, low uncertainty and high uncertainty, require different strategies.

Figure 5 distinguishes between resilience and normative safety. The figure shows two dimensions, uncertainty and available time, providing four quadrants for the ways in which safety is handled in these different combinations. When uncertainty is low and risks are foreseen then Quadrant A and B interventions apply. In Quadrant A, inbuilt interventions (like early warnings, shut off systems and back-up power) buy time before more serious consequences ensue. Quadrant B reflects normal day to day operations that can be handled by standard approaches in response to known signals. Ideally in cases of uncertainty when signals of change are detected it is possible to move to Quadrant C, with time available to think out scenarios and options. In rapidly developing scenarios Quadrant D applies.

Figure 5. Resilience-Normative Quadrants (by permission RIVM)



The quadrant model can be used to characterise different safety strategies, organisations and scenarios depending on the uncertainties and the response times available. For example crisis responders could be considered to be predominantly Quadrant A & D types. Major hazard companies are strong on A and B but still face uncertainties where they need to be in C and on rare occasions end up in D.

The uncertainty line does not specifically refer to a range of variability uncertainties and can include scenario uncertainties and recognised ignorance which cannot be assigned probabilities, as in the spectrum provided by Walker et al (2003) that goes from complete determinism (impossible ideal) where everything could be foreseen to total ignorance where foresight is impossible. The numbers on the axes in the quadrants are simply to enable players to express their feelings of uncertainty about a situation and are not anchored in anything specific. The same goes for time pressure. The quadrants are used in the serious game to track the progress of decision-making against the uncertainty-time axes. Being faced with a decision dilemma under uncertainty, the idea of the game is to gain time and then reduce uncertainty in making the final selection of an option. Because the game has to be played as a team, with players taking different roles and having different individual perspectives, the players also experience challenges to their established views and experience, including confronting the dangers of cognitive bias (Kahneman, 2011) such as anchoring on a first piece of evidence arising in a scenario or accepting the first suggested plausible solution (Tversky & Kahneman, 1974).

4. Summary

A serious game has been described that trains people to understand the properties of a successful intervention through a multi-perspective collaborative approach to uncertainty reduction in a decision dilemma. That dilemma has to be a case where the normative management strategy no longer applies because of the uncertainties and so the intervention needs to be resilient. The issues involved in the game are also set in a more formal modelling perspective, the bow-tie, which can be used for data collection and analysis of real life successes in support of learning more about the success phenomenon.

5. Acknowledgements

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Method RM2: A different way of assessing Resilience³⁶

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Abstract

The constant variation of the Environment (in its largest sense) where a system works, makes each system unique and different from the rest. Those variations may be caused by Disruptions of different nature (from normal accidents to black swans, passing through deliberated acts, acts of God or events related to climate change) but finally all of them impact directly the functionality level of the system because the disruption will modify the system's level of performance.

Usually, the consequences of those disruptions are slight modifications of the *operating level* though remaining in the *Tolerance Range* (i.e. the space between the *theoretical operating level* or the attended performance of the system and the *unacceptable level* or the performance level where the service delivered by the system is under the threshold accepted by the stakeholders). Yet, sometimes, this *Tolerance Range* is reached and the *operating level* falls and crosses the *unacceptable level*. Then the service delivered by the system is no longer ensured.

After years looking for systems able to cope with all kind of possible disruptions, reality has demonstrated that it is impossible: ZERO risk does not exist. So, how are we able to deal with all those disruptions? The answer is to enhance the resilience of the system. Now the next question is: how can we enhance something that is an abstract capacity of a system? Or how can you choose amongst the different available solutions the one that will best upgrade the resilience of the system?

Nowadays, the most common approach to assess the resilience is to consider it as an equation between the loss of the system's performance and the time needed to come back to the *Tolerance Range* after the impact of a Disruption. In this calculation, the smaller is the result the better is the resilience.

Nevertheless, this approach does not consider the different stages of a disruption and following facts: the system's resilience might have prevented the disruption; if it happened, the loss of performance remained inside the *Tolerance Range*; or the disruption itself created a new Environment where the *theoretical operating level* is no longer accepted by the stakeholders.

The RM² method takes a different approach that allows comparing the resilience between similar or different systems because each one is analysed with regards to its own Environment in a determined moment. This assessment method is based on the four **notions** of the Resilience (Resistance, Means, Rapidity and Memory), grouped in two pillars: the first two notions (Resistance and Means) are grouped in the **Material Pillar** and the second ones (Rapidity and Memory) in the **Intellectual Pillar**. This method analyses how each notion acts in each of the disruption's stages. This method, besides establishing a level of resilience, also allows to detect if one of the notions is less developed than the others or if the treatment of one of the stages of the disruption needs to be reinforced.

Keywords

Resilience,
Assessment

³⁶ The present article is based in the author's Masters paper.



1. Introduction

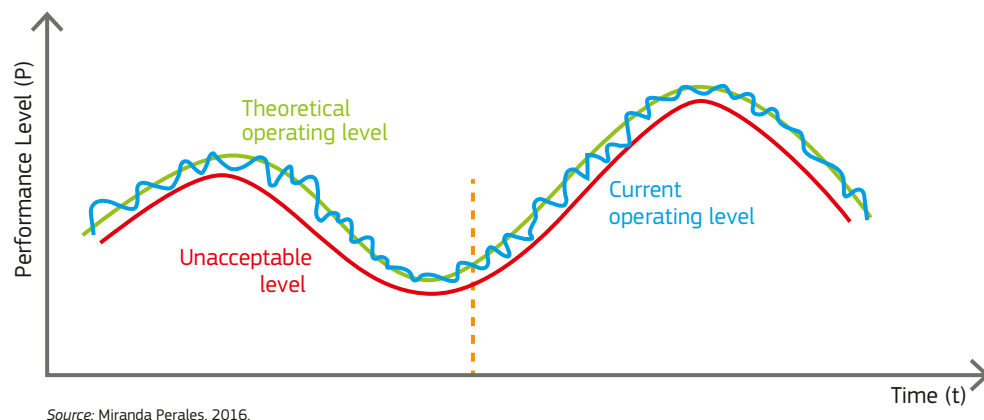
Answer specific needs in a specific moment. To facilitate this answer men create systems of all kind (from very simple as harbouring wild trees to very complex like autonomous cars). All of those systems are designed to achieve a certain Performance level (P) in one specific moment over the time, but the needs evolve over the time.

As needs evolve, the Performance level of the system might require adjustments in the system itself. Nevertheless, those adjustments are usually predictable and happen quite smoothly.

Besides these current adjustments, systems have also to deal regularly with all kind of disruptions. The origin of those disruptions can be external to the systems or come from the interior; they can be done on purpose or because of a system failure; and their source can be linked to acts of Gods, climate change or be caused by men. These disruptions are treated in the day-to-day operations of the system.

Figure 1 shows the fluctuations of the Performance Level (P) over the time. The **theoretical operating** level is in black, and the current operating level is represented in blue. A third level is also represented below the theoretical level. This level in red identifies the point where the performance of the system is below the expected level, it is the unacceptable level. Operating modes located between the theoretical level and the unacceptable level will be those typically considered as degraded modes of operation.

Figure 1. Different levels of performance



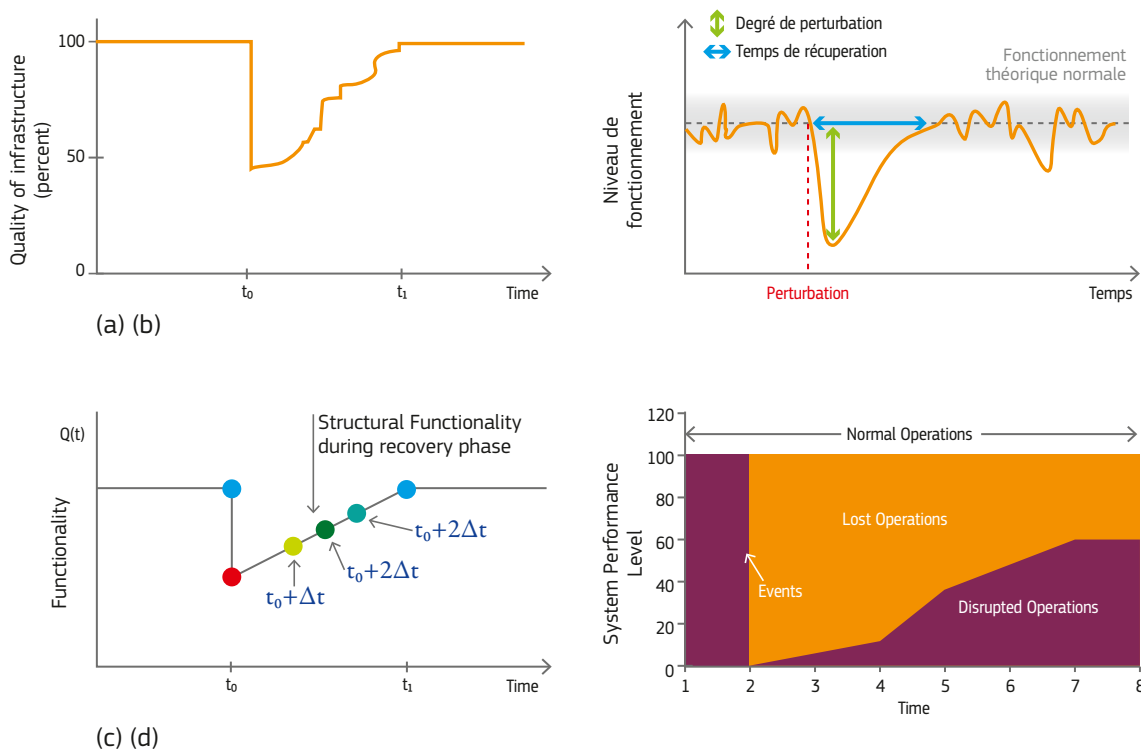
In order to prevent the current operating level to fall the unacceptable level an increased resilience of the system is in now days considered as the solution.

1.1. Achieving Resilience

Once Resilience has been defined as the solution, the next step was to identify a way to measure it in order to take the actions needed to improve it.

Authors in different areas have tried to find a way to represent resilience. Bruneau et al. (2003), Moteff (2012), Toubin et al. (2012) Caverzan and Solomos (2014), to mention just a few, consider resilience as a function more or less mathematical, that will look at the evolution over time of the system's level of performance, as shown in Figure 2.

Figure 2. Examples of Resilience representations



Source: (a) Bruneau et al.,2003 (b) Toubin et al.,2012 (c) Caverzan and Solomos, 2014 (d) Moteff, 2012

Another main characteristic of these way of assessing resilience is consider that, once the disruption has finished, the system must recover the same operating level as before the disruption.

In the end, in those approaches resilience is a surface defined by the amount of performance lost and the time needed to recover the original level. The smaller the area, the higher the resilience.

But considering the time and the loss of performance, those models and methods only allow to measure the consequences of a disruption, and only in a partial way. They cannot take into account that the system's resilience could have:

- avoided the arrival of the disruption,
- reduced the impact of the disruption to not cross the unacceptable level,
- allow the system to adapt to the new environment reshaped by the disruption.

Another weakness of those approaches is that they cannot take in account the system in its own environment. A system, placed in different environments and facing a similar disruption, does not necessary have the same resilience.

So, it might be interesting to have a resilience assessment method that both allows considering the system and its environment and also gives an objective information that will facilitate the decision making.

2. Redefining Resilience / Pillars and Notions

A common problem appears when trying to measure the Resilience: the right definition of Resilience. Almost each sciences corpus has its own definition, and there might be slight or wide differences from one definition to the others. In 2003 Bruneau et al., trying to establish an assessment method, considered 4 criteria as necessary to obtain Resilience Performance.

This approach by criteria allows every science to adapt the resilience definition of resilience. But when those 4 criteria are confronted to existing definitions of Resilience they appear to be incomplete. By extracting the principle concepts and ideas of those definitions, it seems that the choice of 4 criteria was correct because 4 notions or family of ideas get shaped.

These notions are:

- Resistance.
- Means.
- Rapidity.
- Memory.

They can be grouped two-by-two in 2 Pillars of the Resilience, the **Material Pillar** and the **Intellectual Pillar**. The first one will deal with the elements deployed to obtain the resilience of the system. The second one will concern the information needed to better use the Material Pillar.

2.1. Resistance

Resist, absorb, suffer, face, accept, mitigate, suffer, bear, continue to look, reinforcement, persist, project robustness, redundancy, maintain, future protection, minor impact, anticipating, withdrawal, prepare, respond, recover, collect, continue, cope, etc. The notion of Resistance gathers all the words mentioned previously. It has a static connotation but still with reference to an idea of strength and capacity to cope with disruptions without stopping to provide the service required.

Resistance will refer to the various measures taken during the conception of the system. It will be shaped mainly on assumptions and scenarios set before the disruption occurs, because these hypotheses will define the protective measures to be taken.

Their principal objective will be the reduction of the probability of the disruption to occur. This will be done through prevention, risk analysis, management and implementation of protection measures. When a disruption happens, the Resistance will try to ensure, in a more or less degraded way, the functionality of the system. Once the disruption is over, there is a need to assess and remedy damages to correct the points which could not contain the disruption, and to strengthen the points which could have been exceeded if the disruption had requested.

The weak point of Resistance is its rigidity and difficulty to evolve over the time. Once the different hypotheses are set, amending them usually means large investments. If conception errors or sudden environment changes happen the system struggles to adapt.

2.2. Means

Resource, bounce back, recover, walk to the origin, return, react and adapt, recover, restore, recovery, spirit of initiative, competence, move forward, overcome, resume, to identify, return, respond, redundancy, maintain, reorganise, move towards the conservation, , degraded mode, retrieve, renew, etc.

The notion of Means would go along with the words mentioned previously. They could also be called the resources. It encompasses all necessary means to ascertain that the system is able to keep working over the unacceptable level. It refers to the provision and deployment of technical, human and material resources both physical and intellectual, financial and organisational, in their broadest sense.

This concept has a dynamic nature which refers to the measures or actions to prevent the disruption to occur and minimises its impact when it happens. The objective is the reduction of the consequences of disruption over the system functioning by forecasting and planning of protective measures as well as crisis management.

When a disruption happens, Means will make possible to continue with the foreseen contingency plans and remedy the damages caused to the system that Resistance couldn't absorb. They will be the cornerstone for the survival of the system when the disruption happens, since they must also allow the system to adapt to unknown situations.

Their weakness is their requirement of availability at any time and in the need for adaptability. The moment of arrival of the disruption cannot always be predicted and at the same time the protection means foreseen are not completely adapted. The fact that Means must be permanently available requires everybody to have a thorough knowledge of the system and what it should do.

2.3. Rapidity

Speed, without long periods, speedy, automatic, rapidly, reduced time, be prepared, best delay, trained, etc.

The notion of timeliness refers to the need that the system has to shorten the time needed to recover an expected performance level. This time span is fully dependent on the Material pillar because the recovery time is tightly linked to the hypotheses defining Resistance and the Means allocated.

Its weakness lies the establishment of the recovery time. This time is fixed by conceptual approach and it's determined by the functionality of the system, its kinetics and the impact that the loss of the system may have on other systems. Benchmarking is possible in similar systems; however, but it is only the disruption who will validate the choice made.

Once it has finalised, it is necessary to verify whether adjustments are necessary. If the recovery time should be amended, revisions and adjustments shall be provided at the Material pillar, both at the level of Resistance and Means.

2.4. Memory

Increase skills, adapting, learn, develop capacity, previous experiences, overcome, exceed, enrichment, improve innovation, anticipation, memory, rebuilding sustainably, prepare, trained, informed, lessons learned, etc.

The notion of Memory completes Rapidity. It will seek, by permanent observation of recurrent adjustments of the system, at drawing lessons aiming a fairer response time determination, because these adjustments provide a vision of what might happen.

Another source of teaching is the ability to learn from own mistakes and those of others, failures or near accidents, periodic tests and return of experiences because we learn better with trial-error approach than successfully doing at first time.

These sources of education, largely internal to the system should be involved in a third source, external, that is the exchange between peers. Similar systems should have the same problems, but their environment and functioning methods may be different. These differences force them to adapt in different ways.

The weakness of Memory is that is time-consuming. It is difficult to have a short-term return, since Memory is projected in the medium or long term. In order for it to be effective when the time comes, it is necessary to have discipline to learn from small frequent errors. Petit et al. (2014) explain that drawing the right lessons of those situations means having a team with personnel possessing expertise in multiple areas, and it takes time.

This approach needs to be complemented by adequate organisational culture and rapid alert mechanisms in case of disruptions. For these mechanisms to be truly effective, the people who activated them must be recognised if they were right, but shall not be punished if the contrary (Sehffi, 2007). The combination of both two approaches will be beneficial to the human intelligence of all stakeholders which will have a positive impact on the performance of the system.

3. Method RM² for resilience Assessment

Once the concept of Resilience has been determined, and having in mind the fact that it can intervene in any of the 3 phases of the disruption, the next step is to establish an assessment method that is taking in account these elements and allows the comparison of different systems having similar function.

Assuming that a resilient system will be able to cope with any disruption at any time, this will mean that two systems with a similar index of resilience (I_r) should be equally valid while choosing solution. Nevertheless, this assessment corresponds to a specific moment in time and the Performance level in that moment.

3.1. The index of resilience (I_r)

The index of resilience (I_r) is the result of the questioning the system in determined moment. It is the result of the analysis of the four notions of resilience, identified previously in the light of the existing environment at that time. We can easily agree that a resilient system will have an index of resilience (I_r) = 1.

As previously established, each pillar is complementary to the other, and in the same manner each notion, within each pillar, is complementary to the other. This complementarity of notions is justifying the choice to assume that each concept represents 25 % of the index of resilience.

Each concept must be analysed with reference to the various stages of the disruption. Each of the three phases will have a similar importance in the resilience of the component.

The phase (*bfr*), before the disruption happens, corresponds to all the measures taken to avoid the disruption and to verify that the initial assumptions in relation to the environment have not change.

The phase (*drg*), during disruption, needs to observe if the measures planned remain valid with regards to the current environment and if they will be able to prevent the system to cross the unacceptable level. This evaluation needs to be done having in mind the performance levels required at this moment.

The final phase (*aft*), after the disruption, is necessary to the system evolving. It will take into account planned performance developments. These developments will occur following programmed upgrades, but they may also be engaged following a disruption.

Predicting disruption and understanding how the environment is changing will lead to the appropriate measures to be taken in the recovery phase to develop the system. This is necessary because the system might now operate in a new environment for a different level of performance. Once returned, the running phase after the disruption is becoming a new phase before (*bfr*).

The importance of each of the stages justifies the choice to consider that they contribute in an equivalent manner in the index of resilience determination.

After determining how the concepts and phases of the disruption affect the index of resilience, we can by combining them, establish the method of calculation of the index of resilience, as detailed in Table 1.

Table 1. Table for calculation of index of resilience (I_r)

		RESILIENCE			
		Intellectual Pillar		Material Pillar	
		Resistance Re	Means Mn	Rapidity Ra	Memory Me
DISRUPTION	Max.	1/4	1/4	1/4	1/4
Before the disruption	<i>bfr</i> 1/3	Re_{bfr}	Mn_{bfr}	Ra_{bfr}	Me_{bfr}
During the disruption	<i>drg</i> 1/3	Re_{drg}	Mn_{drg}	Ra_{drg}	Me_{drg}
After the disruption	<i>aft</i> 1/3	Re_{aft}	Mn_{aft}	Ra_{aft}	Me_{aft}
Index of resilience (I_r)		1			

Finally, the table is filled out with the data obtained by consulting the stakeholders (from newcomers to top management) and having their point of view with regards to the state of the system. The larger and wider the consultation, the fairest the results will be.

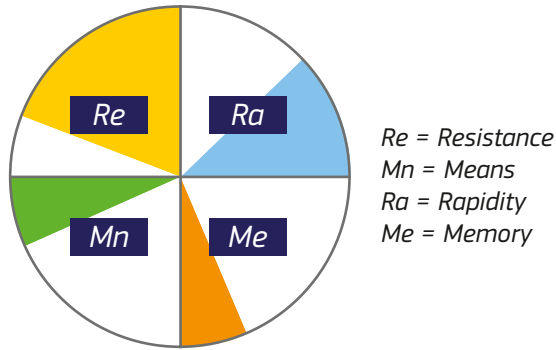
3.2. Representations of resilience

In order to have a better view of the resilience of the component, the results obtained in Table 1 can easily be graphically transformed into a model that will reflect the status of each notion. This index of resilience will take the form of a circle divided into four quarters, a quarter by concept. In the light of the results obtained following the assessment of each notion every quarter will be filled proportionately.

3.2.1 Simplified representation

To establish this representation recovers the results of each concept, and converts them into an equivalent area for each quarter, as shown in Figure 3. This type of representation gives a general idea of the level of resilience of the system at a given time.

Figure 3. Simplified representation

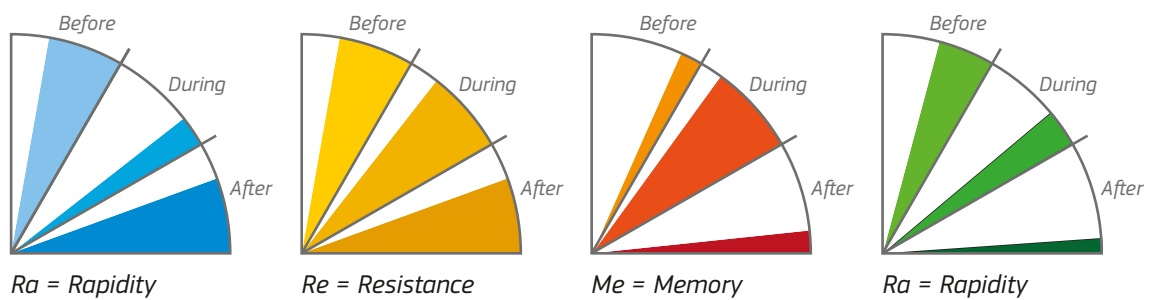


3.2.2 Detailed representation

The detailed representation requires to take into account all the results obtained by the analysis of each notion in relation to every phase of the disruption. In this representation, each quarter is divided into three sectors, each corresponding to one third of the surface of the quarter. Depending on the outcome, each sector will be filled proportionately as represented in Figure 4.

Thus, representing each concept has the advantage to identify not only the concepts to improve, but also the phases of the disruption which are less taken into account.

Figure 4. Detailed model



4. Conclusion

This method of resilience assessment allows decision makers to easily have an idea of the state of the system and to identify where reinforcements must be done. Further works need to be done to establish, for each value of the table of calculation, an objective data acquisition. Once the acquisition method is adjusted, the final step will be the confirmation of the “weight” of each notion and each phase in the calculation of the index of resilience.

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Classification models for the risk assessment of energy accidents in the natural gas sector

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Abstract

Several initiatives have been proposed nationally and internationally to collect information on accidents in the energy sector, assuming that a detailed, integral and targeted analysis of them can reveal the weak points in the energy infrastructure. The influence and relevance of the descriptors (e.g., country, energy chain, infrastructure type) of energy accidents on the outcome, such as fatalities, has so far not been performed on a comparative basis. This paper presents the first attempt to explore these relationships. Furthermore, it contributes to the resilience literature by exploring the capacity of an energy accidents dataset in storing and retrieving information on past events to tackle the forthcoming ones with more awareness of the possible impacts. This research employed a knowledge extraction method (i.e., rough set analysis) to analyse data on energy accidents for natural gas from the most authoritative information source for accidents in the energy sector, i.e., the ENergy-related Severe Accident Database (ENSAD). The main goal of this paper is to show that the rough set analysis can have a substantial contribution in understanding (i) the capacity of the structure of ENSAD to distinguish the accidents with respect to objective measures of outcome; (ii) the decision rules that clearly and simply explain the combination of attributes' values and outcome, in this case fatality ranges; and (iii) how the rules can guide the decision-making process when there is an interest in knowing which class (i.e., low, medium, high) of fatalities an energy accident with a specific set of descriptors could have.

Keywords

Risk assessment;
Energy accidents;
Rough sets;
Decision support;
Classification.

1. Introduction and aim of the paper

Energy is a necessary commodity that billions of people use daily to meet basic needs such as cooking, warming, cooling and transportation (IEA 2016). Several types of disruptions can undermine the reliable and efficient provision of energy and thus decrease the possibility of satisfaction of such needs as well as cause health, environmental, economic and social impacts (Burgherr and Hirschberg 2014). These disruptions can affect energy systems as well as community resilience and they can be triggered by different causes, such as man-made (e.g., lack of maintenance), technological (e.g., collapses of an infrastructure) and natural (e.g., earthquake, floods), resulting in events such as explosions, fires and release of toxic substances. These detrimental happenings can have negative outcomes that can be characterized in multiple forms, including fatalities, injuries, evacuees, ban on consumption of food, release of toxic substances and economic losses (Burgherr et al., 2015, Sovacool et al., 2016). A few initiatives have been proposed to consistently collect information on accidents in the energy sector, by employing descriptors that include the location of the accidents, the type of energy



chain and infrastructure as well as the type of detrimental events (Burgherr et al. 2015, Sovacool et al. 2015, Sovacool et al. 2016). Sovacool et al. (2015) proposed a dataset of 1085 energy accidents for 11 energy systems over the period 1874-2014. The Energy-related Severe Accident Database (ENSAD) of the Paul Scherrer Institute (PSI) has been developed since the 1990s (Hirschberg et al. 1998) and currently includes 32,963 accidents covering multiple energy chains and their whole life cycle (Burgherr et al. 2017). The online Major Accident Reporting System (eMARS) of the European Commission contains information on over 700 industrial accidents and near misses involving dangerous substances (JRC 2017).

The development of datasets such as the one above described is necessary to guarantee that consistent and comprehensive information is available on the accidents that took place along the life cycle of each energy chain. They have been analysed so far through statistical methods looking at frequencies of events, ranges of fatalities, released of fuels and cost of accidents (Burgherr and Hirschberg 2008, Sovacool 2008, Burgherr et al. 2012, Eckle and Burgherr 2013, Burgherr and Hirschberg 2014, Sovacool et al. 2015, Sovacool et al. 2016, Spada and Burgherr 2016, Burgherr et al. 2017).

Retrospective analysis based on traditional statistical methods has however not looked at and revealed the (integrated) influence and relevance of the descriptors (e.g., country, energy chain) of energy accidents on the outcome event, such as fatalities. The research challenges that have not been addressed so far include:

- (i) The assessment of the capacity of the structure of energy accidents datasets to distinguish the events with respect to objective measures of outcome, such as fatalities, injuries, release of toxic material, monetary damage, etc.;
- (ii) The identification of the characteristics of energy accidents that distinguish between different ranges of outcomes;
- (iii) The comprehensive evaluation of concern/risk level that a (future) accident can cause according to the potential outcome, e.g., range of fatalities.

Our multidisciplinary research has started tackling these research gaps by applying a Multiple Criteria Decision Aiding (MCDA) process to a subset of ENSAD. This research supports the advancement of pre-event strategies within the framework for infrastructure resilience assessment of the Future Resilient Systems (FRS) programme at the Singapore-ETH Centre

(<http://www.frs.ethz.ch/>). More specifically, it contributes to the cognitive resilience function named “remember” as recently proposed by Heinimann and Hatfield (2017), which consists in storing and retrieving information on past events to tackle the forthcoming ones with more awareness of the possible impacts.

Building upon 182 severe natural gas accidents (≥ 5) of ENSAD dataset, clustered according to three classes of ranges of fatalities, this research achieves three objectives.

Firstly, the accuracy and quality of classification of the information stored in ENSAD for the selected energy accidents are evaluated and the relevance of the strategy used to collect the information on the accidents is assessed.

Secondly, knowledge clustered in the form of decision rules is extracted from ENSAD. These rules explain the classifications within the dataset and elucidate the relationships between the descriptors of energy accidents and the outcome, i.e., class of fatality.

Lastly, the rules are used as decision support instruments to classify realistic energy accidents in concern/risk levels according to the potential cause of fatalities. Two classification schemes are proposed, a standard and more visual but potentially ambiguous and an advanced one, which always provides a unique risk sorting.

The remainder of this paper is organized as follows. Section 2 describes the ENSAD dataset of natural gas energy accidents that was constructed for the rough set analysis. Section 3 introduces the rough set analysis method that was used to analyze the dataset. Section 4 presents the results and section 5 concludes the paper.

2. ENSAD dataset

This research focuses on ENSAD, which has several strengths that make it one of the most credible and comprehensive databases on energy accidents in the world. These include the trustworthiness of the stored information, the coverage of full energy chains on a global scale and the use of severity thresholds for different types of consequences that guarantee consistent information on the outcomes (Burgherr et al. 2017). In ENSAD, information on each energy accident includes date, location, energy chain and infrastructure typology and sequence of detrimental events. Consequences in the form of fatalities, evacuees, release of toxic material, injuries, economic damage are then associated to every accident.

The ENSAD dataset used in this research is a set of 182 accidents³⁷ attributable to the natural gas sector that caused at least 5 fatalities, on a temporal scale from 1970 to 2006. The reason for this choice is that the natural gas chain is currently a major focus area within the ENSAD team (Lustenberger et al. 2017) and consequently this research project is a complement to the analysis of such dataset to derive a comprehensive perspective on natural gas accidents.

3. MCDA method

The information stored in ENSAD resembles a standard starting point for MCDA, namely an information table, whose rows normally represent alternatives whereas columns are divided into attributes (or criteria if preference ordered) that characterize the alternatives and the decision which represents the overall “evaluation” of the alternatives.

In the current case study, the alternatives are the energy accidents from ENSAD. Eight attributes were selected for the characterization of the ENSAD dataset, because they were considered as main characteristics that allow discerning the accidents according to their entity of consequences. They include country cluster (a_1), energy chain stage (a_2), infrastructure type (a_3), event chain sequence from 1 up to 5 (a_{4-8}) (see Table 1). Details on each of these attributes can be found in Burgherr et al. (2015) and Burgherr et al. (2017).

³⁷ According to the definition adopted in ENSAD, severe accident causes, for example, at least 5 fatalities, or 10 injuries, or 200 evacuees, etc (Burgherr et al. 2012). For simplicity, the adjective “severe” will be omitted throughout the paper.

Table 1. Simplified information table for energy accidents from ENSAD

Accident	Country (a_1)	Energy chain stage (a_2)	Inf. type (a_3)	Event chain 1 (a_4)	Event chain 2 (a_5)	Event chain 3 (a_6)	Event chain 4 (a_7)	Event chain 5 (a_8)	Fatalities (Cl)
1	OECD (1)*	DOM/ COM (8)	Building public (32)	Mechanical failure (10)	Explosion (2)	NA (99)	NA (99)	NA (99)	5 – 10 fatalities (1)
...									
92	Non-OECD (2)	Transport (5)	Pipeline (10)	Corrosion (7)	Human error (1)	Fire (3)	99	99	11 – 20 fatalities (2)
...									
182	2	8	32	7	2	99	99	99	> 20 fatalities (3)

(*) The numbers within brackets indicate the code used for the value of each attribute.
Source: Authors, current research project, 2017.

The “evaluation” of energy accidents (decision in MCDA terms) is currently the number of fatalities (i.e., outcome) that each accident caused, clustered in one of three preference-ordered (from a low to high impact) classes, $Cl_1 = 5 - 10$ fatalities (118 accidents); $Cl_2 = 11 - 20$ fatalities (40 accidents); $Cl_3 \geq 20$ fatalities (24 accidents). The fatalities were selected as the outcome for energy accidents since they are the most accurate and reliable information available in the dataset.

The choice for the three classes derives from an analysis of the distributions of the fatalities per accident within ENSAD, which lead to the definition of a set of classes that can be considered as informative for clustering severity for the accidents and have sufficient accidents to allow knowledge extraction.

The ENSAD dataset was analysed with rough set methodology, which is a powerful method to deal with inconsistent data, derive clusters of knowledge in the form of decision rules and apply these rules to provide recommendations of new and unseen alternatives. Rough set theory was originally introduced by Pawlak et al. (1995) and it has been proven very useful to identify patterns, regularities and develop decisions support tools in areas such as management of extreme natural events (Hu et al. 2016), economy and finance (Podsiadło and Rybiński 2014) and healthcare (Słowiński 1992). The novelty of this research stands in the application of the rough set analysis to a research area (i.e., risk assessment of energy accidents) it has never been used for and also to the extension of such analysis through decision rules that can enhance the decision support capabilities of the approach.

The dataset in ENSAD has been adapted to a “common” information table in MCDA terms and analysed with the rough set approach for analysis of quality in the ENSAD dataset, the discovery of patterns within the dataset, and development of a decision support tool. The rough set methodology has been implemented with the Learning from Examples, Module 2 (LEM2) algorithm (Prędko and Wilk 1999). It identifies clusters that contain indiscernible accidents according to the selected attributes and it extracts from them the patterns in the form of decision rules. Details on the classification schemes can be found in Błaszczyński et al. (2007).

4. Results

The results are presented in three sections, distinguishing dataset quality (section 4.1), decision rules for natural gas energy accidents (section 4.2) and, lastly, in the classification of “new” energy accidents to risk classes (section 4.3).

4.1. Dataset quality

The rough set analysis shows that the quality of classification for the information table based on the ENSAD dataset for natural gas accidents is just under 65%, meaning that close to two thirds (i.e., 121) of the 182 accidents can be classified without ambiguity. In other words, 65% of the accidents can be surely described by the selected attributes and classified according to the three severity classes. Considering that this is a first application of rough sets to a part of ENSAD, the quality of classification can be considered as a promising (though preliminary) outcome (Rawat et al. 2016).

4.2. Decision rules for natural gas energy accidents

79 rules were discovered by the LEM2 algorithm: 48 for Cl_1 , 20 for Cl_2 and 11 for Cl_3 . The rules represent pieces of objective knowledge contained in ENSAD that are characteristics of the energy accidents that caused certain classes of fatalities. Standard rules contain the attributes values (i.e., conditions) of the energy accidents that result in certain outcome (i.e., decision), having caused between 5 and 10 fatalities, between 11 and 20 and above 20. In this manner, it is possible to perform a mapping of the patterns that characterize the accidents that surely represent each class.

An example of rule for the least risky class (i.e., Cl_1) states that:

“If (country cluster, $a_1 = \text{OECD}$) & (event chain 1, $a_4 = \text{human error}$) & (event chain 2, $a_5 = \text{explosion}$) & (event chain 3, $a_6 = \text{not available}$), then the class of fatalities is Cl_1 ”.

The rule is supported by two accidents within the ENSAD dataset, which are n. 5 and 99, and represents a block of knowledge that derives from consistent accidents in the dataset, meaning that there are no other accidents that have the same attributes values as the ones for these accidents and which caused more than 10 fatalities (i.e., Cl_2 or Cl_3).

An example of rule that is supported by an accident causing the most risky class of fatalities (i.e., Cl_3) reads as follows:

“If (country cluster, $a_1 = \text{non-OECD}$) & (infrastructure type, $a_3 = \text{pipeline}$) & (event chain 1, $a_4 = \text{human error}$) & (event chain 2, $a_5 = \text{explosion}$), then the class of fatalities is Cl_3 ”.

The ENSAD accident that supports this rule is n. 169, which indicates that there is no other accident that has such values of the attributes and causes fewer than 21 fatalities (i.e., Cl_1 or Cl_2). Hence, the recommendation from rough set analysis is that the accidents with these characteristics should be handled with extreme care as they have the potential of causing the worst level of fatalities, according to the selected attributes and classification scheme.

4.3. Classification of “new” energy accidents to risk classes

The rules can be used as instruments to guide the decision-making process when there is an interest in knowing which type of potential consequences, expressed as classes of fatalities, an energy accident can have.

- (i) Rules are useful as they can support the understanding of the role of:
- (ii) Individual values of the attributes that might provide a warning sign;

Classification of potential energy accidents in a risk class according to the possible characteristics of country cluster, energy chain, infrastructure type and event chain sequence.

The possible use of the decision rules for the classification of new accidents is illustrated with three realistic accidents (n_1 - n_3) in Table 2, together with the standard and advanced recommendation schemes applied with rough set methodology.

Table 2. Examples of energy accidents and risk class assigned by standard and advanced classification schemes

New accident	Country (a_1)	Energy chain stage (a_2)	Inf. type (a_3)	Event chain 1 (a_4)	Event chain 2 (a_5)	Event chain 3 (a_6)	Event chain 4 (a_7)	Event chain 5 (a_8)	Fatalities (Cl)		
									Std. scheme	Adv. scheme	
n_1	Non-OECD	DOM/COM	Building public	Rupture	Explosion	Fire	NA	NA	Cl_1	Cl_2	Cl_3 (0.017) [^]
n_2	Non-OECD	Storage	Pipeline	Human error	Explosion	Fire	NA	NA	Cl_2	Cl_3	Cl_3 (0.017) [^]
n_3	OECD	Storage	NA	Explosion	NA	NA	NA	NA	Cl_1	$Cl_1 = (0.025)$ [^]	

([^]) highest *score^{net}* for the class.

Source: Authors, current research project, 2017.

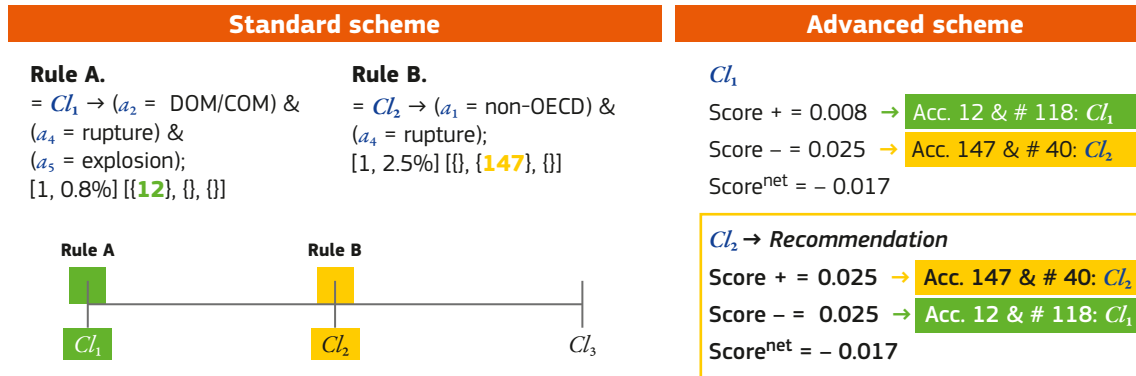
The standard scheme provides the range of classes that are recommended by the covering rules, i.e., the rules that match the values of the conditions of the energy accidents. The width of the individual classes in the standard scheme column in Table 2 is used for representation of the strength of the rules, which is the n. accidents that satisfy the conditions of the rules and which are assigned to the class under consideration. The even distribution for Cl_1 and Cl_2 for n_1 and Cl_2 and Cl_3 for n_2 indicates that the same n. accidents (one) is in favour for each class. On the contrary, Cl_1 is the only one recommended in the case of n_3 because both rules that match the conditions of the accidents suggest Cl_1 .

The ambiguity of the standard scheme shows the limitation in its decision support potentials. Consequently, the advanced classification scheme was introduced to offer a unique recommendation, by accounting for the supporting rules for each class. Each single class is shown with the associated highest *score^{net}*, which is a measure of the strength of the support for the most certain class recommendation (for details of score calculation see Błaszczczyński et al. (2007)).

Figure 1 shows the working procedures of the classification schemes for accident n_1 . The matching rules for this accident are two, indicated here with rule A and B. On the one hand, rule A supports the assignment to Cl_1 with accident n. 12 from the ENSAD dataset as support for such recommendation. On the other hand, rule B advances Cl_2 as recommendation, with ENSAD accident 147 as its support.

As far as the advanced classification scheme is concerned, the operating process is more elaborate and it can be described as follows. In the case of Cl_1 , there is only one accident (n. 12) that supports the rule and considering that there are 118 accidents in Cl_1 then the support for such a class is weak. In this case, $score^+ = (1 \text{ accident satisfies the rule} / 118 \text{ accidents belong to } Cl_1) * 100 = 0.008$, which is the strength of Rule A. The support for Cl_2 is higher, because even if only one accident (n. 147) satisfies the conditions of the rule, the accidents in Cl_2 are fewer than for Cl_1 (i.e., 40), hence the support for such a class is stronger. In this case, $Score^+ (1 \text{ accident satisfies the rule} / 40 \text{ accidents belong to } Cl_2) * 100 = 0.025$, which is the strength of Rule B.

Figure 1. Working procedure of standard and advanced classification schemes for accident n1 from Table 2



Source: Authors, current research project, 2017.

It must also be noted that the rules which recommend a class different from the one under consideration “play against it” through the *score-*. Cl_3 has no rules that are matched by the new accident, therefore only a negative score can be expected due to the rules A and B that are not in favour of such class. The combined effect of *score+* and *score-* allows calculating the overall *score^{net}* that justifies the allotment of n1 to Cl_2 .

The same procedure can be applied to any other accident and the overall recommendation for the level of risk associated is shown in an intelligible and justifiable format, through the standard and advanced classification schemes.

5. Conclusions

One of the key factors for the successful development of resilient energy systems is the capacity of learning what caused deadly accidents. This competency would empower decision makers learning how to possibly avoid them in the future, or to at least mitigate their consequences. Decision support systems for the classification of energy accidents in risk levels can help decision makers foreseeing the potential concern that they could cause and the effort required to re-stabilize the affected system. This paper has presented the first attempt to provide such a decision support system, with the application of rough set analysis on a subset of energy accidents for natural gas from ENSAD. It was demonstrated that rough set analysis is a valuable approach that can shed light on the challenge of “seeing behind the curtain” of the ENSAD dataset, to unveil the hidden objective relationships that are unique for energy accidents causing a certain range of fatalities. These relationships are expressed with simple and intelligible decision rules that can be used to disclose the patterns that could not be otherwise identified. It was confirmed that storing information on energy accidents by accounting for the country, energy infrastructure and energy chain sequence the event took place, like it has been within ENSAD from the early 1990s, is relevant to discern among the concern they can cause. What is more, the provision of a set of energy chain events is also confirmed as a relevant accidents’ characterization strategy. Lastly, the rules can be used for the classification of new energy accidents in risk classes, which has the added advantage of providing a characterization of the possible outcome by objective information using the ENSAD information.

This promising approach for ENSAD analysis can be expanded to assess influence of the attributes (values) on the classification quality, to evaluate the performance of the rules on accidents that were not part of the dataset, and to consider other outcomes such as injuries and monetary damage. Lastly, rough set analysis could also be used to provide similar research contributions as in this case study, but for other energy chains, such as coal and oil, which are well established within ENSAD.

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Optimum Shelter Location (OSL) Tool Development

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Abstract

Establishment of temporary shelters are most widely used method for protecting or sustaining the lives (in an optimum level of standards) of the victims who may have suffered from disasters, social congestions or wars. UNHCR (United Nations Refugee Agency) is one of the efficient organizations acting in this area and their reports are important guides in means of supplying expertise in designing, maintaining and selecting the right locations for shelters. Similar to UNHCR, Humanitarian Charter and Minimum Standards in Humanitarian Response-Sphere Project is concerned with the righteous conditions in shelters and the Sphere Handbook is a valuable product that describes the details of sheltering processes gained by the experiences of the initiative. In addition to these international bodies, temporary shelters established after 2012 Van Earthquake and camps for Syrian refugees are good examples for showing the awareness of a reminder for the importance of the issue. It is shown by several scientific studies that Istanbul may face a big scale earthquake in near future. The main axis of these studies is to assess the vulnerability and estimate the possible results due the adverse conditions of the earthquake. These studies claim that one of the most important issues is the requirement of temporary shelter for the victims. To meet the needs of the victims there are several physical conditions in addition to social components that need to be considered. It was estimated in the study (A Disaster Prevention / Mitigation Basic Plan in Istanbul-2002) carried out by Istanbul Metropolitan Municipality (IMM) and Japan International Cooperation Agency (JICA) that in a case of the possible earthquake 330000 tents and 120 km² area will be needed (JICA, 2002). It is almost impossible to estimate the physical conditions and social problems that may occur in such a situation. Although there have been many improvements following the aforementioned study, the rise of the population, situation of the current building stock, infrastructure is still questionable, and it can be assumed that requirement for huge amounts of shelter will be needed.

In this aspect, one of the critical challenges is the determination of the optimum locations for these shelter areas. In this study, authors developed a decision support model, which generates solution for the problem of temporary shelter site selection in the aftermath of a disaster. A spatial multi-criteria decision support model and methodology through a GIS software was the foundation of this study. Thus, the correct locations for these areas was determined before the disaster and it is now available for the decision makers to develop strategies to enhance and rehabilitate those areas. The system is also efficient in post-disaster situation for evaluating the currently selected sites. Moreover, it is also available to re-evaluate the efficiency of the shelter locations based on the new conditions that arise because of the earthquake. Therefore, decision makers can update the criteria simultaneously and new locations based on these optimum conditions can be assessed. Inexistences of such a study in Turkey proves the importance of this study and highlights the emergence of the situation. This study is funded by the Disaster and Emergency Management Presidency (AFAD), National Earthquake Strategy and Action Plan Support Program with the award number UDAP-Ç-12-03.



Introduction

Site selection, planning and the preparation of shelters have a direct bearing on the preparation of other assistance. These are important considerations in the overall needs assessment and planning of response. Decisions must be made using an integrated approach, incorporating both the advice of specialists and the views of the refugees (UNHCR, 2007). Sources of information for site selection and planning should include local authorities and communities, government offices, educational institutions and UN agencies. UNHCR Headquarters, through the focal point on Geographical Information Systems (GIS), can also support operations with maps, aerial photographs, satellite images and a special geographic database. Furthermore, the Technical Support Section (TSS) at Headquarters, upon request, could assist in the process of site selection and planning (UNHCR, 2007)

Istanbul lies on an active seismic zone ranging from Java – Myanmar – Himalaya – Iran – Turkey and Greece, where many large earthquakes have occurred in the past. Based on worldwide historical earthquake catalogues, Istanbul has experienced earthquakes equal or greater than intensity 9 at least 14 times from 5th century. This means Istanbul has suffered damages due to earthquakes every 100 years, on average (Segawa et al., 2004). Looking back to Turkey's earthquake history, there are two recent strong earthquakes. 1999 Kocaeli, which occurred with a moment magnitude of 7.4 on 17 August at about 3:02 a.m. local time. The event lasted for 37 seconds, killing 17,127 and injuring 43,959 people and leaving approximately half a million people homeless (Marza, 2008). 2012 Van, earthquake was a destructive magnitude 7.1 earthquake that struck eastern Turkey near the city of Van. According to Disasters and Emergency Situations Directorate of Turkey AFAD on 30 October, the earthquake killed 604 and injured are 4,152. At least 11,232 buildings sustained damage in the region, 6,017 of which were found to be uninhabitable. The uninhabitable homes left as much as 8,321 households with an average household population of around 7.6 homeless in the province; this could mean that at least around 60,000 people were left homeless. It is obvious that, the expected earthquake for the Istanbul will cause inescapable and irreversible consequences for human life. That is why, temporary shelter sites should be estimated that which regions will be safer, to be prepared as good as possible to the expected earthquake.

Shelters

Shelter is likely to be one of the most important determinants of general living conditions and is often one of the significant items of non-recurring expenditure. While the basic need for shelter is similar in most emergencies, such considerations as the kind of housing needed, what materials and design to be used, who constructs the housing and how long it must last will differ significantly in each situation (UNHCR, 2007).

When locating or planning emergency settlements, their long-term economic, social and environmental impacts on the surrounding area should be carefully considered. In many situations, such as in northern Iraq and several countries of Eastern Europe and the former Soviet Union during the 1990s, people may independently seek shelter in buildings such as schools, community centers, offices, sports facilities, and even railway carriages and wagons (WHO, 2002).

The important part of the shelter establishment is to select the optimum sites that are suitable for shelters. When establishing post-disaster shelter recovery and reconstruction operations, site selection is the most consequential decision that must be made. No other decision has as profound and lasting an impact on the lives of victims or on the likelihood of long-term project success and sustainability (Haddow and Copolla, 2010). Site selection should focus on keeping recipients as close to their land as is possible given risk reduction goals (Benson, et al., 2007). When a site assessment determines that relocation is the only or best option, government must first identify and secure viable land, and then undertake what amounts to a comprehensive yet accelerated (urban or rural) development-planning effort (Haddow ve Copolla, 2010).

Criteria for Shelter Site Selection

Water

The single most important site-selection criterion is the availability of an adequate amount of water on a year round basis. This most important factor is also commonly the most problematic. A site should not be selected on the assumption that water can be acquired merely by drilling, digging, or hauling. Drilling may not be feasible and may not provide adequate water. A professional assessment of water availability should be a prerequisite in selecting a site (OFDA, 1998). Where water is readily available, drainage is a key criterion. For effective drainage, the entire site should be located above flood level at a minimum of 3 m above the water table, preferably on a gently sloping area. Flat sites can present serious problems for the drainage of waste and storm water. Marshes or areas likely to become marshy or soggy during the rainy season should be avoided. Conditions within the watershed may be a consideration (OFDA, 1998). The accessibility of the water supply from the shelter areas must not exceed 500 meters in pedestrian walking distance. In addition, a clean drinking water supply center should serve at most 250 people (Oxfam GB, 2004).

Topography and Drainage

The whole site should be located above the flood level preferably on a gently sloping area. Flat sites can present serious problems for the drainage of waste and storm water. The watershed of the area itself will be a consideration (UNHCR, 2017). For temporary planned camps, the site gradient should not exceed 6%, unless extensive drainage and erosion control measures are taken, or be less than 1% to provide for adequate drainage. Drainage channels may still be required to minimize flooding or ponding. The lowest point of the site should be not less than 3 meters above the estimated level of the water table in the rainy season (Oxfam GB, 2004).

Open Space

The site must provide a sufficient amount of usable space for the displaced population to engage in communal and agricultural activities, livestock husbandry, or other activities (e.g., recreation, meeting spaces, etc.). Although camp planning should be based on a known design capacity (e.g., shelter and other facilities sufficient for approximately 20K people), the possibility always exists that more people may arrive. To the extent possible, the site should be planned to accommodate a major influx of additional people. If the population has been displaced because of civil strife, the site should be removed from areas of potential conflict too (OFDA, 1998). However, in order to prevent and control contagious disease the maximum human capacity of those areas should not exceed 12K people (Oxfam GB, 2004).

Surface Area

The site must allow sufficient usable space for the refugees too. WHO (2002) recommends 30 sq. meters plus the necessary land for the agricultural activities and livestock. More refugees may arrive and it is essential that the site allow for a major expansion beyond the area theoretically required for present numbers. It is particularly important that having allowed space for expansion, this be safeguarded until really needed. Otherwise, the initial settlement will occupy all the space, and major upheavals of existing arrangements will be necessary as more refugees arrive (UNHCR, 2007).

Land Usage Rights

The land should be exempt from ownership, grazing, and other uses by local populations. Using such land can be a cause of local resentment. Authorities proposing the site may be unaware of customary rights exercised by local populations. Sites are often provided on public land by the government. Any use of the land must be based on formal legal arrangements in accordance with the laws of the country (OFDA, 1998).

Accessibility

The site must be accessible by vehicles and close to communication links and sources of supplies and services such as food, cooking fuel, shelter material, and national community services (OFDA, 1998).

Hazard

The aim of the shelter areas is to provide physical conditions to the refugees or homeless people to settle for a limited period. Another aim of the shelter areas to provide psychological support to the people following the disaster situation. The effect of the disaster is one of the most important psychological trauma sources. According to United Nations High Commissioner for Refugees (2007), shelter sites should be selected both away from the disaster area and should not be in a zone that may be effected from secondary or other disasters or emergencies too. That is why, first the possible hazards on the candidate sites should be determined and the hazard maps should be analyzed with the risks on the site. By this way, the sites with the lowest hazard risk should be registered as the shelter areas.

Site suitability assessments should be conducted to assess hazard risk, environmental impact, topography, geology, hydrology, soil structure, and several other factors in order to determine the best location and layout of structures, and the housing design and construction materials to ensure safety and sustainability (Haddow and Copolla, 2010).

AHP

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making approach and was introduced by Saaty (1980). Since the 1970s, AHP has been applied in a wide variety of application areas such as location analysis (Min 1994), allocation (Cheng and Li 2001), marketing (Davies, 2001), energy policy (Kim and Min 2004), education (Saaty et al. 1991), risk analysis (Millet and Wedley 2002), environmental impact assessment (Ramanathan 2001), suitability analysis (Banai-Kashani 1989), and site selection (Erden and Coskun 2010). AHP assists the decision making process by providing the decision makers with the opportunity to organize the criteria and alternative solutions of a decision problem in a hierarchical model (Karaman and Erden, 2014). In AHP, the decision problem is first decomposed into a hierarchy of more easily comprehended sub-problems that can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time (Saaty, 1980). In this study, the importance of each criteria was considered according to its weight after calculating from the questionnaires using pairwise comparison and AHP, which obtained from various experts given in Table 2.

Table 1. Surveyor Institutions for the Questionnaire

Institutions Responded to Questionnaire
Ministry of Family and Social Policies
GEA: (Gesellschaft für Entstaubungsanlagen)
AKUT: Search and Rescue Association
MAG : Neighborhood Disaster Volunteers
Istanbul Technical University Civil Engineering Faculty
Istanbul AFAD (Disaster & Emergency Management Presidency)
Kızılay (Red Crescent)
DASK (Turkish Catastrophe Insurance Pool)
Istanbul Provincial Directorate of Health
Technical University of Wien Department of Geography
Middle East Technical University Department of Social Sciences
University of Tebriz Department of Geomatics Engineering
Bogazici University Department of Economy
Bogazici University Kandilli Observatory

Criteria and Sub-Criteria

Criteria for decision-making processes with AHP should not be correlated to each other. That is why six independent criteria were selected as main criteria and half of the main criteria included at least four sub-criteria as seen in Table 2.

Table 2. Shelter area criteria and sub-criteria with the weights

Sub-Criteria						Main Criteria
	Natural Gas (0.063) (GZ)	Electricity (0.152) (EL)	Sewage (0.489) (KN)	Potable Water (0.234) (SU)	Communication (0.063) (IL)	Infrastructure (0.173) (AL)
		Railways (0.233) (DM)	Heliports. (0.140) (HP)	Maritime Lines (0.085) (DN)	Road Network (0.542) (KR)	Accessibility (0.207) (ER)
Fire Hazard Map (0.361) (YT)	HAZ-MAT Hazard Map (0.227) (KT)	Flood Hazard Map (0.132) (ST)	Landslide Hazard Map (0.132) (HT)	Tsunami Hazard Map (0.074) (TT)	Earthquake Hazard Map (0.074) (DT)	Hazard (0.313) (TH)
<i>No Sub-Criteria</i>						Topography (0.095) (TO)
<i>No Sub-Criteria</i>						Capacity (0.155) (KA)
<i>No Sub-Criteria</i>						Land Use (0.057) (AK)

Accessibility sub-criteria acquired from Istanbul Metropolitan Municipality, and all applied to Near analysis, then reclassified to 7 classes. After these steps weighted-sum analyses was applied to each sub-criteria.

Infrastructure sub-criteria obtained from Istanbul Metropolitan Municipality as Natural Gas and Wastewater and respectively, near analysis, reclassification and weighted-sum analyses were applied. For communication data, receptions of GSM base station of various providers in Turkey were used. Respectively, near, reclassification and weighted sum analyses were conducted. For electricity, the data from underground and electric lines were merged and then been a near analysis was used. For potable water two maps of water lines and water-connections were merged together as water supplies. Respectively, near, reclassification and weighted-sum analyses were applied.

Hazard maps were acquired from different sources. For all kind of hazard maps, classification analysis done by considering being far from these areas as an advantage. Earthquake hazard map was obtained from HAZTURK program, and classified into 7 classes as the other maps. Tsunami hazard map was acquired from Istanbul Metropolitan Municipality and reclassified to 7 classes. Flooding hazard map was a combination of flooding areas and distance from riverbeds. First, they were reclassified and then combined with weighted-sum analysis. Fire hazard map was received from Erden T. and Coskun M.Z. (2012) study. Since it was for a specific part of Istanbul, in reclassification section for empty land were given the value of 1 as those areas are not suitable according to Fire risk.

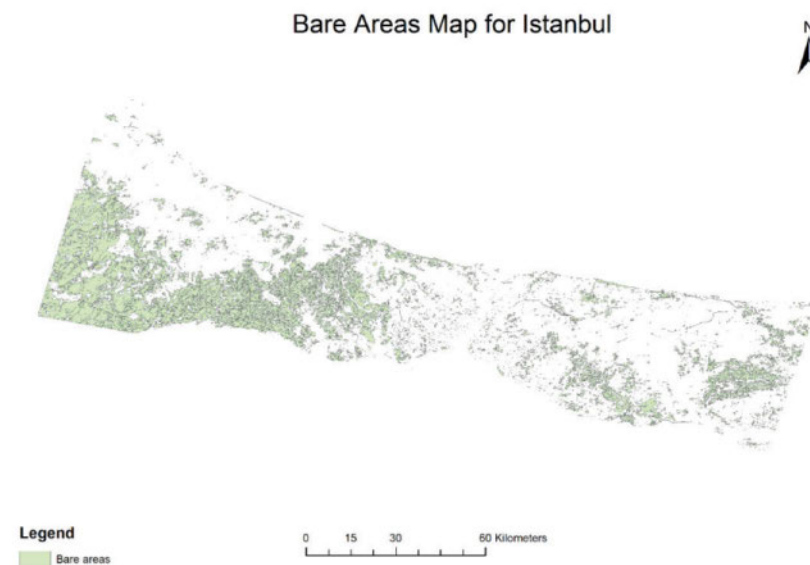
Topography map was obtained from HAZTURK program (Karaman et al., 2008). For classification, all the values were applied manually from 1% slope to 30% slope.

Land usage maps were obtained from two separate maps. Both of them were provided by Istanbul Metropolitan Municipality. For reclassification, each class was given a value manually according to their suitability for a shelter site. For example, parks had the most suitable score while, forests and urban facilities had the least score in the classification.

Capacity map was obtained from Landsat 8 satellite images, which were taken on 30.07.2013. To detect the empty areas with the proper size first the areas covered with buildings were eliminated by using Manno-Kovacs and Sziranyi (2015) building detection method. Then,

NDWI (Normalized Difference Water Index) (Gao, 1996) used to detect water bodies, and NDVI (Normalized Difference Vegetation Index) (Rouse et al., 1973) used to detect vegetation areas. After the bare area analysis, suitable bare areas were detected as in Figure 1.

Figure 1. Bare area map of Istanbul in vector formatted data



Model builder tool of ArcMap Geoprocessing was used to create the Optimum Shelter Location (OSL) model. The Figure 2 shows the process of each criteria and sub-criteria within the model. Model works the following procedure. First classification applied to the raw raster data. Then the weights of the sub-criteria, which were calculated from the questionnaires results, are inputted to the weighted sum analysis. In addition, capacity and topography maps directly applied to weighted sum because they do not have sub-criteria. After all the raster data of the main criteria generated following the first set of weighted sum. Then, main criteria raster data were classified into seven classes again and the second set of weighted sum analysis applied to them. At the end, the resulting raster map extracted by using the vector bare area map and the optimum shelter areas determined and represented as raster map.

Figure 2. Model algorithm of the OSL

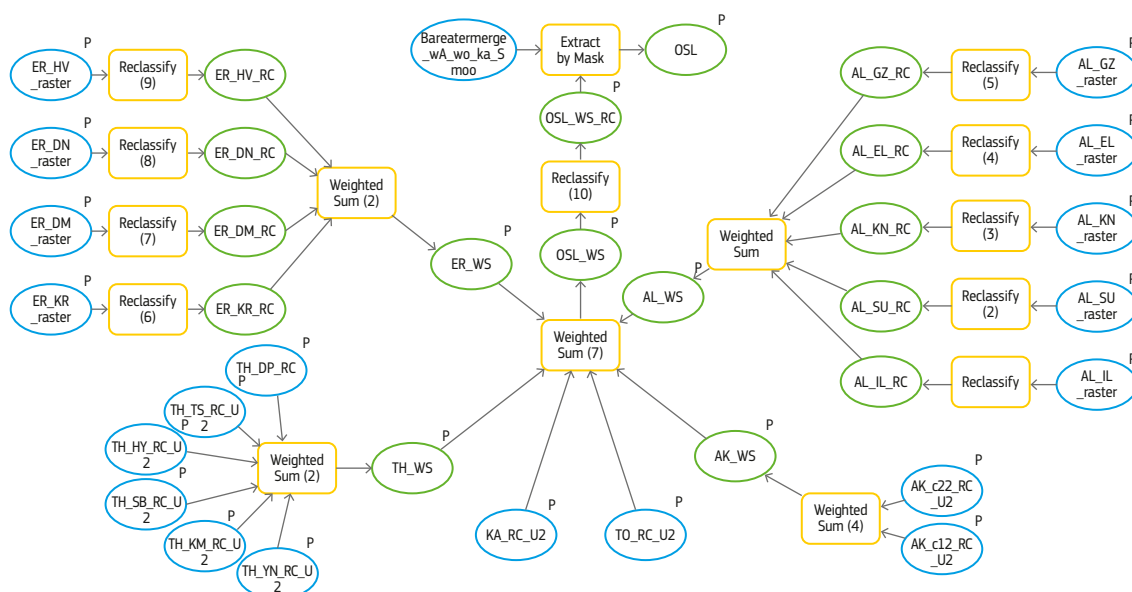
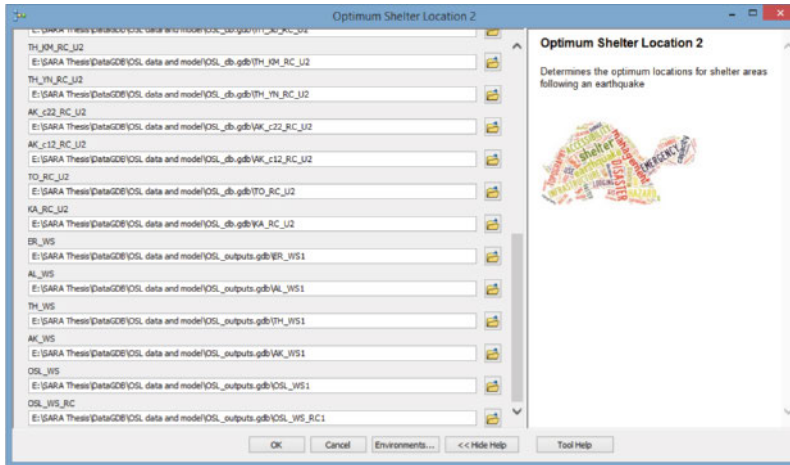


Figure 3 presents the user interface of the model tool. The standard input data type and format is designated as seven classed raster data and for extraction process a vector bare area data.

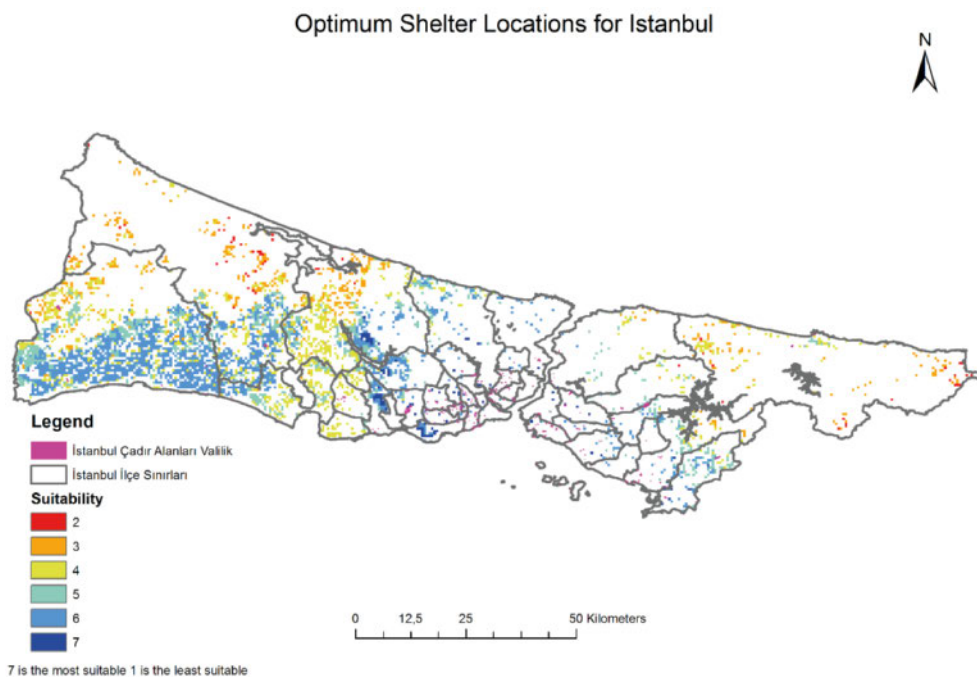
Figure 3. Graphical user interface of the OSL model



After the reclassification of the result map to seven classes, the result map added to the extend showing from the best to the worst sites for the optimum locations for shelter site following an earthquake in the city of Istanbul as in Figure 4 below.

As a result, in 2002 total areas of shelter sites in Istanbul was 4.616 km². Now it is 2.503 km². In other words, if we consider the most suitable areas (class 7), total area is 0.683 km² with a possibility to settle 22 thousand people. The capacity was 153 thousand people in 2002 and today, 131 thousand people will not be able to use shelter areas.

Figure 4. The resulting map of the model showing the seven class optimum shelter locations (OSL) for Istanbul



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The seismic resilience of the built environment: the case of the masonry buildings

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Abstract

In the last years in the framework of risk analysis, there has been a progressive recognition of the importance of vulnerability of the built environment, especially related to resilience concept, adaptation and response capability. In fact, the actual impact of last natural disasters, especially earthquake, has highlighted the inability of the environment to react to them and the presence of non-resilient cities, above all in Italy. In fact the last Italian seismic events, despite moderate magnitude, have shown that, compared with other natural disasters, paralyze societies and their economies for a long time.

In this context, the authors propose a procedure to establish quantitative measures useful to support the assessment of structural resilience of masonry buildings in a seismic area, determined by the integration of loss and downtime assessment. In particular, the paper is focused on the procedure for the computation of the direct loss, following a component-based approach and developed within a probabilistic framework. It is based on: numerical and analytical models, static and dynamic nonlinear analyses. In the paper, the procedure is proposed for a single building, but it can be extended for portfolio analyses since it is mainly aimed to resilience assessment.

1. Introduction

The consequences of an earthquake as the physical damage to buildings and other facilities, the casualties, the potential economic losses due to the direct cost of damage and to indirect economic impacts, the loss of function in lifelines and critical facilities and also social, organizational and institutional impacts, are just a number of significant Decision Variables (DV) that need to be considered in the assessment of the seismic risk.

Until now, in the field of risk analysis at the European scale, the DV has generally been a damage scenario. Nowadays the scientific community shows an increasing interest in a seismic risk analysis developed in economic terms, recognizing that it could be more effective for different scopes: i) cost-benefit evaluations, comparing the costs of a mitigation tactics, such as retrofits, to the benefits achieved from improved seismic performance; ii) the calibration of insurance premia; iii) the "Building Seismic Performance Classification" (Calvi et al. 2014, D.M. 28/02/2017); iv) the development of seismic resilient society.

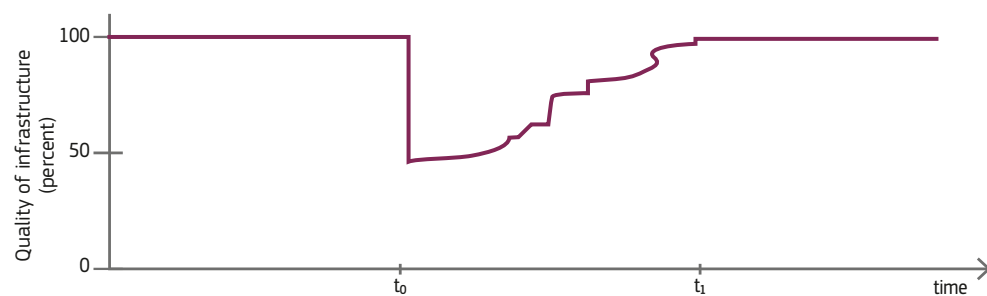
Focusing on the last issue, it is important to note that the concept of resilience has several definitions, due to its employment in ecology, social science, economy and engineering fields, with different meanings and implications (Cimellaro et al. 2016). In the framework of the engineering field, the resilience is the ability of a given area to bounce back after a negative shock (Cavicchi 2015). Bruneau et al. (2003) developed a conceptual framework for quantifying seismic resilience of a system based on: its probability of failure during an earthquake, the consequences of failure and the time to recovery.



The resilience is defined using a mathematical function $Q(t)$ describing the serviceability of the system, which is described as functionality (Cimellaro et al. 2010) and captures the three abovementioned features (Figure 1 from Bruneau and Reinhorn 2006). The functionality $Q(t)$ is measured as a non-dimensional (percentage) function of time. If an earthquake occurs at time t_0 , the system could be damaged and the quality measure, $Q(t)$, decreases (from 100% to 50%, as an example, in Figure 1). After that, the system could return to normal over time, as pointed out in that figure, until time t_1 when it is repaired and functional as before the event (quality of 100%). Therefore, the resilience R , with respect to that specific earthquake, can be quantified by the size of the expected degradation in quality, over time (that is, time to recovery). Mathematically, it is defined by:

$$R = \int_{t_0}^{t_1} Q(t) dt \quad (1)$$

Figure 1. Representation of seismic resilience (Bruneau and Reinhorn 2006)



The resilience rests on four properties: robustness, redundancy, resourcefulness and rapidity. The vertical and horizontal axis in Figure 1 measure, respectively, the robustness and the rapidity of a system. They can be defined as the results of a loss and downtime assessment (Almufti and Wilford, 2013).

In this framework, the paper presents a procedure to support the quantification of the seismic resilience of a particular system that is the masonry built environment, focusing herein to the direct loss as explained in the §3. It is worth noting that, the resilience concept is applicable at multiple levels within the scale of the built environment, progressing from structural components to single structures to networks of structures to entire communities (Marjanishvili et al. 2014). The paper is focused on the quantification of the resilience for a single structure.

The notion of seismic resilience began to acquire importance in the United States hazard management in the late 1990s and at the international level in the 2005 World Conference (Bonstrom and Corotis 2015). Only in the last years, it reached Europe and later Italy, therefore the paper aims to present an innovative approach to the vulnerability assessment and risk analysis in Italy, following a resilience-based approach, even if until now only for the loss assessment.

2. The resilience approach for masonry buildings

The interest in the resilience of masonry structures arises from two issues.

The first is the importance of the resilience approach since, the recent seismic events occurred in Italy, despite their low magnitude, have pointed out once again that they paralyze communities and their economies for a long time in terms of lack of trade, tourism, production, and service management. This is due to the fact Italy is a medium-high seismicity region, for frequency and intensity of the events, with a high vulnerability, for the fragility of the built environment, and extremely high exposure, for housing density and the presence of a unique historical, artistic and monumental heritage in the world.

The second issue is related to the masonry built environment. This structural typology represents a significant portion of the existing built environment in Italy, as in many other earthquake prone countries. They are usually ancient buildings, often of cultural value, with a complex structure and without engineering design, but rather built following rules-of-thumbs, based on the experience of the builders of the past. Moreover, they have often undergone many transformations in the course of their lives, for example enlargement or rising up works, which have made them more complex and often vulnerable. Furthermore, due to the above-mentioned reasons, in general existing masonry structures have not the characteristics of regularity, symmetry, simplicity and good connection between the structural elements required today for new constructions in order to improve the seismic response and guarantee a box-behavior. In fact, they are in general irregular structures, both in plan and in elevation, with flexible floors that in many cases are not able to provide a box-behavior. These characteristics have made them particularly vulnerable to the earthquakes.

The masonry is the structural material of the oldest existing buildings, the monumental heritage (Figure 2.a, Figure 2.b) and the historic centers of the cities (Figure 2.c). For this reason, it plays a key role in the evaluation of the seismic resilience of a society. In fact, the historical centers of medium and large cities are often the headquarters of strategic function (Dolce 2012) whose operability during and after seismic events is fundamental for the civil protection activities (e.g. hospitals), as well as those of great importance in relation to the consequences of their collapse (e.g. schools). Figure 2.a shows a bad example of this issue, since the Government Palace of L'Aquila was collapse during the 2009 earthquake, but it should have been one of the key elements for the recovery.

The monumental heritage and the smallest towns are instead the socio-cultural identity of a country (Figure 2.b and Figure 2.c), whose conservation is needed for the recovery and the improvement of the social and economic life.

For these reasons, the safety and conservation of the masonry structures guarantee the development of resilient society.

Figure 2. a) The Government Palace of L'Aquila collapse during the 2009 earthquake (Wikipedia); b) Basilica of St. Benedict in Norcia, 2016 (source: <http://www.atg-oxford.co.uk>); c) Pescara del Tronto before and after the 2016 Amatrice Earthquake (SkyTG24).



Among the categories of existing masonry buildings the paper is focused on palace that can belong to heritage buildings or residential ones as well.

3. Direct financial loss assessment for masonry buildings

In the analysis of seismic consequences in terms of direct losses, the lack of literature and tools is particularly noticeable, above all for masonry buildings of the Italian and European built environment. In fact loss estimation in general is based on the definition of consequence functions that relate Limit States or Damage States to Repair Cost. These functions can be derived from different approaches: experimental data, empirical data and analytical data, from the structural response of a building. In literature, most consequence functions are determined from the first two approaches, but they are more addressed to other types of construction. The masonry structure, in fact, are based on a technology that varies a lot from region to region, dependent from the local seismic culture and the available materials in the area, for this reason also the losses can vary a lot according to the different country and typologies. Therefore, the advisable approach is the analytical one, which is based on the definition of a cost function directly dependent on the damage level identified by specific engineering demand parameters (EDP), related to the response of different structural elements (as proposed for example in CNR-DT 212/2013 for the Significant Damage LS). For this reason, the paper proposes a loss estimation analytical model, that can be applied to any single-building or classes of masonry buildings with homogeneous seismic behavior.

It is worth noting that the collapse mechanisms observed in a masonry structure can be traced back to two groups: the global response activation, with prevailing in-plane damage modes, and out-of-plane mechanisms, mostly occurred only on local portions of the structure. The methodology proposed considers both responses and it is described in detailed in Ottonelli 2016 and Ottonelli et al 2017.

In particular, the loss assessment process proposed follows a logical process of steps starting with the characterization of hazards and continuing through analysis simulations, damage modeling, and evaluation of the associated consequences (Bonstrom and Corotis 2015). It is based on a rigorous probabilistic framework that allows consistent characterization of the inherent uncertainties. In fact, the procedure complies with the aims and general framework of FEMA P-58 (2012) and it is aligned to the PEER (Pacific Earthquake Engineering Research) PBEE (Performance-Based Earthquake Engineering) procedure (Porter 2003), based on the integral (2):

$$\lambda_{DV} = \iiint p(DV | DM) p(DM | EDP) p(EDP | IM) \lambda(IM) dIM dEDP dDM \quad (2)$$

It is an example of total probability theorem that allows the disaggregation of the assessment problem into the four basic elements of hazard, structural, damage and loss (decision) analysis, by the introduction of the intermediate variables **DM** (damage measure), **EDP** (engineering demand parameter) and **IM** (intensity measure of the hazard). The four stages allow for each aspect of the seismic assessment to be treated in a probabilistic way. Equation (2) implies the computation of λ_{DV} , the mean annual occurrence of a certain decision variable, DV, relative to a particular building, or class of buildings, and site, characterized by a specific hazard curve, $\lambda(IM)$. Furthermore, the general term $p(x|y)$ represents the probability density of **x** given **y**. The outcome λ_{DV} of the PEER PBEE methodology represents only one metric of performance (annualized repair cost due to damage), yet the seismic performance can consider numerous sources of loss expressed in a variety of metrics. These metrics can be annualized, such as expected annual loss (**EAL**) in the Equation (3):

$$EAL = \int_{DV} f_{DV}(DV) dDV \quad (3)$$

The loss assessment procedure, in fact, is firstly based on the selection of a representative **DV** that measures the seismic performance of the facility in terms of losses and consequences. In the proposal, the **EAL**, representing the likely loss for any given year (seen as fraction of the overall value of the building), is chosen as **DV**, together with the internal parameters of it that can include loss due to repair costs, called direct losses.

The methodology for estimating the overall loss to a building is found on the losses to its individual components, according to the Component-Based approach (Mitrani-Reiser 2007). The components are the parts, structural and non-structural, that all together comprise a building. For this approach, the direct loss is calculated by summing the losses over all damageable components in the building. In particular, the contribution of the damageable building components to total repair cost is represented by a vulnerability function, that is the relationship between repair costs and intensity measures levels. After the evaluation of this curve, the loss assessment is performed through the construction of the loss curve for each component, defined by the mean annual frequency of exceedance of each intensity measures ($\hat{\lambda}$) and, relative, loss ratio (**L_R**, the percentage of the replacement cost). The area under the loss curve is the **EAL**. In particular, the total **EAL** in a building is equal to the sum of the **EAL_j** of each component (Equation 4) that derives from the repair and replacement costs of them damaged during seismic events properly weighed:

$$EAL = \sum_{j=1}^n EAL_j \cdot \alpha_j \quad (4)$$

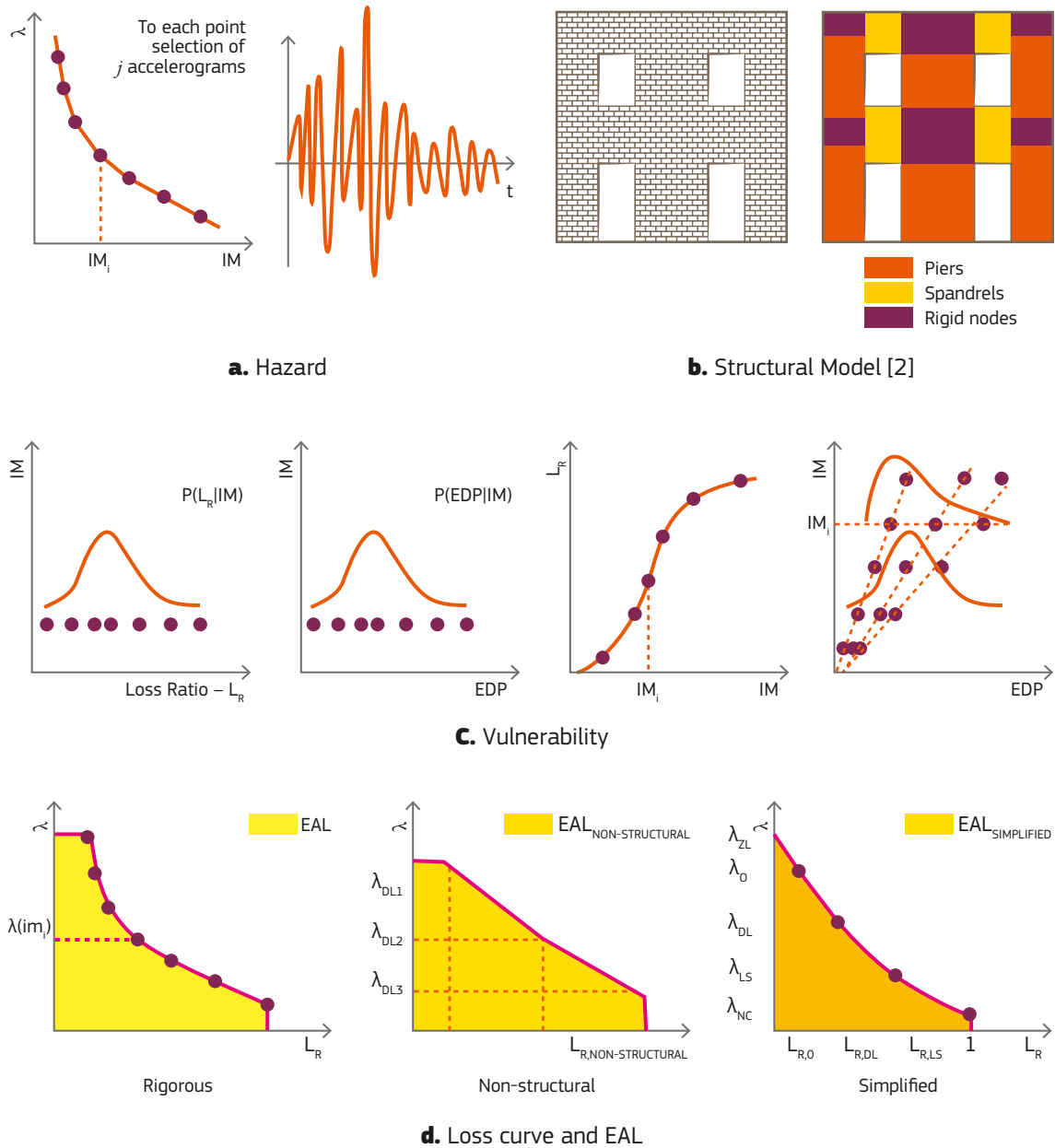
Where α_j is the economic weight of each component in a masonry building. At the base of the research, in fact, the awareness of the weight of each component (structural, non structural and contents) in the overall loss of a masonry structure has been analyzed. From which emerged that the repair costs of non-structural elements are not significant, because, unlike the reinforced concrete building, they have a marginal impact since substantially almost all walls are structural.

In this framework, the methodology developed for the loss assessment is based on the following steps:

1. the construction of the inventory of the building, where the components to be considered for a masonry buildings are listed. For each one component the following parameters are reported: the corresponding EDP assumed as representative of their seismic response; the unit of measure for the costs; the cost C_x for each element (x) per square meters or per unit; the total loss of each components (L); the percentage of the loss of each component than the overall losses. The C_x correspond to the maximum repair value, equivalent to the reconstruction value;
2. the definition of the hazard (Figure 3.a) in terms of: seismic hazard curve, with i values of IMs and sets of accelerograms (j) with which perform nonlinear dynamic analysis (NLDA);
3. the definition of a numerical model, to carry out structural analyses. The proposal is based on a 3D equivalent frame (EF) modeling strategy, which belongs to the structural element models (SEM), Figure 3.b. For this reason, the structural components are divided in piers and spandrels (elements through which the wall is discretized in an EF model and where the nonlinear response is concentrated, connected by rigid area, nodes), if other strategies of modeling are adopted the components for the structural part may change. In fact, it is important to note that the methodology herein proposed maintains a certain generality and could be properly adapted to other modeling strategies;
4. the construction of the vulnerability curve (relationships between expected loss and seismic intensity) through the structural analysis of the building that may be established in two ways (Figure 3.c): i) passing directly from the intensity measure to repair cost ($IM-L_R$); ii) passing through the incremental dynamic analysis IDA curves, that implies a IM-EDP relation. Furthermore the vulnerability curve can be drawn also in simplified practice-oriented way, the latter passing through the identification of the limit states L_S ;
5. the performance calculation, that entails the determination of the probable loss distributions and the computation of the expected annual loss (Figure 3.d). It is important to note that, to account for the many uncertainties for this type analysis, the methodology uses a Monte Carlo procedure to compute loss calculations. According to the practice-oriented procedure, the simplified vulnerability curve allows construing also a simplified loss curve (Figure 3.d), correlating the mean annual frequency of exceedence of each L_S and its economic losses ($L_{R,LS}$).

In the following the procedure for the construction of the rigorous vulnerability (the step 4) curve is detailed.

Figure 3. Steps of the loss estimation procedure developed for masonry buildings in seismic area



As introduced above, once defined the inventory and the structural model of reference, the nonlinear analyses have to be executed in order to define the vulnerability and, consequently, the loss curves, following two ways:

- passing directly from the intensity measures to repair costs ($IM-L_R$). This is based on the definition of a cost function built on the diffusion of damage (Figure 5) in piers and spandrels (according to the structural modeling strategy adopted) and dependent on a specific EDP as a function of the given examined component (Figure 4.a). In the case of vertical structural elements the assessment is based on an analytical cost function dependent on the drift of piers and spandrels, instead, for the floors, the variable that describes the replacement cost is the angular deformation. Figure 4.b shows the cost function for the piers based on actual repair costs, differentiated with the prevailing failure mode occurred, if associated to a flexural

or shear response. This is justified by the fact that the spread of damage is different in these two cases: mostly concentrated at the end sections in the flexural response and more spread on the whole panel in the shear one (Figure 4.b);

- passing through the IDA curves, that implies: a **IM-EDP** relation that is a description of the structural seismic response or “demand” versus the **IM**; the estimation of the seismic capacity of the structure; the determination of a probabilistic characterization of the variability of capacity and demand, and therefore the fragility function for the structural model considered (Iervolino and Manfredi 2008). After the definition of the fragility, the consequence functions (Damage Level, **DL** – Loss Ratio, **L_R**) are introduced to estimate the repair costs.

Figure 4. a) Repair cost function related to the constitutive models of the elements of the EF model of reference Tremuri (Cattari and Lagomarsino 2013); b) Pier cost function and pictures of the two collapse mechanisms involved in the function: shear (left) and flexural (right) (Ottonelli 2016)

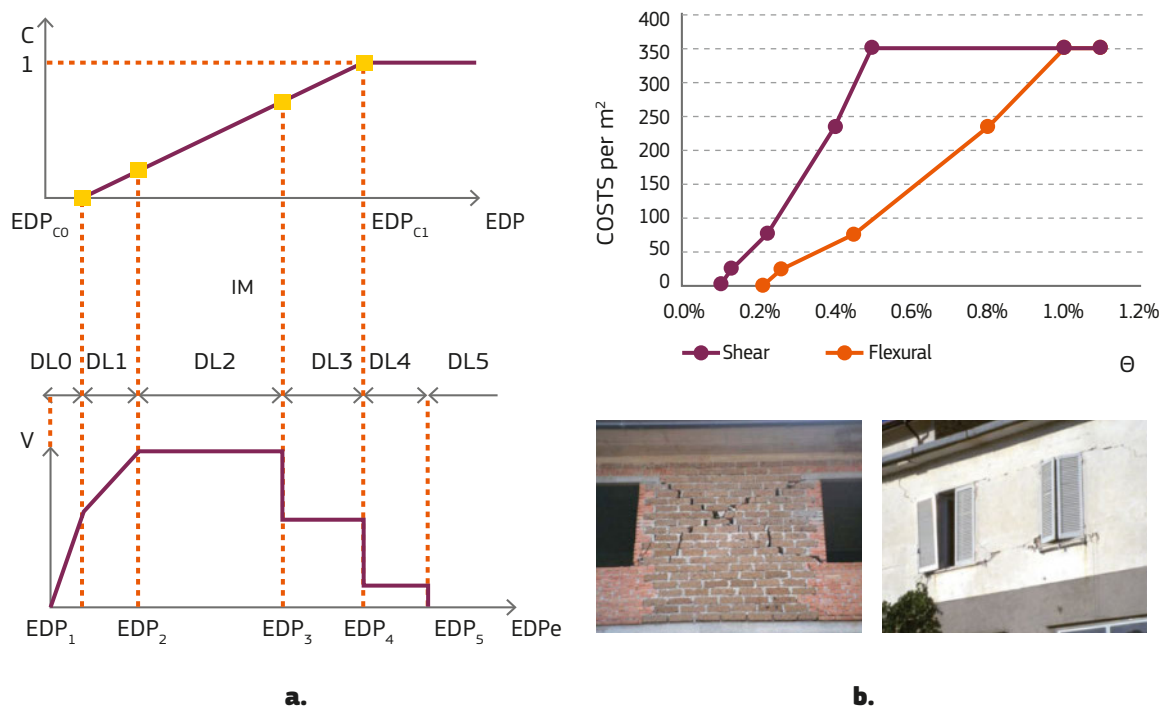
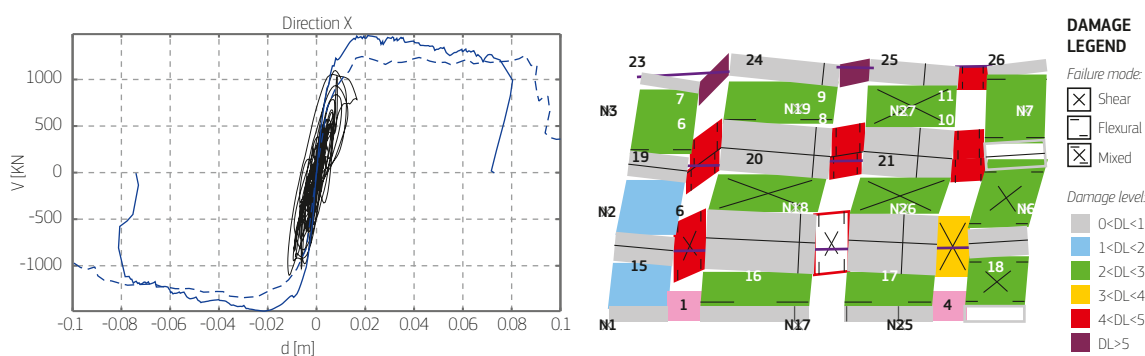


Figure 5. Example of damage pattern of a wall after a Nonlinear Dynamic Analysis (NLDA)



For some components, for example the non-structural ones, both approaches can be followed, since for them it is possible to define an EDP representative of their structural behavior directly related to their cost. Vice versa for the structural ones, only the first approach is feasible, because, it is limitative to consider their response in terms of loss described by a single EDP, in fact the losses are the sum of the costs of individual elements but also the result of the interaction of the response of the various structural elements.

From the first approach, the vulnerability curve ($IM-L_R$) on structural elements is obtained immediately (Figure 3.c). Introducing the hazard curve that reports the Mean Annual Frequency (MAF), λ_{IM} , of the relevant IM (with which the NLDA are performed), the loss curve ($\lambda_{IM}(im)-L_R$) can be construed (Figure 3.d). By taking the area under the loss curve the EAL is computed (Equation 2).

From the second approach, the IDA curve ($IM-EDP$) is computed (Figure 3.c). Introducing the occurrence of DLs in the IDA and the SAC/FEMA approach (Cornell et al 2002, Vamvatsikos 2012), the mean annual frequency of the different DLs , λ_{DL} , are evaluated. The introduction of the DLs or LSs and the SAC/FEMA formulation is also essential for the evaluation of the simplified loss curve, that correlates the λ_{LS} and its economic losses ($L_{R,LS}$) that are chosen from reliable consequence functions.

4. Conclusion

The seismic resilience of a built environment is based on the evaluation of three elements: its probability of failure during an earthquake, as well as the consequences from such failures and the time to recovery. In this framework, this paper investigates the first two elements for the masonry buildings for which the literature is particularly limited, proponing for them a numerical and analytical procedure. It allows to determine the robustness of a system in economic terms, and it is an essential step to future development in the definition of the downtime assessment and complete the resilience evaluation for a masonry structure.

The main advantage of the proposal is the possibility to be applied in different types of masonry structures, representing different classes of homogeneous seismic behavior, to establish limit states (or damage levels) and repair cost relationships, on which the consequences functions are based. The availability of cost functions for buildings characterized by different collapse mechanisms and damage distribution would be a useful reference for the literature. This step is essential to perform portfolio risk analyses, essential to determine a resilience of a built environment.

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Linking Risk to Resilience: A Quantitative Method for Communities to Prioritize Resilience investments

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Abstract

Resilience is the ability of a community to respond to and recovery from disaster. The characteristics of a community that impact resilience include demographic statistics, built infrastructure, the natural environment, economic robustness, and community planning efforts and can number in the hundreds. Critically, these characteristics are not often linked to the hazards to which a community is at risk, limiting the ability of a community to make risk-informed, targeted investment decisions. To help communities prioritize investments in resilience, we describe here a method to define hazard-specific risk based on hazard impacts, correlated with the resilience characteristics aligned with community priorities and rank these investments based on their relative benefit. Using flood as the proof-of-principle hazard, we describe a method and corresponding decision support tool, in development through an effort funded by the US Department of Homeland Security Science and Technology Directorate (DHS S&T), to perform a rapid flood risk assessment to support data-driven investments in resilience enhancement. Flood impacts are described in either cost or population common units and are cross-referenced with a short list of resilience characteristics chosen by the community from an inventory collated from the resilience literature. This approach ensures the list of community resilience characteristics chosen for analysis are limited to those directly linked to flood risk, known to have a direct effect on resilience, and of priority to the community. The decision support tool provides communities support in defining investments to address and enhance resilience related to each community resilience characteristic and evaluate these investments based on relative benefit as defined by the cumulative probabilistic impacts across a range of flooding scenarios. This proof-of-principle effort is designed specifically to support flood resilience, but is designed to be transferrable to any other hazard for which a community can perform a rapid risk assessment – to our knowledge, the first of its kind to be specifically tailored to evaluating and communicating risk to community-level end users.

Keywords

flood risk, risk assessment, community, decision support, investment, resilience



1. Introduction

Resilience is defined as “The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events” by the Committee on Increasing National Resilience to Hazards and Disasters at the US National Academies (National Research Council, 2012). Community characteristics related to resilience include demographic metrics (social factors), built infrastructure, and the natural environment as well as economic robustness and community planning efforts. Methods to measure resilience on the basis of these characteristics within communities have been developed (Cutter et al., 2010, 2003; Flanagan et al., 2011; and others), but principally provide a baseline assessment of community resilience and are not intended to be a framework for prioritizing actions to improve resilience. Indeed, communities tasked with improving resilience often have little practical guidance, and this limited guidance is rarely based on locally-relevant risk. Here we present a method to support informed, risk-based decision making for flood resilience investments at the community level.

Community resilience is directly linked to hazard risk. Flooding is the most frequent, widespread, and costly natural hazard in the US. Estimates place 2016 flood-related financial losses in the tens of billions (Benfield, 2015; Bevere et al., 2011) an amount 21 percent above the 16-year average of USD174 billion. The losses were an even more robust 59 percent higher on a median basis (USD132 billion and floods caused a significant number of fatalities each year both in the US and internationally. Therefore, enhancing community flood resilience is a central focus for resilience and flood risk mitigation investments to protect lives and reduce financial losses, whether caused by smaller, more frequent floods (e.g., 10-year return interval events) or large, catastrophic flooding (e.g., 500-year return interval events).

Here we present the framework for a decision support tool, including graphics developed to communicate results and provide context for community decision makers in choosing the most effective resilience investments. The method provides communities with a data-driven approach to focus investments in resilience enhancement to efforts that address flood risk and are of priority to the community.

2. Methods

2.1. Identification of resilience characteristics

Community resilience characteristics were identified through a review of published literature and other open source reports. Though hundreds of community resilience indicators have been reported in the literature, we found that resilience indicators are not directly linked to underlying hazard risk faced by the community (see results in Table 1 for selected examples). Community resilience indicators identified in this literature review formed the basis for a crosswalk from flood risk to community resilience to fill this gap in available tools for investment prioritization.

Table 1. Translating flood risk profile into resilience characteristics

Community characteristics at risk to flooding	Resilience characteristics (risk-resilience crosswalk)	
	Population impacted	Financial losses
Hospitals inundated	Number of patients to relocate	Cost to repair inundated hospital and replace contents
Inundated substations serving population using electricity-dependent medical equipment (EDME)	Population using EDME without power	Cost to repair inundated substation
Socioeconomically vulnerable population in inundation zone	Vulnerable population requiring evacuation and resource support	Cost of food and water support for 3 days
Schools inundated	Number of students likely to have education disrupted	Cost to repair inundated school
Residential building stock inundated	Population predicted to be displaced	Cost to replace residential buildings and contents

2.2. Converting flood impacts to common units

Using a rapid assessment flood risk modelling method (Longenecker, et al, in preparation) community characteristics are identified that are at risk to the flooding events of greatest concern to the community, are included in the resilience characteristics defined in the literature, and of priority to the community. The relative impacts of flooding to these characteristics are defined by common units (i.e., population or cost) and calculated for a range of flooding events. For example, relocating patients from a hospital can be calculated by multiplying the number of beds by the percentage occupancy to define the number of people impacted. The cost of inundation to the same hospital may be calculated by multiplying the total cost to replace the interior of the basement and first floor by the depth damage function to determine a total cost of impact for each event type.

2.3. Investment benefits calculation

Investment benefits are calculated using a counterfactual approach that compares “before and after” flood risk for each investment. The method is designed to predict the difference in outcomes under two conditions (C versus C^*), where C is the factual (i.e., current reality) and the system operating with the hypothetical C^* is the counterfactual (i.e., the alternative reality reflecting a new resilience investment) (Bottou et al., 2013). Benefits are adjusted to account for the difference in likelihood between events using expected value decision analysis (Albright et al., 2010), a method designed specifically to assess aggregate benefit across a probabilistic range of scenarios used to inform decision-making in a wide range of fields.

The expected value of each decision D is equal to the probability-weighted sum of the outcomes' benefits. Here, decisions correspond to a specific investment, outcomes correspond to the benefits provided by the investment across a range of probabilistic flood events, and the expected value of the decision corresponds to the expected benefit of the investment across the cumulative risk of flood in the community. Mathematically, the expected value of decision D_i , denoted $E[D_i]$, is given by the equation

$$E[D_i] = \sum_{j=1}^2 p_i b_{i,j}$$

where p_i is the probability of outcome O_j , and $b_{i,j}$ is the benefit of outcome O_j under decision D_i . Additional details of how this method is used to rank and prioritize resilience investments using flood event probability are described in the results section below.

3. Results

The list of community characteristics at risk to flooding can be extensive; likewise, the comprehensive list of characteristics associated with resilience is hundreds long. In addition, communities have unique local priorities: some are focused on protecting a robust small business community; some are specifically concerned about an economic hub – a factory, community college, or regional hospital; some view themselves as a transportation hub and are primarily concerned with maintaining access to transportation infrastructure. By cross-referencing characteristics associated with resilience, at risk to flooding, and aligned with community priorities, a list of target characteristics and corresponding investment strategies can be prioritized. Starting from a list of community resilience characteristics linked to the population and infrastructure at risk of flooding focuses community resilience investment efforts to where they best address flood risk.

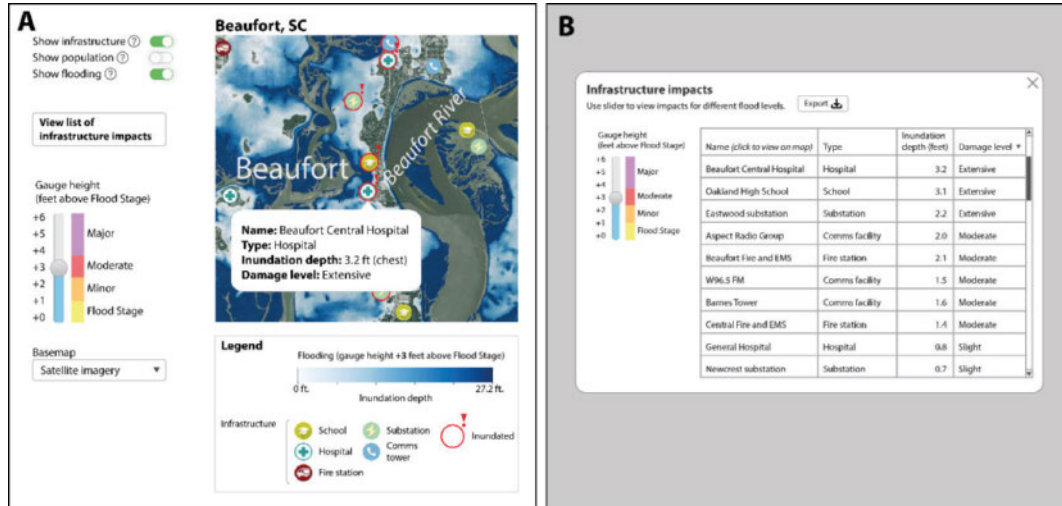
3.1. Applying flood to target resilience priorities

To assess flood risk, communities need to map predicted inundation for a range of flood event severities faced by the community and overlay these maps with population distribution and infrastructure locations to determine predicted flood impacts across scenarios. The core requirements for inundation maps used in this method are inclusion of point-depth estimates at regular intervals (i.e., in a 10-meter by 10-meter grid) and include each of the recurrence intervals of concern to the community (e.g., 10-, 20-, 50-, 75-, 100-, 200-year floods). Potential sources of inundation maps in the US include the FEMA RiskMAP program (US National Flood Insurance Program), detailed flood studies previously conducted in the community, and local flood modelling subject matter experts using publicly available tools (e.g., models from the US Army Corps of Engineers Hydrologic Engineering Center). Population and infrastructure are available from national-level sources and by applying locally collected data. In a related effort, we are also developing a rapid flood risk model in collaboration with FEMA to directly support flood modelling required for the investment prioritization method and improve access to flood risk information for communities that do not have ready access to flood risk assessment methods.

Figure 1. shows an example of flood modelling outputs – an inundation map with nationally-available infrastructure and population datasets. Impacts are described graphically on the map (Figure 2 A) and in a linked table (Figure 2 B) to provide additional detail. Importantly, the slider bar indicates the ability of the end user to evaluate a wide range of events, from frequent, less severe events to rare, but catastrophic events, including an overview of the impacts, as defined by the infrastructure and population affected by inundation. The primary goal of the visualization is to provide non-experts in flood modelling an intuitive sense for the severity and impacts both to infrastructure and population for flooding events defined both by water depth above flood height and annual exceedance probability (AEP).

Figure 2. Modelled flood impacts to infrastructure.

(A) Map of infrastructure inundated by a moderate flood (+3 feet above flood stage). Inundated infrastructure is circled in red. (B) Detailed infrastructure impacts table with inundation depths and damage to specific infrastructure.



3.2. Linking flood impacts to resilience in common units

Prioritizing investments in resilience first requires quantification of flood impacts in common terms. Impacts are described in two common unit types: financial loss and population impacts (see Methods) forming the quantitative basis to compare resilience investments to address flood impacts. Financial losses are calculated for both infrastructure and population impacts. In the case of infrastructure like a hospital, investment in sandbags, relocation, or drainage ditches can prevent inundation for smaller floods or lower local inundation depths and wide-scale protection from a levee may be the only effective investment to protect a hospital at risk of more significant flooding. In Figure 2A, an example is shown for a community concerned with protecting the local hospital during a flood. The inset table in the graphic shows the quantified resilience characteristics for an example hospital, calculated for each flood severity, for patients needing relocation (population impacted) and repair costs (financial loss). As shown in Figure 3, investment options can alternatively be targeted to address infrastructure or populations of concern. An option to build a levee to protect a hospital is shown in Figure 3A. As shown in Figure 3B, deploying generators or planning effective evacuation routes could significantly reduce impacts to the general population or sub-populations of special concern (e.g., elderly or those reliant on electricity-dependent medical equipment-EDME).

Figure 3. Defining target resilience investments for impacted infrastructure and population.

(B) The impacts to the population using electricity-dependent medical equipment (EDME) for different flood levels, and potential investment options. The option “Update evacuation plans” is selected, and the interface guides users in defining how many people are supported by the updated plan and the cost to update it.

A

Resilience investment assessment

Beaufort Central Hospital

Impacts				Investment options	
Flood severity	Patients needing relocation	Repair costs	Inundation depth (feet)		
Flood stage	0	\$0	0	Build levee	
Minor	165	\$10,000,000	2	Click "Draw levee" to draw a levee near Beaufort Central Hospital.	
Moderate	165	\$20,000,000	3.2	Draw levee	
Major	165	\$47,300,000	3.5		

B

Resilience investment assessment

Population using EDME

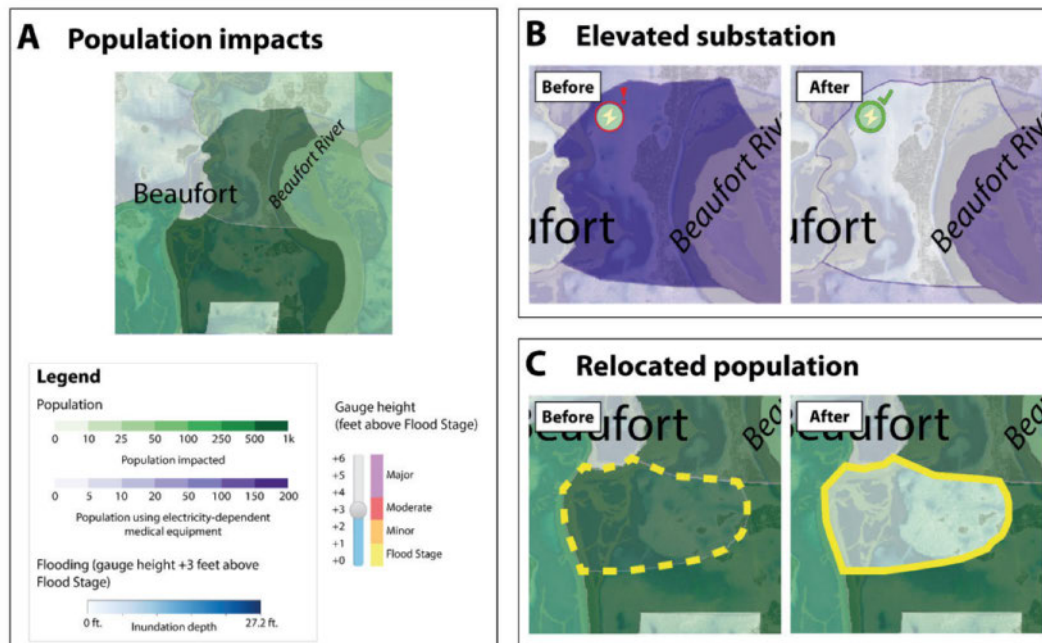
Impacts			Investment options	
Flood severity	People needing evacuation	Cost to evacuate		
Flood stage	122	\$14,600	Update evacuation plans	
Minor	401	\$48,100	Enter population supported by updated evacuation plans, cost to implement updates, and click "Confirm."	
Moderate	800	\$96,000	Population supported: Cost:	
Major	832	\$99,800	<input type="text" value="enter number"/> \$ <input type="text" value="enter cost"/> Confirm	

3.3. Modelling investment benefits

Communities can most effectively improve resilience by targeting investments that also reduce risk. Figure 4 shows examples of how the method developed here can be implemented to assess risk-weighted investment benefit by iteratively modelling the effects of each target investment under a range of flood conditions. In the example show in Figure 4, power outages due to flooding impact a subset of the population in a community with EDME populations at particular risk. This method calculates the benefit of raising a substation as the reduction in power outage impacts to the EDME population for a range of flood events (e.g., different flood depths). A three foot elevation of the substation protects against a 10-year, 50-year, and 100-year flood, but not against a 200-year or larger flood.

Figure 4. Population protected by investments.

(A) Map of population inundated by a moderate flood (+3 feet above flood stage). US Census tracts inundated are darker. (B) Flood impacts to population using electricity-dependent medical equipment (EDME) before and after investment. (C) Flood impacts to general population before and after investment.



Investments may reduce flood impacts either by decreasing the likelihood of the event occurring (e.g., reinforcing a dam, building or raising a levee) or specifically by targeting specific impacts (e.g., sandbagging a specific piece of infrastructure, writing and implementing evacuation plans). Evaluating the benefit of investment in flood control structures (e.g., levee or drainage ditch) that alter the flood event itself are calculated by comparing the results of event characterization and consequence modelling to compare inundation levels and corresponding impacts. Investments related to specific population or infrastructure protections or enhancements are calculated by comparing impacts as determined by consequence modelling alone, as there is no change in the flood event itself.

Investment benefits depend upon the severity of the flood and this method applies a risk-weighting approach to calculate the aggregate benefit across flood severities. Table 4 demonstrates the risk-weighting of benefits using flood event probability. Each event is assigned a probability weight equal to the difference in AEP between that event and next event of greater severity. To produce the results in Table 4, the first-order flood risk assessment method was used to model each flood recurrence interval shown, both in the absence of a levee and after construction of a levee that protects that hospital. The hospital was not inundated by the 10-, 20-, or 50-year flood events. It was inundated by 75-, 100-, and 200-year events, with the levee providing protection for the 75- and 100-year events, but not the 200-year event. Benefits are shown for the 75- and 100-year floods as the financial loss prevented by the levee. The levee has no financial benefit for the hospital at less severe floods because they do not cause inundation and no benefit for the 200-year event because the hospital was inundated despite the levee. The benefits for the 75-year and 100-year floods are weighted using their respective probability weights. By applying the same method to all target investments under consideration, the risk weighting step provides a common framework to compare disparate types of investments using a common, flood risk-based estimate of investment benefits.

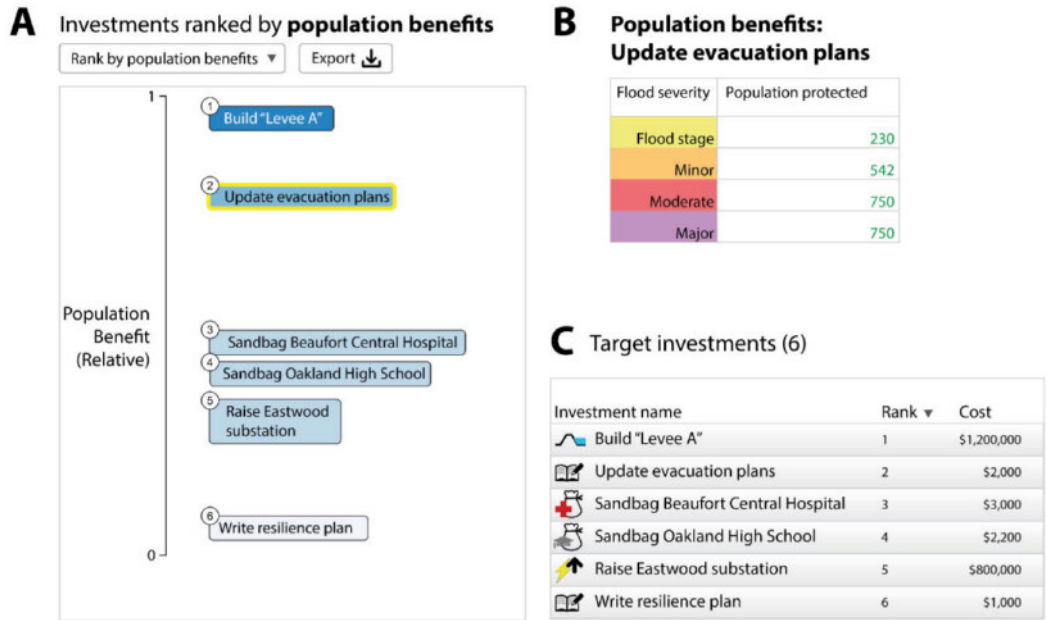
Table 2. Calculating the mean weighted investment benefit (expected benefit) for a levee protecting a hospital.

Flood recurrence interval (years)	Flood annual exceedance probability	Cost to replace interior (no levee)	Cost to replace interior (with levee)	Investment benefits (losses prevented)	Probability weight	Weighted investment benefits
10	0.10	\$0	\$0	\$0	0.050	\$0
20	0.050	\$0	\$0	\$0	0.030	\$0
50	0.020	\$0	\$0	\$0	0.0067	\$0
75	0.013	\$20.0M	\$0	\$20.0M	0.0033	\$0.067M
100	0.010	\$45.5M	\$0	\$45.5M	0.0050	\$0.23M
200	0.0050	\$47.3M	\$47.3M	\$0	0.0050	\$0
Expected investment benefit						\$0.30M

Based on modelled flood impacts, this method provides communities to link to flood risk with community resilience characteristics and develop a short list of potential investments that reflect both an assessment of what drives local flood risk and the selection of local priorities for resilience enhancement. Once the statistical method is applied to calculate a risk-weighted sum of benefits for each target investment (Table 4), these benefits are considered on a relative scale where the investment with the greatest benefit is set to 1 and all other investments are plotted as a relative comparison either based on population or cost (Figure 6A and 6B). This format supports best practices in risk communication identified in the research literature, including limiting quantitative information to only that most relevant to the decision, using clear terminology and plain language, and driving toward the end-goal – namely selecting resilience investments (Melkonyan, 2011; National Oceanic and Atmospheric Administration, 2016; Vaughan and Buss, 1998). These results can then be applied in the context of other factors important to the local investment decision making process, including budgetary constraints or alignment with other ongoing resilience enhancement efforts (see Figure 6C).

Figure 5. Ranking target investments by population benefits.

(A) Target investments are ranked by relative population benefit. Toggle to view relative benefits by population or cost not shown. (B) Detail of population benefits provided by updating evacuation plans for different flood levels. (C) The list of target investments ranked by relative population benefits, with user-provided implementation cost shown.



4. Discussion

Communities worldwide have been asked to improve their resilience. The method described here is a critical proof-of-principle effort demonstrating how rapid risk analysis for a single hazard can be applied to support risk-based investment prioritization at the community level. The method and corresponding web-based tool in development is specifically designed to inform decisions in the absence of more robust modelling or local subject matter expertise and is designed to inform more in-depth analysis once a community has established initial investment priorities. This community-focused approach presents the results of a complex flood risk modelling and statistical analysis in a way that communicates these priorities to support practical decision making by members of the community and stakeholders involved in resilience and disaster planning efforts. Though flood was used here as a proof of principle hazard, the approach is broadly applicable for other hazards for which risk assessment models are available including earthquakes or disease outbreaks for which epidemiological models are available.

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Measuring Resilience Using a Comprehensive Approach to Assess Disaster Risk Management Performance

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Abstract

Disaster risk reduction and adaptation to climate change considering economic, social, and environment issues, are the objectives of an integrated, interdisciplinary and multi-sectoral disaster risk management. Sustainability and transformation of development are only possible if there is a suitable strategy of vulnerability reduction and resilience improvement; i.e. through the governance strengthening and its capacity to anticipate, cope and recover. From this perspective, the best way to assess resilience is implementing a methodology to evaluate the disaster risk management performance and effectiveness.

This article presents the Disaster Risk Management Index, **DRMi**; developed to assess and benchmark the risk management performance, providing the overall set of targets and actions to be implemented improving resilience and safety from natural hazards point of view. The **DRMi** provides a quantitative measure of the degree and effectiveness of management based on predefined qualitative targets (benchmarking) that risk management efforts should aim to achieve. The design of the **DRMi** involves establishing a linguistic scale of achievement levels or determining the 'distance' between current conditions and objective thresholds in a country, subnational region, or city used as reference. The **DRMi** was built using a fuzzy logic approach by quantifying four public policies, each of which being described by six composite indicators. The policies include the risk identification (**RI**), risk reduction (**RR**), disaster management (**DM**) and governance and financial protection (**FP**). In addition, this paper presents some results to illustrate the application of the **DRMi** as a method to give account of the resilience level of the countries.

The **DRMi** is an innovative indicator for the measurement of the performance and feasible effectiveness of risk management, developed in the framework of the Program of Indicators for Disaster Risk and Risk Management in the Americas of the Inter-American Development Bank. It has been applied to evaluate twenty-six countries in Latin America and the Caribbean. The FP7 project on Methods for the Improvement of Vulnerability Assessment in Europe, MOVE, applied the **DRMi** to the city of Barcelona, Spain, as an example.

Keywords

risk management,
performance of
risk management,
risk management
index,
decision making.



1. Introduction

Several methods based on composite indicators and other approaches have been proposed, mainly, to evaluate vulnerability and disaster risk issues. The contributions of Bates (1992), Cutter (1994), Tucker et al. (1994), Davidson (1997), Puente (1999), Cardona et al. (2003 a,b; 2012), UNDP (2004), World Bank (2004), Carreño et al. (2005, 2007a, 2017), Khazai et al. (2015), Salgado et al. (2016) and Jaramillo et al. (2016) among others, have attempted to measure vulnerability and risk-related aspects using quantitative or qualitative figures. In these methods, vulnerability or disaster risk is evaluated from different point of views, using techniques which are, certainly, similar in approach but different in purpose and scope, particularly if the objective is to measure the performance of risk management or the degree of resilience. The attention in the resilience concept has been increased in recent years in several sectors, each one defines it according to their interests and objectives. The concept of resilience has developed in different schools of thought, such as ecology (e.g. Holling, 1973), psychology (e.g. Bonanno et al., 2006), social-ecological systems research (e.g. Berkes et al., 2003; Folke, 2006) and critical infrastructures (e.g. Boin and McConnell, 2007). In few words resilience is the capacity to anticipate, absorb and overcoming adverse change. The UNISDR (2017) defines resilience as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management”.

Integrated Disaster Risk Management involves the disaster risk reduction and the adaptation to climate change considering economic, social, and environmental issues. These require a suitable strategy of vulnerability reduction and resilience improvement. This article presents the Disaster Risk Management index, **DRMi**, and shows how the best way to assess resilience is implementing a methodology to evaluate the disaster risk management performance and effectiveness. The **DRMi** was designed as an indicator transparent, robust, representative and easily understood by public policy makers at national, subnational and urban level. The **DRMi** involves data with incommensurable units or information that only can be valued using linguistic estimates. The calculation methodology uses the fuzzy sets theory as tool to evaluate the effectiveness of risk management and by this way the degree of resilience.

2. Disaster Risk Management Index, DRMi

The **DRMi** was designed to assess risk management performance and, by this way, its effectiveness (Carreño et al., 2007b). It provides a quantitative measure of management based on predefined qualitative targets or benchmarks that risk management efforts should aim to achieve. The **DRMi** was constructed by quantifying four public policies, each of which having six indicators. Risk identification index, DRM_{RI} , comprises the evaluation of individual and social perception, risk knowledge and understanding and the appropriate assessment of risk. Risk reduction index, DRM_{RR} , the implementation of corrective and prospective prevention and mitigation actions and measures to reduce vulnerability. Disaster management index, DRM_{DM} , comprises the advances on preparedness, response and recovery and governance and financial protection, DRM_{FP} , measures the degree of institutionalization and risk transfer strategies to financial protection (Cardona, 1990, 2005). The four public policies and their indicators were defined after an agreement with several stakeholders and evaluators. The **DRM** is defined as the average of the four composite indicators.

$$DRMi = avg (RMI_{RI}, RMI_{RR}, RMI_{DM}, RMI_{FP})$$

Six indicators are proposed for each public policy, they are presented in Figure 1. Following the performance evaluation of risk management method proposed by Carreño et al. (2004, 2007b). The indicators for each type of public policy (*RI, RR, DM, FP*) are obtained by means of the following equation,

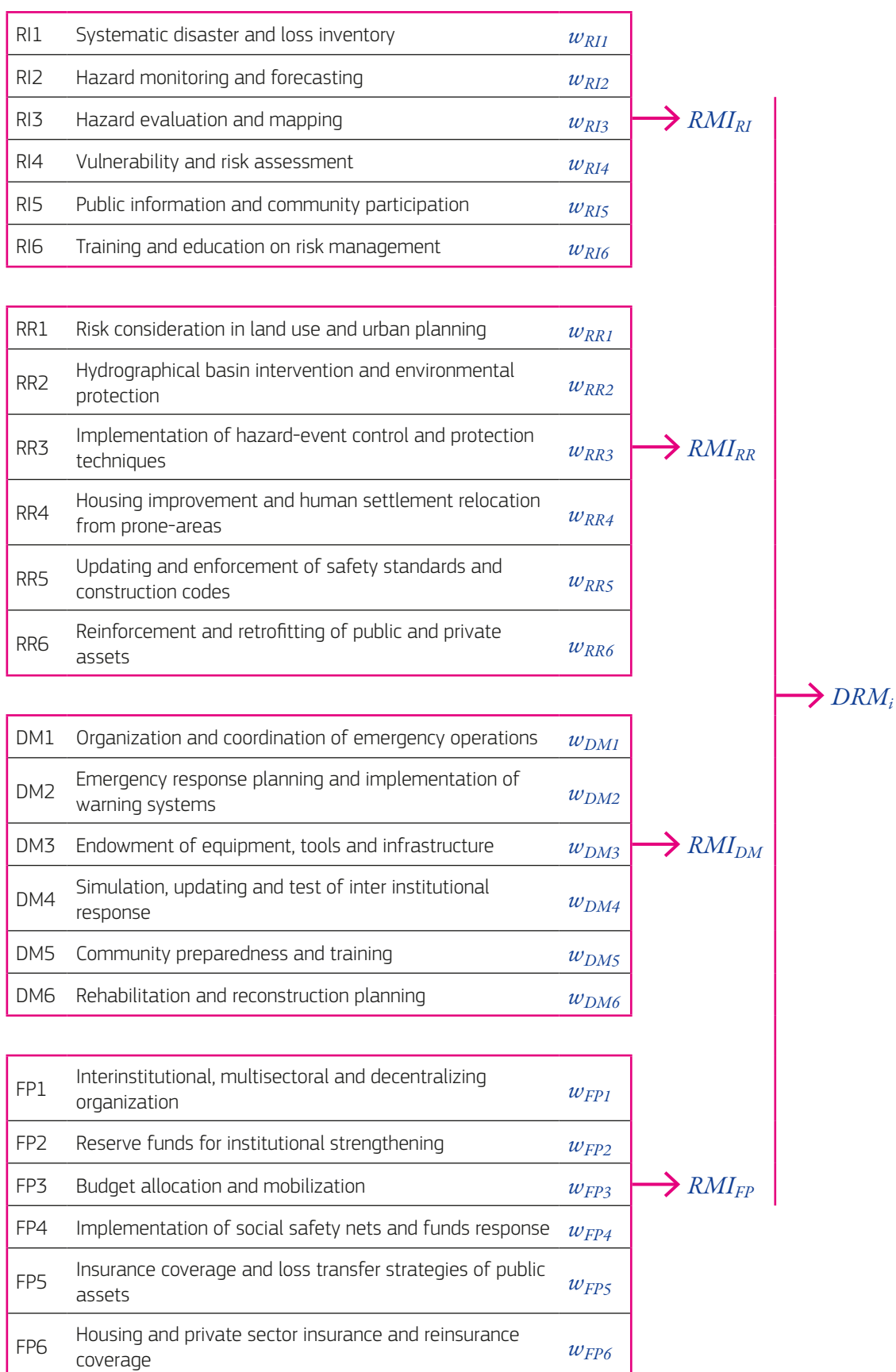
$$RMI_{c(RI,RR,DM,FP)}^t = \frac{\sum_{i=1}^N w_i I_{ic}^t}{\sum_{i=1}^N w_i} \Big|_{(RI,RR,DM,FP)}$$

where, w_i is the weight assigned to each indicator, for the country (or city) in consideration c and the time period t –normalized or obtained by the defuzzification of the linguistic values.

Each indicator is estimated based on five performance levels (*low, incipient, significant, outstanding, and optimal*). This methodological approach permits the use of each reference level simultaneously as a performance objective or target and allows for comparison and identification of results or achievements. Government efforts at formulating, implementing, and evaluating policies should bear these performance targets in mind. Such linguistic values are the same as a fuzzy set that have a membership function of the bell or sigmoidal (at the extremes) type, given parametrically by the following equations,

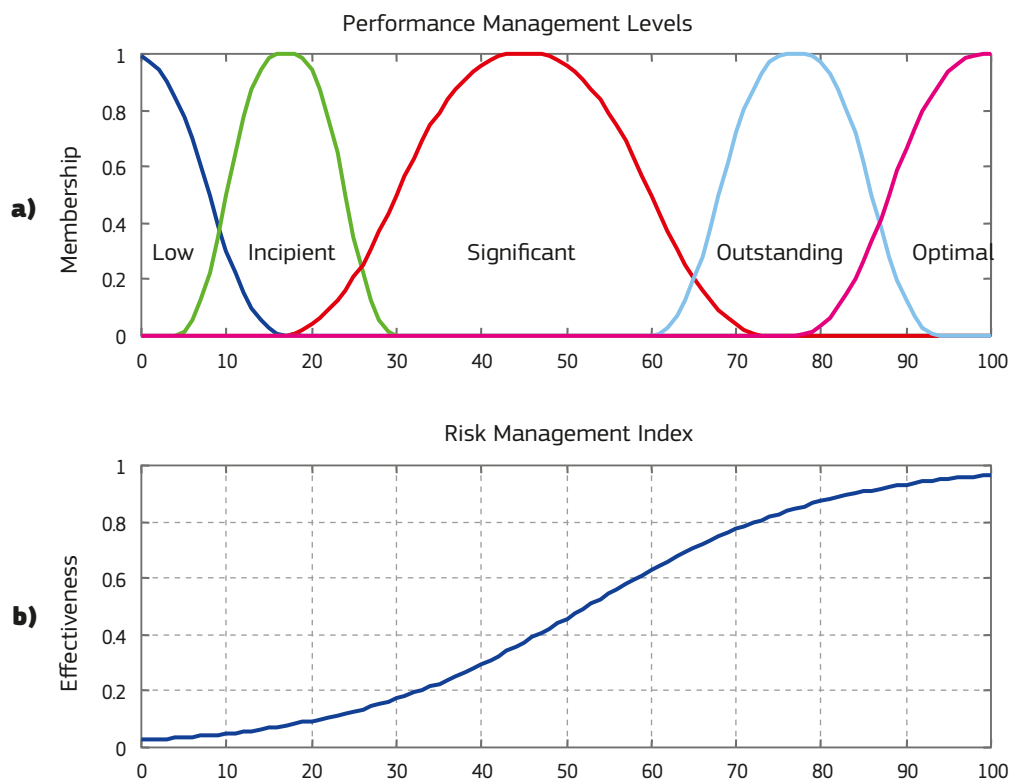
$$bell(x; a, b, c) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}} \quad sigmoidal(x; a, c) = \frac{1}{1 + \exp[-a(x - c)]}$$

where the parameter b is usually positive and a controls the slope at the crossing point, 0.5 of membership, $x = c$.

Figure 1. Component indicators for DRM_i

Membership functions for fuzzy sets are defined, representing the qualification levels for the indicators better than crisp values. The value of the indicators is given in the x-axis of Figure 2.a and the membership degree for each level of qualification is given in the y-axis, where 1.0 is the total membership and 0.0 the non-membership. Risk management performance is defined by means of the membership of these functions, whose shape corresponds to the sigmoid function shows in Figure 2.b, in which the effectiveness of the risk management is represented as a function of the performance level. Figure 2.b shows that increasing risk management effectiveness, that can be considered as well as a resilience proxy, is nonlinear; since it is indeed a complex process. Progress is slow in the beginning, but once risk management improves and becomes sustainable, performance and effectiveness also improve. Once performance reaches a high level, additional (smaller) efforts increase effectiveness significantly but, at the lower levels, improvements in risk management are negligible and unsustainable and, as a result, they have little or no effectiveness.

Figure 2. a) Functions that represents the qualification level, b) Effectiveness degree of the risk management. It provides an equivalent level of Resilience.



Source: Carreño et al. (2007b).

Assessment of each indicator is made using the performance levels: *low*, *incipient*, *significant*, *outstanding* and *optimal*, which corresponds to a range from 1 to 5. The Table 1 illustrates the benchmark description of the performance levels for one of the indicators, where 1 is the lowest level and 5 the highest. In this methodological focus, each reference level is equivalent to a "performance objective", and hence it allows for the comparison and identification of achievements towards which governments should conduct the efforts of formulation, implementation and evaluation of policies.

Table 1. Example of performance levels of one sub-indicator of the DRM_{RR}

Indicator and performance levels	2017
RR5. Updating and enforcement of safety standards and construction codes	
1. Voluntary use of norms and codes from other countries without major adjustments.	1. Low
2. Adaptation of some requirements and specifications according to some national and local criteria and particularities.	2. Incipient
3. Promulgation and updating of obligatory national norms based on international norms that have been adjusted according to the hazard evaluations made in the country.	X 3 Significant
4. Technological updating of most of security and construction code norms for new and existing buildings with special requirements for special buildings and lifelines.	4. Outstanding
5. Permanent updating of codes and security norms: establishment of local regulations for construction in most cities based on microzonations, and their strict control and implementation.	5. Optimal

Once performance levels of each indicator have been evaluated, the value of each component of the DRM_i determined through a non-linear aggregation model based on fuzzy logic. The value of each component ranges between 0 and 100. The evaluation is based on opinions from local experts who provide qualifications of the indicators and assign relative importance between them for each public policy according to their experience and knowledge. This relative importance is processed using the Analytic Hierarchy Process (AHP) to assign weights (Saaty, 1980). Weights assigned sum 1 and they are used to give height to the membership functions of the fuzzy sets corresponding to the qualifications made.

Qualification for each public policy (RMI_{RB} , RMI_{RR} , RMI_{DM} and, RMI_{FP}) is the result of the union of the weighted fuzzy sets

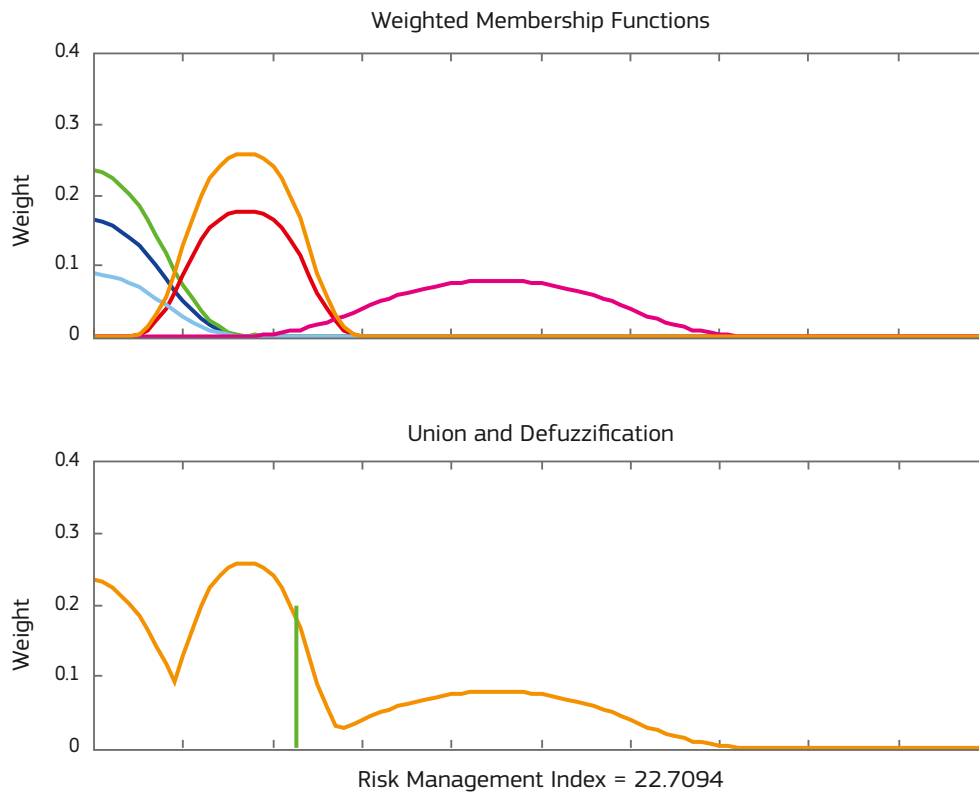
$$\mu_{RMI_p} = \max(w_1 \times \mu_C(C_1), \dots, w_N \times \mu_C(C_N))$$

where w_1 to w_N are the weights of the indicators of Figure 1, $\mu_C(C_1)$ to $\mu_C(C_N)$ are the membership functions of the estimates made for each indicator and μ_{RMI_p} is the membership function of the RMI qualification of each public policy p . The risk management index value is obtained from the defuzzification of this membership function, using the method of centroid of area, COA

$$RMI_p = [\max(w_1 \times \mu_C(C_1), \dots, w_N \times \mu_C(C_N))]_{centroid}$$

The value of each composed element is between 0 and 100, where 0 is the minimum performance level and 100 is the maximum level. Total DRM_i is the average of the four composed indicators that admit each public policy.

Figure 3. Example of union of fuzzy sets and defuzzification to obtain the crisp value of a RMI



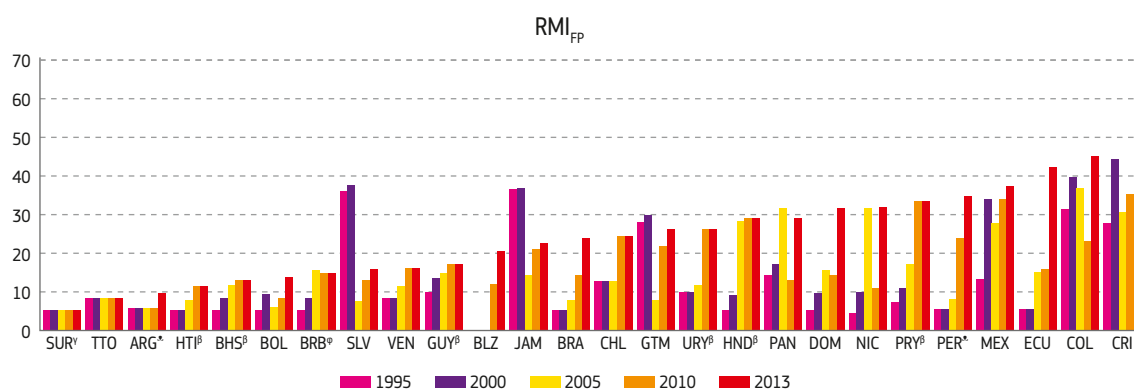
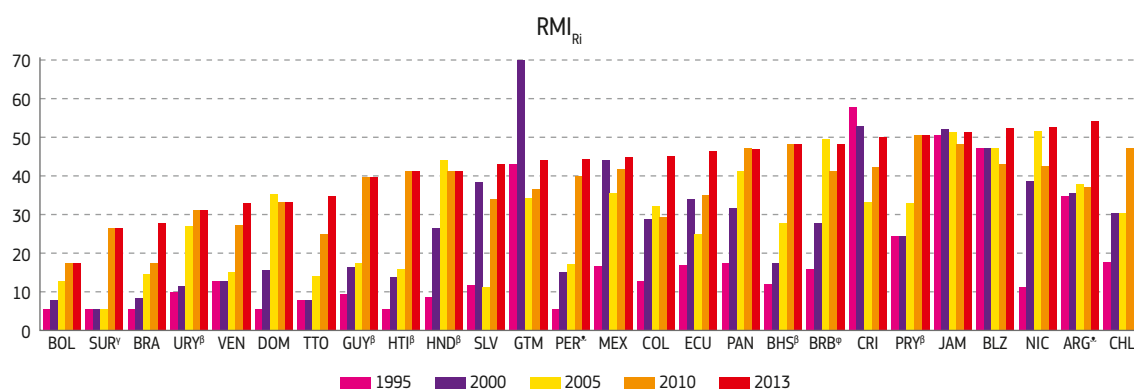
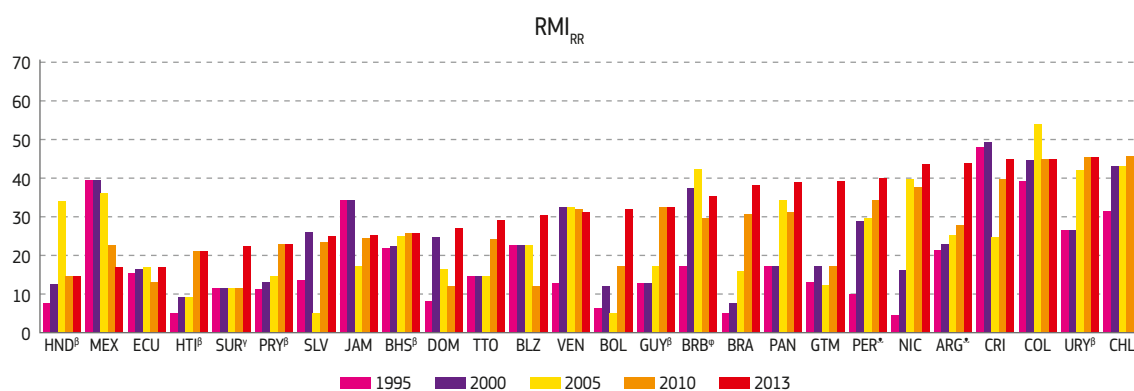
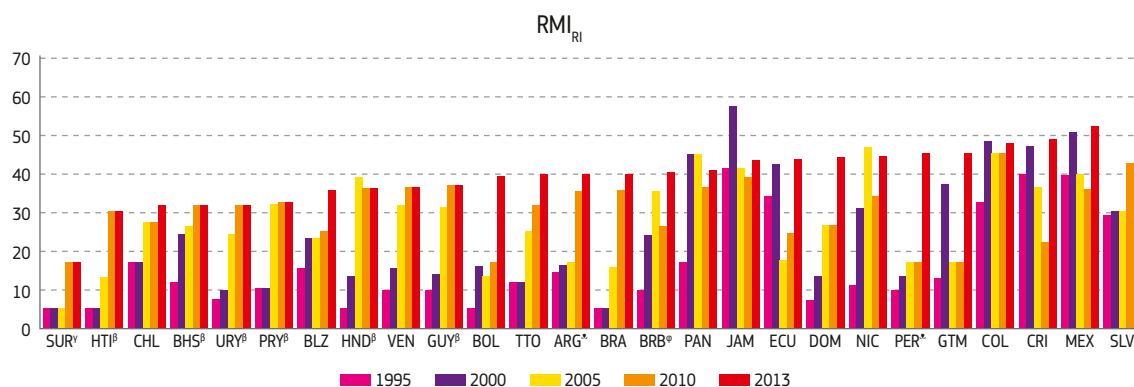
Source: Carreño et al. (2007b).

As abovementioned, the **DRMi** or total index is the average of the four composite indicators that represent each public policy.

3. Evaluation for the Latin-American and Caribbean Region

The **DRMi** has been used by the Inter-American Development Bank to assess the performance of the disaster risk management in 26 countries of the Latin-American and Caribbean region. The countries included are: Argentina (ARG), Bahamas (BHS), Barbados (BRB), Belize (BLZ), Bolivia (BOL), Brazil (BRA), Chile (CHL), Colombia (COL), Costa Rica (CRI), Dominican Republic (DOM), Ecuador (ECU), El Salvador (SLV), Guatemala (GTM), Guyana (GUY), Haiti (HTI), Honduras (HND), Jamaica (JAM), Mexico (MEX), Nicaragua (NIC), Panama (PAN), Paraguay (PRY), Peru (PER), Suriname (SUR), Trinidad and Tobago (TTO), Uruguay (URY), and Venezuela (VEN). Figure 4 shows the comparison of the components for different years.

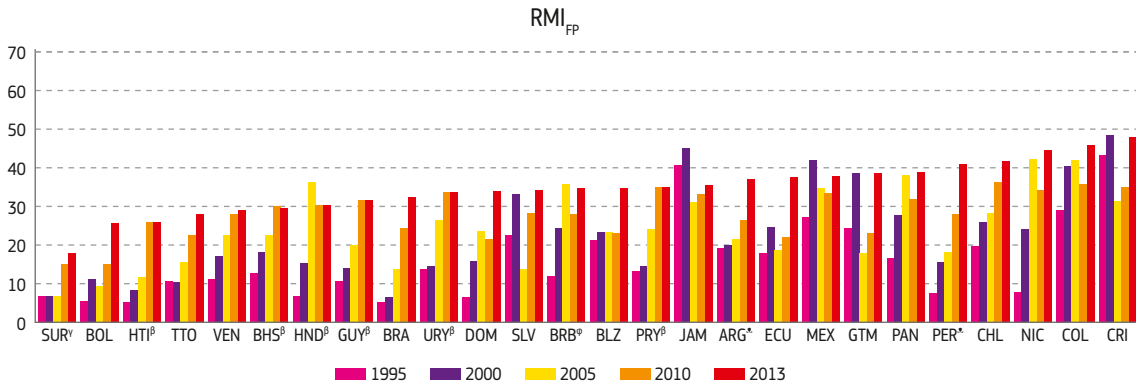
Figure 4. RMI for 26 countries of the Americas considering Risk Identification, Risk Reduction, Disaster Management, and Governance and Financial Protection.



Source: CIMNE & INGENIAR

Figure 5. presents the **DRMi** considering the four public policies. These results indicate that still there is a lot of work to do in all the evaluated countries regarding disaster risk management.

Figure 5. Disaster Risk Management Index for all countries of Latin America and the Caribbean



Source: CIMNE & INGENIAR

- * The results presented for these countries for the year 2010 correspond to the assessments conducted for the year 2008, since assessment for that year was not available.
- β The results presented for these countries for the year 2013, correspond to the assessment conducted for the year 2010, since assessment for that year was not available; that is to say a most recent assessment that is consider useful inasmuch as the difference could not be significant.
- γ For Surinam, results from 2013 in this figure, correspond to a 2012 assessment.
- φ For Barbados, results from 2013 in this figure, correspond to a 2014 assessment.

On average, according to this methodology, the risk management performance in the region is about 30 to 40. Figure 6 illustrates that effectiveness, in the best cases, and by this way, the resilience, is still very incipient (0.2). This suggests that considerable efforts are required to promote effective and sustainable risk management, even in the more advanced countries.

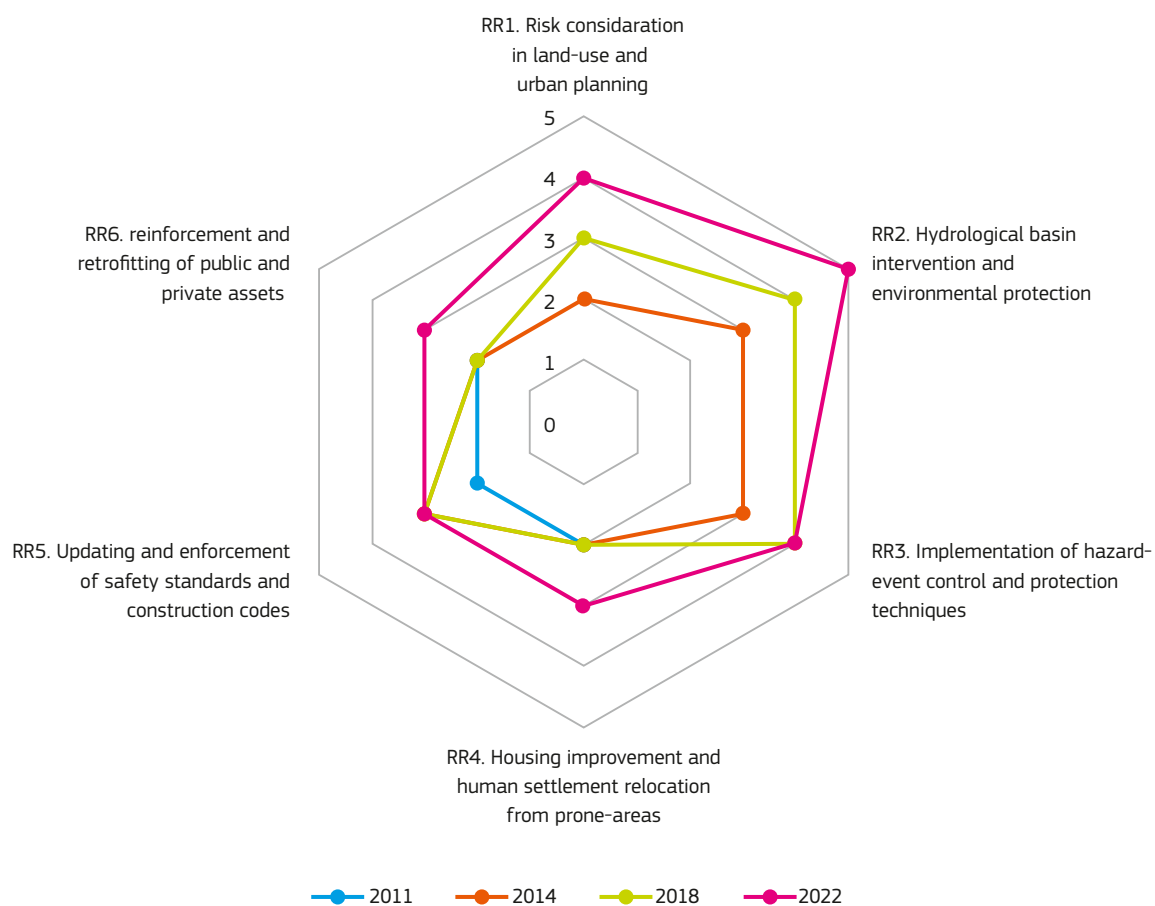
Figure 6. Disaster Risk Management Index for all countries of Latin America and the Caribbean



The results of this type of assessment are also useful to formulate integrated disaster risk management or adaptation plans or to identify the needs to improve relevant aspects of disaster risk management in a country or a city. The next actions or steps to achieve are easily identified. Figure 7 shows the results of a participative evaluation in a prospective way, thinking to provide inputs for the formulation of future steps to improve disaster risk management in a country.

In summary, the **DRMi** has been a systematic and consistent technique developed to measure risk management performance and, by the way, it can be useful to measure resilience as well. The conceptual and technical bases of this index are robust, even though it is inherently subjective. Although the method may be refined or simplified in the future to deal with resilience and adaptation, its approach is quite innovative because it allows the measurement of disaster risk management effectiveness.

Figure 7. Prospective exercise for Risk Reduction for a country.



Additional information related to the methodology and the previous results of **DRMi** is available at: can be found at:

<http://idea.unalmz.edu.co>

<http://idea.bid.manizales.unal.edu.co/> and at:

<http://www.iadb.org/es/temas/desastres-naturales/indicadores-de-riesgo-de-desastres,2696.html>

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How interconnected critical infrastructures can support societal resilience under future climate: The EU-CIRCLE approach

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Abstract

The EU-CIRCLE project (H2020 GA:653824) has defined a holistic framework, that identifies and assesses the risks caused by several climatic hazards and climate-change stressors to heterogeneous, interconnected and interdependent critical infrastructures (CI). This risk management framework is the first step in ensuring the resilience of vulnerable technological, social and economic infrastructure systems to climate change impacts and in climate proofing the existing critical infrastructures (in terms of identifying indicators and reference states, anticipated adaptive / transformation activities, and investment costing). The framework enables the identification of climate-driven CI risks and the strengthening of relevant resilience capacities (anticipation, absorption, coping, recovery, and adaptation) that are vital for ensuring the resiliency of CI.

Keywords

Interconnected
Critical
Infrastructures,
Climate Change,
Risk, Resilience

1. Introduction

Most existing infrastructures have been designed under *the assumption of stationary climate* conditions, where key variables are considered as fluctuating around an unchanging mean state. This assumption of stationarity is still common practice for design criteria for new CI (CEN, 2014), even though the notion that climate change may alter the mean, variability and extremes of relevant weather variables is acknowledged.

The aim of EU-CIRCLE project is to use a validated scientific approach to:

- Assess climate risks to CI using improved methods and new knowledge, from the literature, partners expertise and opinions of stakeholders.
- Identify how climate risks to CI interact with other socio-economic factors to affect the level of risk or risk mitigation or climate change adaptation.



- Estimate the multi-hazard effect, either due to concurrent timing, acting on the same location or the same receptor (coincidence).
- Assess the magnitude of impact to interconnected CI and their importance on society.
- Assess the uncertainties, limitations and confidence in the underlying evidence, data used and analyses for different risks.
- Develop of resilience estimates, CC adaptation and risk reduction options, that can be directly communicated to CI operators, governments and other stakeholders

2. EU-CIRCLE methodology

The EU-CIRCLE project has defined a holistic framework, to identify and assess the risks caused by several climate-change stressors and climatic hazards to heterogeneous interconnected and interdependent critical infrastructures. This is considered to be the first step to ensure the resilience of vulnerable technological, social and economic systems to climate change impacts and improve climate proofing of existing critical infrastructures (in terms of identifying indicators and reference states, anticipated adaptive / transformation activities, and investment costing).

The assessment of impacts in the multi-hazard risk framework is directly compatible with National Risk Assessments, EU Disaster Management Guidelines (EC SWD 1626 final/2010) (EC, 2010) and EPCIP Directive (114/2008) as well as with International initiatives (Sendai Framework) and related standards (ISO 31000), accounting for impacts directly affecting CI and the corresponding consequences to society, the environment and other sectors of the economy. The developed approach for estimating and modelling risk is based on the **Consequence – based Risk Management (CRM) generic approach** the can be used to support the entire project's objectives and scope of assessing an interconnected infrastructure's exposure to climate stressors and determining which hazards carry the most significant consequences. (Shand et al., 2015; Wennersten et al., 2015).

The sectors considered within the EU-CIRCLE framework include energy, water, ICT, transport, chemical and governmental services, as they are all highly sensitive to relative thresholds of hydro-meteorological extremes. The analysis of such extreme events and how they will be affected by changing climate patterns can be used to assess between different options for improving resilience of CI to climate change.

3. CI and assets

EU-CIRCLE has created, for each of the six CI sectors, a registry of CI assets which are considered essential for the operation of each CI and the provision of its critical services. The registry was prepared in cooperation with CI operators and experts in the field. It includes a characterisation of the key attributes of each asset, its function and role within the CI (sub) sector it belongs to; including its role in the provision of critical CI services. As modern CI are found in interdependent networks or 'network of networks', the registry further identifies the interconnections between the assets; both within individual CI sectors and across them. These interconnections have been described as per (Rinaldi et al., 2001) and are characterised as uni-directional (dependency) or bi-directional (interdependency) and as physical, cyber, geographical or logical (inter)dependencies.

The registry enables the case study partners to construct a detailed CI network or 'network of networks' in order to implement and validate the EU-CIRCLE risk assessment methodology. In order to support the risk assessment process, information on the natural hazards that can impact the operation of the asset (e.g. flood, extreme temperatures, wildfire etc.) has been collected in the registry and an estimation of the potential impacts different natural hazards may have on the CI operation is provided using tools such as fragility curves and damage functions, as collected from available literature sources (including grey literature) and contribution from subject-matter experts.

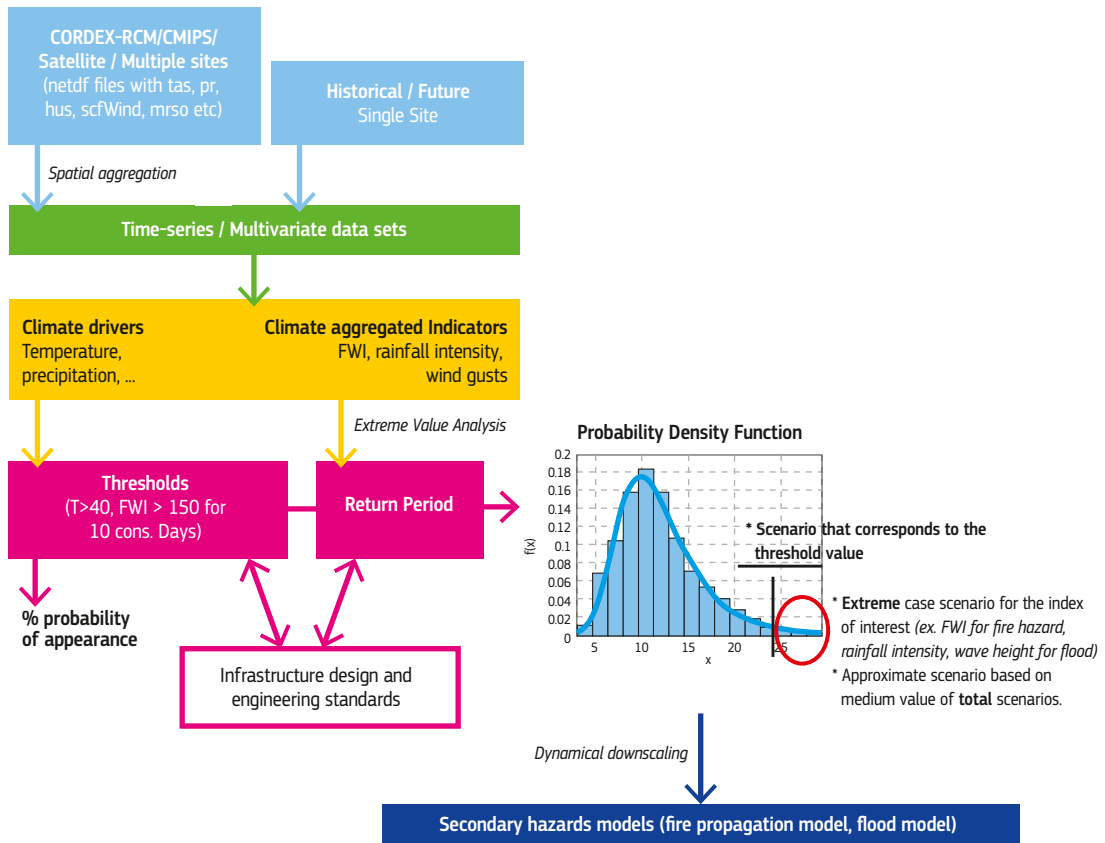
4. Climate data capturing and processing

The climate data needed to conduct the risk CRM modelling approach are obtained through a sequential procedure customised to each specific application.

- Identification of the required climate data for risk assessment.
- Identification of the relevant datasets
- Data gathering and collection
- Estimate Likelihood of future climate / extreme event

For conducting the latter, different data processing tools have been implemented, which include models for production of localized climate projections (statistical ESD - and dynamical downscaling), spatio-temporal processing of climate information and/or hazards parameters in order to account for the exposure of the CI(s) under question, climate scenario selection and secondary hazards models, facilitating their precise introduction into the computational platform (see the workflow on Figure 1).

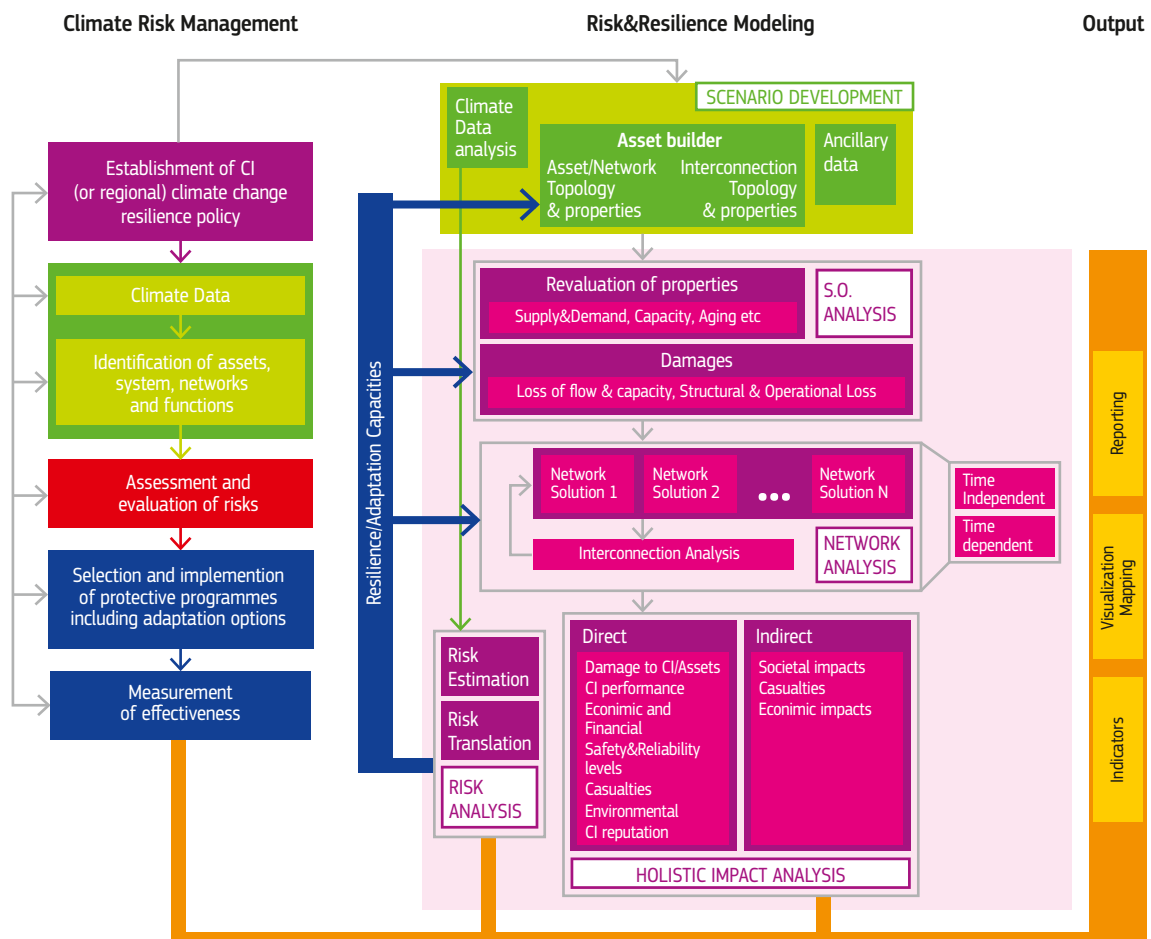
Figure 1. Climate processing overview



5. Risk Management Framework

The EU-CIRCLE risk management framework, consists of the following steps (Figure 2):

Figure 2. Detailed view of EU-CIRCLE risk and resilience framework



1. Establishment of CI (or regional) climate change resilience policy, or specific business oriented decision that will be addressed. Exemplary policy questions to be answered can be: What must and what should be protected? Which potential consequences are relevant (economic, social, environmental etc.) for this appraisal? Which are the priorities? What is an acceptable risk and what is a non-acceptable risk?
2. Identification, collection and processing of climate data and secondary hazards.
3. Identification of assets, systems, networks, relations and functions.
4. Assessment and evaluation of risks.
5. Selection and implementation of adaptation programmes and resilience enhancements options.
6. Measurement of effectiveness of the examined solutions

5.1. Risk matrix approach

Within EU-CIRCLE and in accordance with ISO31000, National Risk Assessments (NRA), JRC initiatives Risk has been defined as: Risk = Likelihood x Consequences

Likelihood (probability of occurrence) refers to the initial probability of the climate scenario to occur and is usually defined as:1/ frequency of one or more incidents at various time scales (as defined by CZ, IE, LT, NO, PL, HU in their NRAs) 2/ probability of occurrence within 1 year (as defined by EE, EL in their NRAs)

Consequences – Impacts are the result of the realization of a hazard (Sect 5.3).

With the Likelihood and Consequences/Impacts being classified into 5 distinct categories each, an original risk matrix consisting of 25 cells and five irregularly shaped zones is built to determine the overall risk (Table 1).

Table 1. Risk matrix

LIKELIHOOD	CONSEQUENCES/IMPACTS				
	NEGLIGIBLE	SMALL	MEDIUM	HIGH	SEVERE
VERY HIGH	Low	Medium	High	Critical	Critical
High	Very Low	Medium	Medium	High	Critical
Medium	Very Low	Low	Medium	Medium	High
Low	Very Low	Very Low	Low	Low	Medium
Very Low	Very Low	Very Low	Very Low	Very Low	Low

5.2. Describing the event – Likelihood

The levels of likelihood, in the framework of EU-CIRCLE, are defined by the internationally accepted descriptive terms, classified into a set of five categories, corresponding to numerical values from the NRAs and IPCC (Table 2):

Table 2. Examples from classifications of likelihood by the MS and IPCC.

Country	Very Low	Low	Medium	High	Very High		
CZ	< 1 in 1000 y	1 in 100 – 1000 y	1 in 10 – 100 y	1 in 1– 10 y	>1 in 1 year		
EL	less than 0.001% per year	0.001% to 0.01%	0.001% to 0.01%	0.01% to 0.1%	> than 1%		
IPCC	Except. unlikely	Very unlikely	Unlikely	Medium	Likely	Very likely	Virtually certain
IPCC	<1%	1-10%	10-33%	33-66%	66-90%	90-99%	>99%

5.3. Impacts

Impacts are defined as a quantifiable measure of the damages and performance disruption on a single asset, and to society in general. Within the EU-CIRCLE framework for the determination of the incident consequences builds upon a two tier approach.

- **Direct impacts** to the interconnected CI network
- **Indirect impacts** to society, that directly resulting from the CI not being able to operate according to their intended scope

Table 3. Impact description

Direct Impacts	Indirect Impacts
Damages to CI assets	Impact on societal groups
CI performance	Casualties
Casualties	Economic impacts
Economic and Financial Perspectives	
Environmental Losses	
CI reputation	

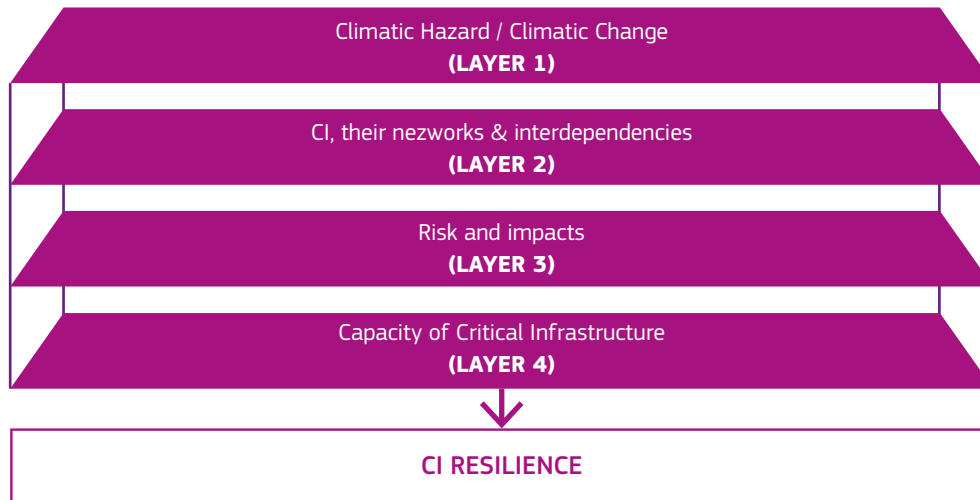
6. Resilience Framework

Based on a comprehensive review of resilience definitions, the **term resilience in the context of critical infrastructure for EU-CIRCLE has been defined as** the ability of a CI system to

- PREVENT: predict and resist the impact – prepare for / anticipate / preservation
- WITHSTAND: sustain the damage – absorb / withstand / accommodate / robustness
- RECOVER: damage can occur but the system will recover – respond to / rapidity
- ADAPT : modifications to system – change / restoration / improvement / learn

6.1. Resilience Layers

Taking into account the nature and incorporation of multidimensional components within a resilience framework, a layered approach is chosen as it has the flexibility to modify each layer (each component) independently and yet the collective output will be based on the interconnection between the layers.

Figure 3. Layers of resilience

6.1.1. Resilience Capacities and the Resilience Assessment Tools (RAMTs)

The capacities of critical infrastructure is one of the main ingredients for infrastructure resilience. The different types of capacities, are defined as:

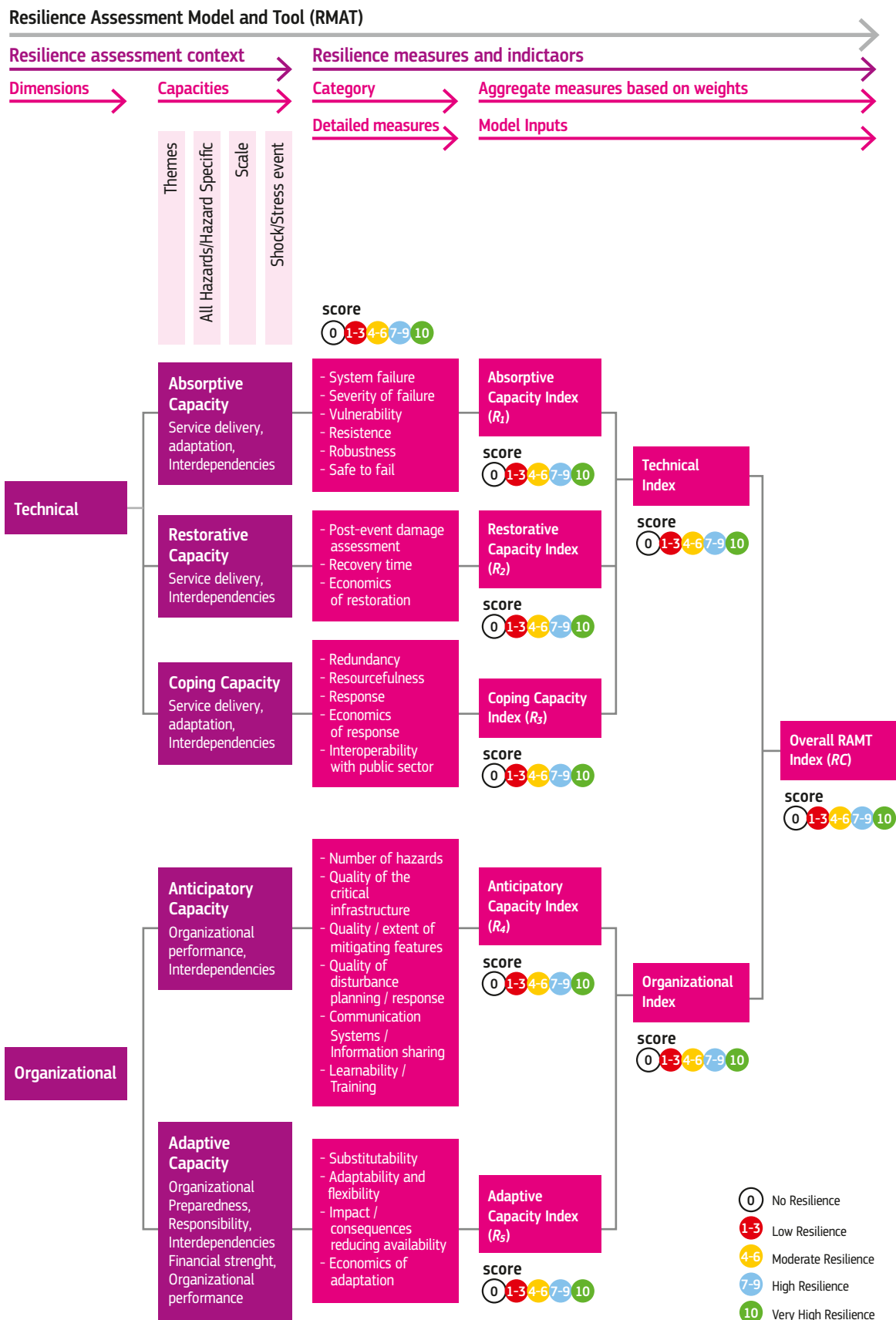
Anticipatory capacity: is the ability of a system to anticipate and reduce the impact of climate variability and extremes through preparedness and planning (Bahadur et al., 2015). As such it has close links to vulnerability, hazards and prevention.

Absorptive capacity: is the ability of a system to buffer, bear and endure the impacts of climate extremes in the short term and avoid collapse (Béné et al., 2012), acting as the first line of defence (Biringer et al., 2013).

Coping capacity: is the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters (UNISDR, 2009). The absorptive is immediately after a disaster whereas coping can be for a comparatively longer period.

Restorative capacity: is the ability of a system to be repaired easily and efficiently (Biringer et al., 2013), associated with recovery too.

Figure 4. RAMT and the calculation of resilience capacities. Adapted from Hughes and Healy (2014).

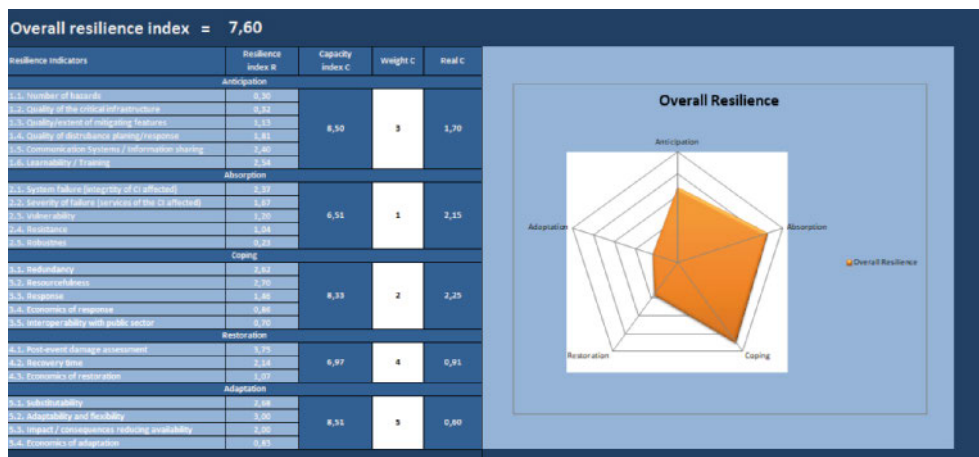


Adaptive capacity: is the combination of assets, skills, technologies and confidence to make changes and adapt effectively to the challenges posed by long term trends, such as future climate change (UNISDR, 2009).

The **Resilience Assessment Model and Tools (RAMTs)** has been developed on the basis of the defined resilience capacities. The only difference here is that they are first divided into the broad categories of Organizational Capacities (Anticipative and Adaptive) and Technical (Absorptive, Restorative and Coping).

Within the project a specific RAMTs spreadsheet has been defined which goes into the details and describes how the indicators can be measured and generates scores on a scale of 10 (very high resilience) to 0 (very low resilience). An individual capacity score is generated in RAMTs and shown below in **Table 4**. The resilience index is generated for overall resilience for this example. The RAMTs also generates a web diagram showing the relative scores of the five resilience capacities. It provides a summary dashboard for users to view the various scores and also has the capacity to add weights to the scores to reflect the relative importance of each capacity for the asset, network or NoN.

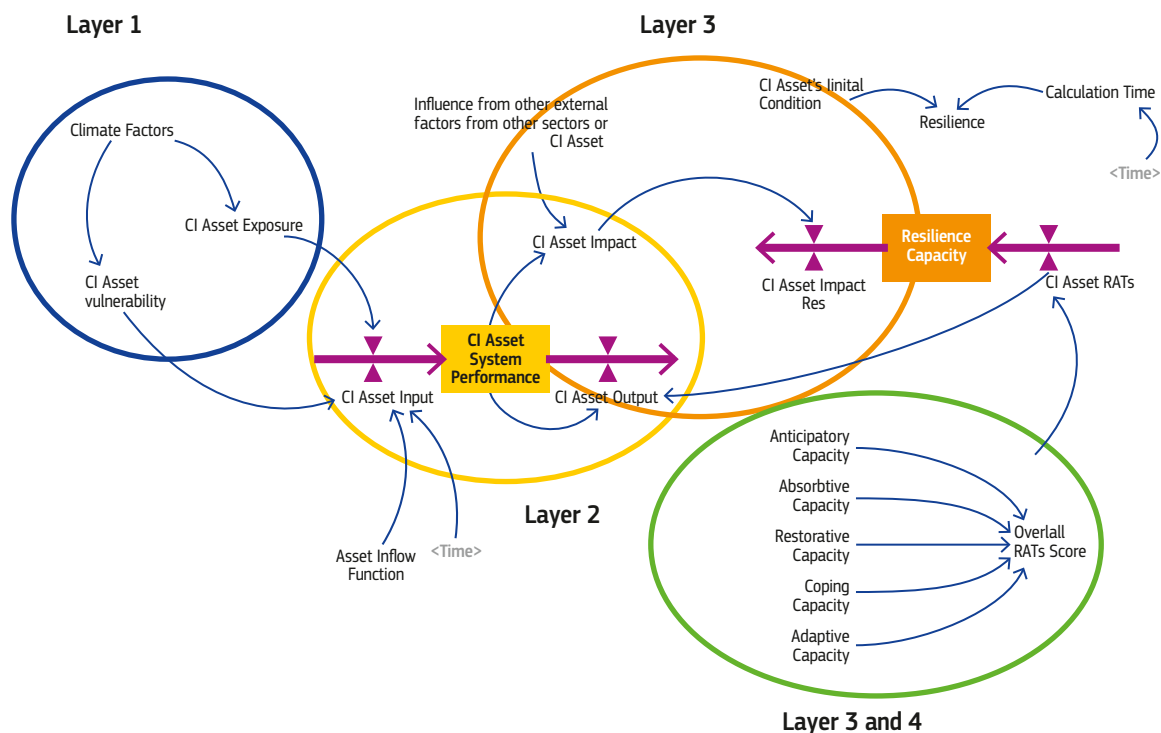
Table 4. Overall resilience score in RAMTs



The resilience framework is converted into the conceptual SD model using the diagram shown below in **Figure 4** introducing the feedback and interaction between resilience and system performance that interact across the 4 resilience layers. In SD, stocks are variables that accumulate over time, represented by a box, while flows are represented by arrows with “spigots”. The flows are connected to stocks and can either add to or take away from stocks over time at a controlled rate. Other texts and arrows provide additional information and connections between variables.

For the analytical framework as a whole, where several layers are combined for analysis, we will need to use a two stock model that can demonstrate the feedback present in the system and also demonstrate the ability of SD simulation methods to capture CI interdependencies as well. **Figure 4** illustrates how resilience can be conceptualized as a stock over time (box titled resilience capacity) with flows coming in to denote the level of resilience at this point in time (t1). The “spigot” on the incoming flow represents the contribution to overall resilience of the scores generated from the RAMTs process indicating that the overall resilience is a function of RAMTs. The “flow out” show how the size of shocks or impact of a hazard event is related to the level of resilience present at (ti) in the system.

Figure 4. The layers combined in a stock and flow model of the final resilience framework



7. Validation

EU-CIRCLE methodology has been validated in a workshop held in Cyprus and organised by the European University of Cyprus, CI operators from the energy, ICT, water and public sectors identified for the first time the various interconnections between them and realised the importance of being prepared to respond to future extreme weather conditions. The operators acknowledged that more needs to be done by them to build-in resilience to climate change.

8. Conclusions

Thus far EU-CIRCLE has achieved important objectives such as:

Establish a Holistic framework for defining climate resilience into Europe's interconnected infrastructures, bridging multiple temporal and spatial scales. The EU-CIRCE process of climate risk management, adapting the NIPP framework for different temporal and spatial scales.

A **multi-hazard risk modelling** approach, where an asset based approach is used to identify damages to CI from climate stressor's leading to the identification of the impacts on CI operations using network simulation for the modelling of critical services within interconnected CI. This is compatible with national, EU and International initiatives (NRA, EPCIP, Sendai Framework) and standards (ISO 31000).

The **identification of resilient capabilities** (anticipation, absorption, coping, restoration, adaptation) and its introduction to a systems dynamic model.

Move from response & prevention to resilience. EU-CIRCLE introduced a high level concept for assessing CI resilience which is a collective process to "ensure that they remain safe, effective and operational during and after disasters in order to provide live-saving and critical services"³⁸.

³⁸ Sendai Framework for Disaster Risk Reduction 2015-2030, Priority 4

Acknowledgements

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Resilience-Related Configurations of Civil Infrastructure and Community Systems

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Abstract

Civil infrastructure and community systems can be classified into different resilience-related configurations, depending on their post-disaster reaction. After a disaster, the supply capacity of civil infrastructure systems as well as the demand of a community for services and, consequently, effective service consumption, may be impacted in different ways.

Eight resilience-related configurations are herein identified, differing in their vulnerability and recovery paths. Notably, it is shown that Lack of Resilience can also be observed for systems that are characterized by low vulnerability. In addition, this classification allows to identify a system post-disaster behavior, indicate how best to increase its resilience, and, therefore, support an optimal resilience based design strategy of both civil infrastructure systems and communities they serve.

Keywords

resilience, civil infrastructure system, community

1. Introduction

Modern societies rely on the services supplied by civil infrastructure systems (CISs) to maintain their living standards. Services provided by CISs include, for example, electric power, (potable) water, health care, and transportation. CISs are, however, vulnerable to external excitations, especially when exposed to exceptional disaster loads. To give some examples, in 2005 Hurricane Katrina led to extensive damage of the electric power supply system in several states of the United States (Reed et al., 2010), and during the 2015 Gorkha (Nepal) earthquake the electric power supply system of Nepal (Didier et al., 2017a), and the water and cellular telecommunication systems of the Kathmandu Valley (Didier et al., 2017b) were damaged, causing financial losses of more than 500 million USD. In addition to direct (physical) damage to components of the CISs, persisting service black-outs can cause indirect costs (e.g. due to business interruptions), delay recovery efforts, and, thus, put additional strain on the already weakened society. Therefore, in a holistic approach, it is important to not only quantify the vulnerability of CISs or a community to disasters, but to include their recovery, and, thus, to quantify their resilience (e.g. Bruneau et al., 2003).

Different CISs and communities can react quite differently to disasters. CIS service supply capacity is often expected to drop after disasters, due to damage to the CIS components. For example, if a water pump of a water distribution system is damaged, the system may not be able to provide the same amount of water supply as before the disaster. In some cases, CISs can, however, be designed to increase their supply capacity: e.g. hospitals can be prepared to set up temporary emergency rooms to handle a probable increase in patients after major disasters. In fact, demand for service may increase or decrease after disasters: demand to cellular communication system or hospitals often raises after major disasters (e.g. ASCE, 2011), while demand for electric power might decrease due to damage to the



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building stock and its contents (i.e. electric appliances, Didier et al., 2017c). These evolutions can lead to different demand/supply configurations, leading to different behaviors of the CIS-community system. In addition to quantifying a possible Lack of Resilience (LoR) of a CIS, it is essential to identify different system resilience-related configurations with respect to their vulnerability and recovery paths. The Re-CoDeS framework (Didier et al., 2017d) allows to quantify the resilience of such CIS-community systems and to identify possible post-disaster configurations. In the following study, different resilience-related configurations identified in the Re-CoDeS framework are presented, and their implications on the resilience of a CIS-community system are discussed.

2. The Re-CoDeS framework

The Re-CoDeS framework (Didier *et al.*, 2017d) allows to quantify and qualify the resilience of a CIS-community system. It distinguishes two system layers, namely the supply system layer and the demand system layer, and the following metrics on a component and system level (composed of $i \in \{1 \dots I\}$ demand components or nodes, and $j \in \{1 \dots J\}$ supply components or nodes):

The component demand $D_i(t)$ and the system demand $D_{sys}(t)$ are the demand of the community for the service of the CIS at interest at a given demand node i at time t (e.g. an electric distribution substation) and the demand to the entire CIS at time t , respectively. Note that $\sum_{i=1}^I D_i(t) = D_{sys}(t)$.

The component available supply $S_i^{av}(t)$ is the service supply available at a node i at time t to satisfy the demand at the same node. It depends on the system service model, describing the operations of the CIS at interest. The system service supply capacity at time t is denoted by $S_{sys}^c(t)$. Note that due to the influence of the system service model and the network topology, $\sum_{i=1}^I S_i^{av}(t) \neq S_{sys}^c(t)$.

- The service consumption at node i at time t , $C_i(t)$, and the consumption of service in the entire CIS at time t , $C_{sys}(t)$. The consumption is the minimum of the available supply and the demand for service at a given node and time, $C_i(t) = \min(D_i(t), S_i^{av}(t))$. $C_{sys}(t)$ is, then, the sum of all component consumptions, $\sum_{i=1}^l C_i(t) = C_{sys}(t)$.

Using the metrics described above, the Lack of Resilience of the CIS observed at a node i over a given time period $t_0 \leq t \leq t_f$, LoR_i , is defined as:

$$LoR_i = \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt = \int_{t_0}^{t_f} (D_i(t) - C_i(t)) dt$$

where t_0 is the start time of the resilience assessment (often set to the moment of occurrence of the disaster), t_f is the end time of the resilience assessment (e.g. a given time period, or the control time of a system, etc.) and $\langle \cdot \rangle$ is the singularity function. The Lack of Resilience of the entire CIS over a given time period, LoR_{sys} , is defined as the aggregation of the **LoR** at all the nodes of the system:

$$\begin{aligned} LoR_{sys} &= \sum_{i=1}^l LoR_i = \sum_{i=1}^l \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt \\ &= \sum_{i=1}^l \int_{t_0}^{t_f} (D_i(t) - C_i(t)) dt = \int_{t_0}^{t_f} (D_{sys}(t) - C_{sys}(t)) dt \end{aligned}$$

Both metrics can be normalized by the component and system demand respectively, and the resilience observed for at a given node i , R_i , and for the system, R_{sys} , is defined as:

$$\begin{aligned} R_i &= 1 - \widehat{LoR}_i = 1 - \frac{\int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt}{\int_{t_0}^{t_f} D_i(t) dt} = 1 - \frac{\int_{t_0}^{t_f} (D_i(t) - C_i(t)) dt}{\int_{t_0}^{t_f} D_i(t) dt} \\ R_{sys} &= 1 - \widehat{LoR}_{sys} = 1 - \frac{\sum_{i=1}^l LoR_i}{\sum_{i=1}^l \int_{t_0}^{t_f} D_i(t) dt} = 1 - \frac{\sum_{i=1}^l \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt}{\sum_{i=1}^l \int_{t_0}^{t_f} D_i(t) dt} \\ &= 1 - \frac{\int_{t_0}^{t_f} (D_{sys}(t) - C_{sys}(t)) dt}{\int_{t_0}^{t_f} D_{sys}(t) dt} \end{aligned}$$

The supply reserve margin at a component i at time t , $SR_i(t)$, can be defined as the difference between available supply and demand at component i at time t : $SR_i(t) = S_i^{av}(t) - D_i(t)$. The system supply reserve margin at time t , $SR_{sys}(t)$, is the difference between the demand to the entire CIS and the system supply capacity at time t : $SR_{sys}(t) = S_{sys}^c(t) - D_{sys}(t)$. The supply reserve margin is a measure for the redundancy and the robustness of the CIS, as a supply reserve can be used to substitute for a loss of supply at the component or system level.

3. Resilience-Related Configurations

The Re-CoDeS framework allows not only to quantify the resilience of CISs but also a clear classification of post-disaster system configurations. The amount of service demand and supply is expected to change after major disasters. Both metrics can increase, decrease or stay constant, depending on various factors, including the impact of a disaster on the community and the CISs. Depending on the magnitude and the rate of change of these metrics, different CIS-community demand-supply configurations can be identified. Some configurations are more, and others are less prone to a high value of LoR. Every configuration can lead to a good or a bad disaster resilience performance, depending on the arising LoR. The classification allows to qualify a possible reaction of the CIS-community system and to estimate the potential risk to observe a high value of LoR after a disastrous event.

Table 1. Resilience-related system configurations, t_0 corresponds to the moment of occurrence of the disaster (adapted from Didier et al., 2017d).

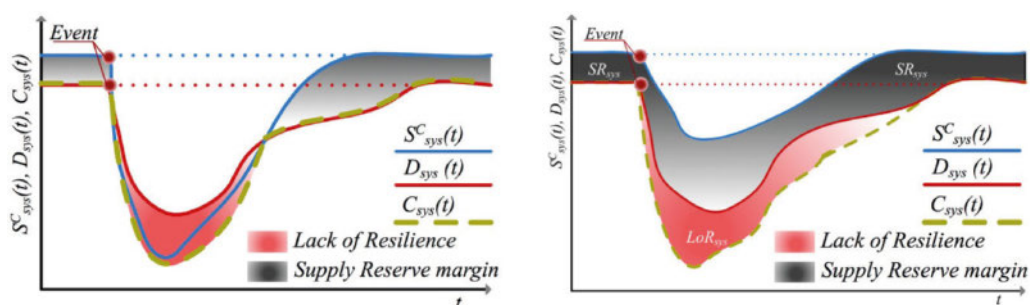
Configuration	$S_{sys}^c(t)$	$D_{sys}(t)$	$C_{sys}(t)$
Classical	$S_{sys}^c(t) \leq S_{sys}^c(t_0)$	$D_{sys}(t) \leq D_{sys}(t_0)$	$C_{sys}(t) \leq C_{sys}(t_0)$
Inefficient	$S_{sys}^c(t) > S_{sys}^c(t_0)$	$D_{sys}(t) \leq D_{sys}(t_0)$	$C_{sys}(t) \leq C_{sys}(t_0)$
Fragile	$S_{sys}^c(t) \leq S_{sys}^c(t_0)$	$D_{sys}(t) > D_{sys}(t_0)$	$C_{sys}(t) \leq C_{sys}(t_0)$
Anti-Fragile	$S_{sys}^c(t) > S_{sys}^c(t_0)$	$D_{sys}(t) > D_{sys}(t_0)$	$C_{sys}(t) > C_{sys}(t_0)$
Reserve-Margin	$S_{sys}^c(t) \leq S_{sys}^c(t_0)$	$D_{sys}(t) > D_{sys}(t_0)$	$C_{sys}(t) > C_{sys}(t_0)$
Cliff-Edge	$S_{sys}^c(t) > S_{sys}^c(t_0)$	$D_{sys}(t) > D_{sys}(t_0)$	$C_{sys}(t) \leq C_{sys}(t_0)$
Inadequate	$S_{sys}^c(t) > S_{sys}^c(t_0)$	$D_{sys}(t) \leq D_{sys}(t_0)$	$C_{sys}(t) > C_{sys}(t_0)$
Under-Designed	$S_{sys}^c(t) \leq S_{sys}^c(t_0)$	$D_{sys}(t) \leq D_{sys}(t_0)$	$C_{sys}(t) > C_{sys}(t_0)$

To classify a component, the knowledge of the evolution of the available supply and the demand for service at the component level are usually sufficient. The reaction of systems to disasters is more complex and, therefore, difficult to assess. In fact, systems can include components with very different disaster resilience-related configurations. Additionally, the effect of the distribution/transportation system and the system service model (determining the allocation and distribution of service) needs to be considered. In fact, CIS supply is often produced or enters the system at different locations than it is consumed (e.g. electric power produced at generation plants consumed in cities or by industries). Distribution/transportation links can fail, and the allocation of the supply might change in post-disaster situations (e.g. due to different prioritization strategies for service dispatch or potential transmission losses). It is, thus, possible to observe a supply reserve margin and a LoR on the system level at the same time. For example, suppose that the post-disaster system supply capacity is still larger than the demand of the whole community for the services provided by the CIS. Despite broken links, some nodes can still be supplied and have a large supply reserve margin. Others, however, are disconnected and cannot be supplied anymore at all, thus, having a high LoR. On a system level, it is, therefore, important to consider additionally the system consumption to include such effects. To classify the system resilience-related configurations, the 3 system variables $D_{sys}(t)$, $C_{sys}(t)$ and $S_{sys}^c(t)$ are employed. Table 1 lists the different system resilience-related classifications. After disasters, it is possible to observe different configurations over the various absorption and recovery phases (e.g. Figure 5b).

3.1. Classical configuration

The classical configuration has been often observed after major disasters in the past: the demand for a CIS service decreases (e.g. due to damage to the community), as well as the supply capacity of the system (e.g. due to damage to the system components). Consequently, the consumption decreases as well (or stays constant). Depending on the supply reserve margins available prior to the disaster and on the magnitude and rate of decrease of the demand and supply, a LoR can potentially be observed (Figure 1a)). If the supply reserve margins are large enough, the decrease of supply can be substituted to a certain extent. Finally, the dispatch of service depends on the distribution/transportation system. Scenarios like the one shown in Figure 1b) indicate link failures or an inefficient service dispatch: a high LoR is observed at the same time as a supply reserve margin. An example of a CIS-community system expected to show such a resilience-related configuration is the electric power supply system: some generation plants are damaged during a disaster and the amount of electric power that can be supplied decreases. At the same time, the demand for electric power decreases due to damage to the community: buildings collapsed and industries are shut down. In an extreme scenario, demand and supply capacity can even decrease to zero (e.g. Fukushima region after the 2011 Tohoku earthquake, or Pompeii after a large volcano eruption and earthquake).

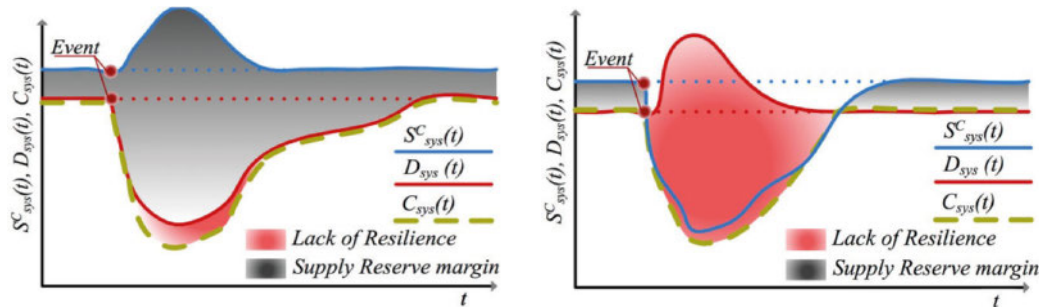
Figure 1. a) Classical configuration (from Didier et al., 2017d),
b) Classical configuration with a LoR and a system supply reserve margin at the same time



3.2. Inefficient configuration

A CIS-community system is classified as inefficient, if an increase in service supply is observed at the same time than a decrease of the service demand after a disaster (Figure 2a)). Similar to the classical configuration, the demand can decrease, for example, due to extensive damage to the community. The system supply capacity, however, increases, for example, since the CIS has been designed to increase its supply after disasters. This configuration is not very prone to large LoR during disasters, however, the supply reserve margin is likely to increase unnecessary and inefficiently. An example for such a configuration are donations of food and clothes, as often observed after major natural catastrophes: after the 2012 hurricane Sandy, large quantities of clothing were generated through donations and wasted, since they could not all be allocated to any people lacking thereof (Fessler, 2012).

Figure 2. a) Inefficient configuration,
b) Fragile configuration (both from Didier et al., 2017d)



3.3. Fragile configuration

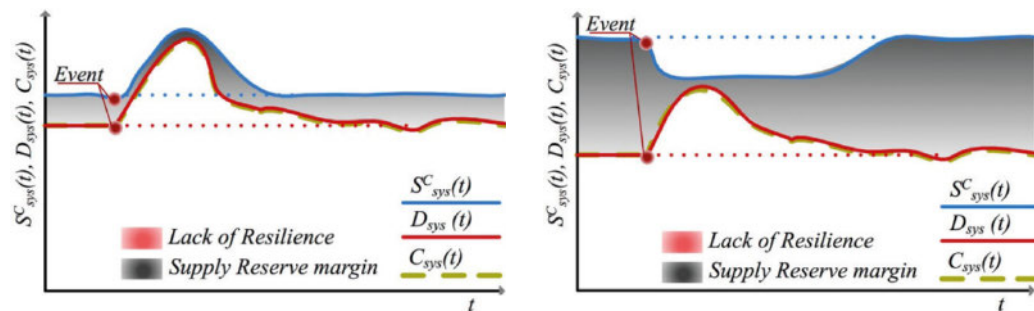
The fragile configuration (Figure 2b)) is, like the classical configuration, another configuration that is observed relatively often after disasters. This configuration is characterized by an increase in community demand for service at the same time as a decrease in the supply capacity of the CIS. The decrease in the supply capacity can, again, be attributed to damage to the CIS supply or service generation facilities. In this scenario, the increase in community demand is often related to emergency actions and reactions immediately after the disaster. Examples of systems likely to belong to the fragile configuration are cellular communication and transportation systems. In the immediate aftermath of a disaster, there is a sudden increase of communications causing a congestion of the cellular communication system. This has, for example, been observed after the 2011 Tohoku (Japan) earthquake, after which the call rate rose to up to 10 times the demand during normal conditions (ASCE, 2011). This configuration is very prone to large LoR, as has been observed after past disasters (e.g. for the cellular communication system of the Kathmandu Valley after the 2015 Gorkha earthquake, Didier et al., 2017b). Another example are water distribution systems dealing with post-earthquake fire situations: the demand increases due to firefighting, while the supply cannot be assured anymore due to a damaged distribution system.

An important observation can be drawn from this particular configuration. Even in the case for which the system is designed to be effectively not vulnerable, there can be a large LoR. Therefore, in a resilience design approach not only the reliability of the system is of interest, but also the one that directly affects the demand. In addition to this, a reserve margin should be considered as a key element of the design.

3.4. Anti-Fragile configuration

The anti-fragile configuration (Figure 3a)) distinguishes itself from the fragile configuration such that the CIS supply is designed to increase after a disaster. The demand still increases, but in relation with the increase in supply, this configuration is less prone to situations resulting in a LoR. In fact, if the supply was sufficient before the disaster, anti-fragile systems will never have a LoR if the service supply capacity is designed in a way that it exceeds the increase in demand and if there are reliable and efficient supply distribution systems. An example for such a configuration is the health care system that can be designed to react to disaster related increases in the number of injured patients, for example, by setting up temporary emergency rooms and additional beds at the different hospital locations. The challenge is similar than for the reserve-margin configuration (see below): an excessive increase in the CIS supply capacity and/or an excessive supply reserve margin might increase costs.

Figure 3. a) Anti-fragile configuration, b) Reserve-margin configuration (from Didier et al., 2017d)



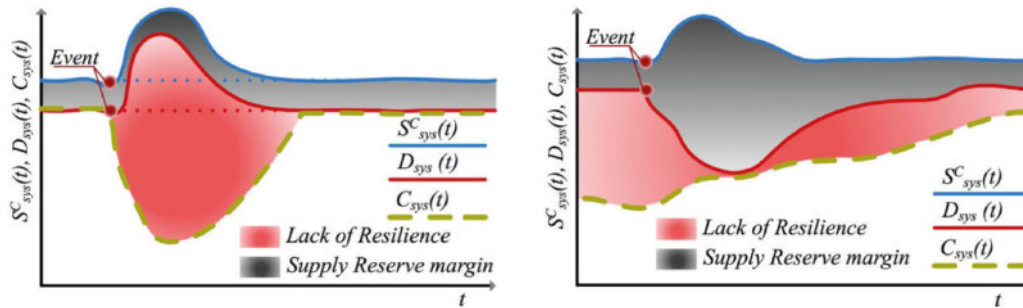
3.5. Reserve-Margin configuration

Reserve-margin system configurations (Figure 3b)) are characterized by large supply reserve margins available to absorb potential shocks and to cover post-disaster increases in service demand. The system supply reserve margin can be used to substitute for a possible loss of supply capacity due to damage to the system and to prevent a LoR. The large supply reserve margins are usually combined with a highly redundant and reliable distribution system and efficient service dispatch strategies to prevent delivery failures. This configuration is characterized at the same time by an increase in demand, and consumption, since the increase in demand can (in part or completely, depending on the exact magnitude of the changes in demand and supply and the available supply reserve margin prior to the disaster) be covered. However, if supply reserve margins are not high enough or the distribution system are not reliable enough, a LoR is still possible. Such a configuration can, for example, be found in nuclear power plants: they are designed to cover increases for reactor cooling demand even if there are many failures in the reactor cooling system(s). The possible high consequences of a nuclear reactor overheating justify such costly investments in large supply reserve margins.

3.6. Cliff-Edge configuration

Systems classified as cliff-edge (Figure 4a)) exhibit sudden dramatic failures due to non-redundant vulnerable elements or due to cascading failures. Even though the supply capacity can be designed to increase after a disaster to cover an increase in demand (similar to anti-fragile systems), the supply cannot be delivered to the consumers due to failure of the transmission system or due to inefficient or inadequate system service models. The post-disaster system service consumption will consequently decrease. A simple example for such a system is a hospital that can only be reached by a highly vulnerable link, for example a bridge. However, after a major earthquake, the bridge may be severely damaged and impassable. While there is a large increase in potential patients due to injuries during the earthquake, and even though the hospital has been designed to provide a large number of additional beds and to setup temporary emergency rooms, the patients cannot be treated, as they are unable to reach the hospital. Therefore, the consumption (i.e. the number of treatments effectively provided) will decrease if compared to the pre-disaster level. Another example is, to some extent, the large 2003 Northeast US power blackout, which was partly due to an overloaded line of the transmission system. Even though the generation plants were not damaged and emergency power generators could be set up and the demand was large, the consumption went down due to blackouts related to the failure of the transmission system. Observe that likewise the fragile configuration, a large LoR can occur even if the supply system is invulnerable and the reserve margin adequately designed.

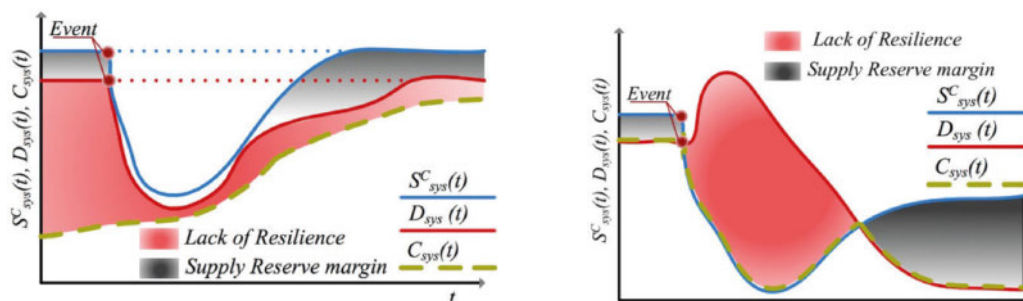
Figure 4. a) Cliff-edge configuration, b) Inadequate configuration (both from Didier et al., 2017d)



3.7. Inadequate configuration

Inadequate systems (Figure 4b)) are characterized by an increase in the post-disaster supply capacity of the system and a decreasing community demand. However, in difference to the inefficient configuration, the post-disaster consumption is higher than the pre-disaster one. This indicates an inadequate or poor system design, a bad system service model, or a (damaged) distribution system with high losses prior to the disaster. In fact, such systems may have supply reserves at some components before a disaster, but at the same time (large) LoR in other parts of the system. After a disaster, the (often costly) supply reserves are activated and/or distributed to other points in the network with service deficit to limit the supply gap. A hypothetical example may be a city with a poor water distribution system: already before the disaster, a main pipe was damaged and a part of the city was disconnected from water delivery. After the disaster, it is decided to deliver water to this part using (costly) water tanker trucks requested from other cities in the region in order to not put additional strain on the community. The supply capacity of the system and the consumption raise, but at a high distribution cost. Another hypothetical example of such a scenario would be the use of emergency power supply generators to supply a residential neighborhood with a power service deficit, i.e. LoR, even before the earthquake. In such a case, due to extraordinary but costly post-disaster measures and the general decrease in demand, the post-disaster LoR may decrease compared to the pre-disaster one.

Figure 5. a) Under-Designed configuration (from Didier et al., 2017d), b) subsequent configurations during different phases of the absorption and recovery process



3.8. Under-Designed configuration

The under-designed configuration (Figure 5a)) is similar to the inadequate configuration. Before the disaster, a supply deficit is already observable in (some parts of) the CIS. Again, the service consumption increases after the disaster, despite a decrease in demand and, in this case, combined with a decrease of the supply capacity. This is again an indication of poor system design or inefficient and costly supply generation or distribution. This configuration was observed for the Nepalese electric power supply system after the 2015 Gorkha earthquake (Didier et al., 2017a). The transmission and large parts of the electric power generation system were damaged during the earthquake, inducing a decrease of the system supply capacity. The building stock was severely damaged and industries were shut down, leading to a decrease of the demand for electric power. Already before the earthquake, electric power was only available for a few hours a day in many parts of the country. After the earthquake, the operator decided to run fuel generation plants, which are usually shut down in normal condition due to high operation costs, and to run the remaining hydropower plants at the maximum possible capacity in order to limit the load shedding after the earthquake. In fact, this led to a welcome raise of the consumption of electric power after the disaster as well as a reduction of the LoR.

4. Conclusion

CIS-community systems have different resilience-related configurations, depending on the nature of the disaster and the post-disaster evolution of their system supply capacity, the community demand and the effective service consumption. Some configurations are more, others are less prone to a LoR. However, every configuration can lead to a good or a bad system performance in terms of the observed LoR. The potential magnitude of the LoR depends, additionally, on the pre-disaster supply reserve margins and on the system service model. The main challenge is to find a balance between reliable and redundant system design, the size of the supply reserve margins, and the system design and maintenance costs. An anti-fragile system configuration can be a resilience-based design target, since such systems resourcefully adapt to the new post-disaster conditions to minimize a LoR. In combination with the quantification of a potential LoR for different possible hazards, classification of the CIS resilience-related configuration is an important step in CIS-community system resilience assessment and a first step in a CIS resilience-based design process.

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A framework modeling flows of goods and services between businesses, households, and infrastructure systems

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Abstract

Societies can be represented as flows of goods and services between companies and households. Typical flows are transportation, power, communication, water, which are delivered by infrastructure systems. Whereas considerable amount of research exists on response and recovery of infrastructure systems, we are only at the very beginnings of studying their impact on societal entities i.e. firms, households, and economic systems. There is a need to better understand this type of impact.

Taking up the above challenge, in this paper we develop an agent based modeling system that mimics the behavior of companies and households, being able to transform a multitude of service inputs into a set of service outputs, while interacting with services that infrastructure systems are providing.

We designed and implemented a prototype environment, and ran a series of simulation experiments. The prototype represents a set of production nodes, each implementing a production function, and a set of demand nodes. Production nodes use a subset of 6 types of resources to produce another resource in accordance with their production function, while demand nodes only demand a subset of these resources from the network. The allocation of resources is based on combined cost of production and cost of transportation. We have developed a proof-of-concept network of agents based on 5 production nodes and 9 demand nodes, and ran a series of simulation experiments to investigate sensitivity of the network, which has proved feasibility of the concept.

Based upon the prototype, in the future, we will investigate the effects of changing the demand of the nodes dynamically. Moreover, we plan to explore the consequences of failing edges, i.e. edges that are disrupted and disappear from the network, or whose capacity decreases. Finally, we intend to look at multi-layer networks, and research how such networks may influence the systems' performance.

Keywords

system of systems, resilience, agent based modeling, input-output, infrastructure modeling, interdependencies

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1. Introduction

As societies become more and more interconnected and dependent on different services and each other for their daily survival, it becomes crucial that their weaknesses are studied and understood in more depth, in order to prevent threats to these societies. Similarly, resilience of infrastructure and economic systems is becoming of immense importance to communities across the globe. More frequent and more impactful shocks to various systems are threatening societies and businesses (Boin & McConnell, 2007). These shocks materialize in numerous regions, both in rural, and in urban areas. Moreover, these shocks emerge on both macro and micro scales. Today, even small, micro shocks, due to multitude of interdependencies, can have catastrophic outcomes. This is especially true as disruptions are constantly becoming more and more random. Therefore, predicting these shocks, establishing their impact, and subsequently responding to them and preventing their consequences is becoming central to many societies' existence. To achieve this, we need to be able to model interactions between physical, economic, and social systems to understand links between these systems, and to see how a shock emerging in one system can affect other systems.

Presently, there exist models that describe recovery and response to disruptions of infrastructure systems; however, these models do not incorporate impacts of these systems on societal entities such as households and businesses. Current models primarily focus on a single type of infrastructure system. For example, these models include power system simulation (Eusgeld & Nan, 2009), water supply system simulation (Liu, Liu, Zhao & Tang, 2013), transportation systems (Tamvakis, Pavlos & Xenidis, 2012).

We believe that societies can be represented as a model of flows of goods and services between households, businesses and infrastructure systems. Developing such a model can enable us to better understand how infrastructure systems should be designed, and what are the consequences of their failures. Moreover, we can better prepare societies for failures of these systems, when we recognize what types of disruptions are especially dangerous, and what causes their occurrence in infrastructure systems. Finally, we can design mechanisms for societies, businesses and infrastructure systems to recover faster after any failures occur. (Vugrin, Warren, Ehlen & Camphouse, 2010) The development of a robust simulation

of modeling flows of goods and services in an economy will have a huge impact on understanding the resilience in the economy.

In this paper, we describe the agent based modeling system that we propose for the modeling of flows of goods and services between households and businesses in an economy.

2. Model framework and design

In this section, we present the framework used for modeling the flow of goods and services. Firstly, we describe the high level overview and the motivation of the framework. Subsequently, we describe the mechanics of each agent. Finally, we describe how agents interact with each other under this framework.

2.1. Conceptual framework

The flow of goods and services can be used to represent a society. Under such model, the agents exchange goods and services with each other, while producing particular resources and demanding resources from other agents to be able to perform their tasks. To produce raw resources these agents interact with infrastructure systems. The conceptual framework is shown on Figure 1.

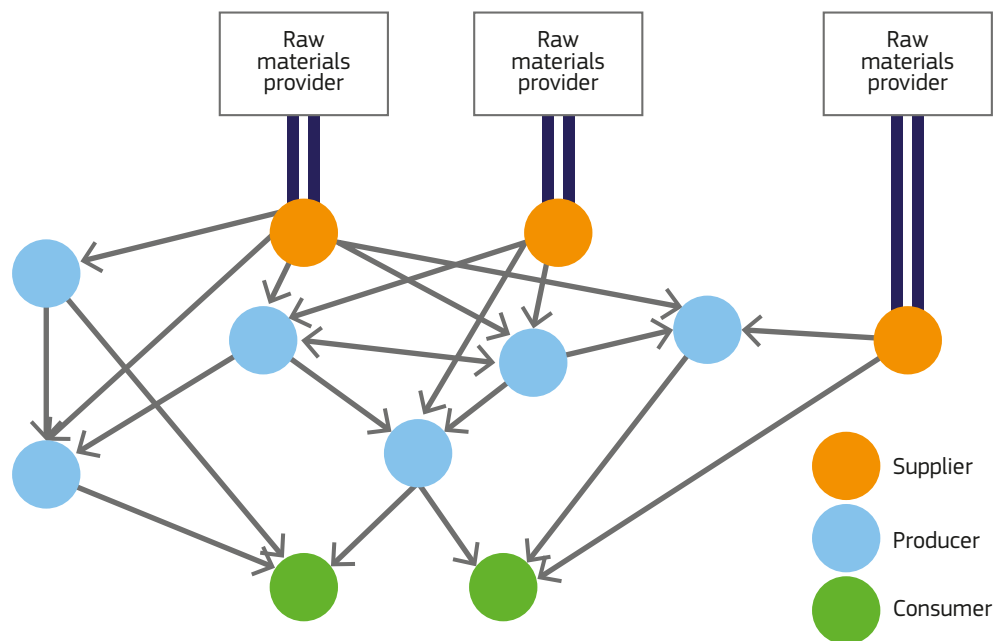
The workings of individual infrastructure systems are widely researched and well understood. However, modeling how a set of businesses and households responds to infrastructure systems' disruptions and how these businesses and households exchange goods and service is still an area that requires further research. Better understanding of the recovery and response to disruptions of these systems is needed. Therefore, we attempt to achieve this through the development of a model for the interaction of households and businesses among themselves, and with infrastructure systems through the exchange of flows of goods and services.

We look at how infrastructure systems might impact societal entities and economy. Flows of goods and services might be disturbed through disruptions in infrastructure systems such as breakages in transportation network or power distribution network. These failures can be represented as destruction of links between agents, or changes to the production process within the agents. Such failures might have profound effects on a society, which relies heavily on these systems to provide basic services to their communities.

2.2. Agent specification

A single agent represents a producing unit or a demand unit. Each agent represents a functionality of a production process. It abstracts a production process of a particular set of goods and services. These production processes can represent a company, a household, or at a larger granularity a set of households and businesses.

Figure 1. Overview of the framework. Different agents exchange goods and services in a network while interacting with infrastructure systems. The infrastructure systems are represented by raw material providers and link to agents that introduce these resources.



Each producing unit agent mimics a behavior of companies and households, being able to transform a multitude of input resources into a set of output resources. Additionally, each agent can simply transport the resources further in the system without providing any operations on these resources. Moreover, the producing agents can introduce raw materials into the system with a given cost. This means that an agent can not only perform production in the form of transforming one set of resources into another set of resources, in what is called a production process, but they can also perform mining or introduction of new resources into the system. An outline of a producing agent is shown on Figure 2.

The above model description is based on an input-output model, where the input-output matrix describes the inputs to the system, and the outputs of the system (Leontief, 1986). Here, the input-output matrix associated with each agent describes the production process, which takes place in this particular agent. These input-output matrices vary between the agents to represent different production processes depending on the agent. The input-output matrix can represent a production process of a company, a household, or a region or society.

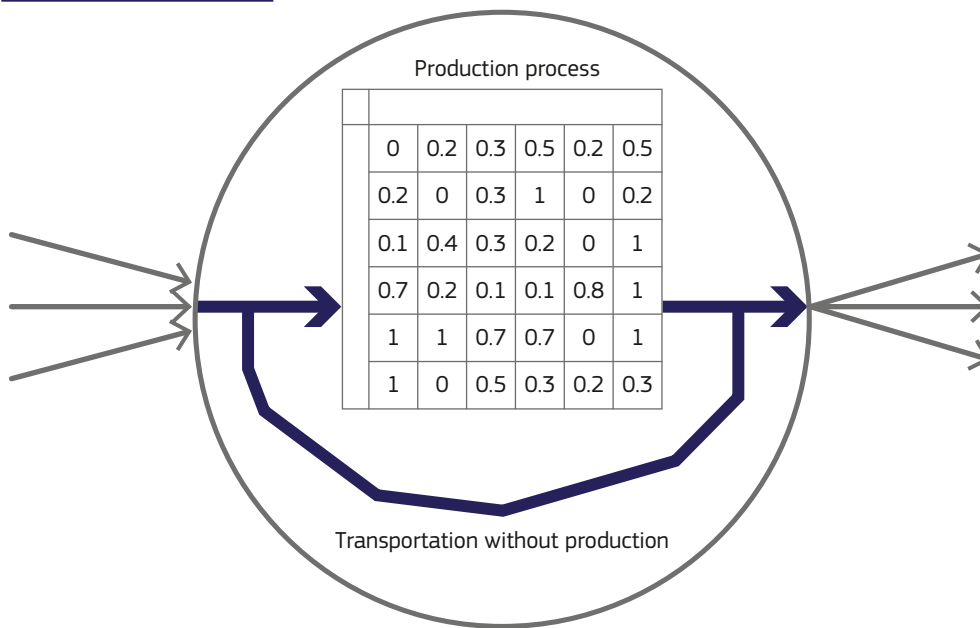
Furthermore, the demand unit agents simulate external demands of the system. They only demand resources from the system. Consequently, these are treated as sinks of the system that define in aggregate what is the total need for production in the system, and what is the need at each particular node. These agents can represent the end consumers such as households in their consumer capacities, or external connections of the system with their demands or a loss of resources at each producing unit.

2.3. System-of-systems configuration

Finally, the agents are combined together to form a system-of-systems (Keating et al., 2003). These agents exchange goods and services with each other. This is achieved through combing the individual agents in a network of agents. In such network the links between agents, i.e. edges of the network simulate the transportation of resources between the agents.

Each link in the network has a cost associated for a unit of each resource transported through this link. The cost is specified for each resource, which can be transported using that particular link, separately. Thus, we include links that can transport different types of resources at different costs between the same two agents. A sample of a whole network is shown on Figure 1. Arrows between the nodes represent the links on the figure. These links have a vector associated with each, specifying the cost of transportation of each production resource over this link.

Figure 2. Overview of the internal function of a producing agent. The agent takes inputs and transforms them according to a production process specified in the matrix. Subsequently the products are passed onwards to the following agents.



To allocate the distribution of goods and services in the network, we use the mechanism of minimizing of costs. The goods and services are allocated and consequently produced in such a way as to minimize the total cost incurred in the whole network. The costs are primarily incurred in the process of obtaining raw materials and in transportation, however this model also allows for money to be included as one of the resources transported between the agents. Thus, effectively including the monetary costs in individual production processes associated with producing unit agents too.

3. Model application

In this section we describe the application of the framework that we have designed, where we implement the framework with a particular network.

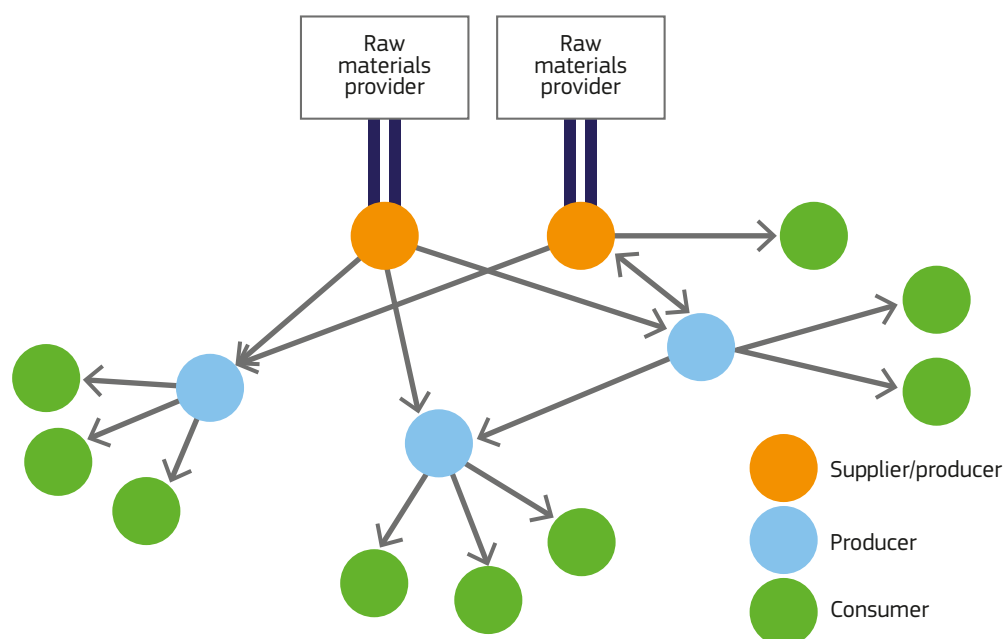
We have developed a network of 5 producing units and 9 demand units. These units produce and interchange 6 types of resources. The producing units produce resources. This production can happen either in the form of raw materials being created from nothing at the unit, thus mimicking the process of obtaining raw materials e.g. at mines, forests, farms etc. Alternatively, the production can be an effect of a production process. On the other hand, we have the demand units, which only demand resources from the network and cannot perform any production. The demand units represent the end-users of resources that the particular network produces.

These units are incorporated in a network. In such network, the production and demand units are represented as nodes, while the edges represent transportation links between the production and demand units. Each link represents a method of transportation between the two units that this link connects. The links can be limited in the types of resources that they transport. Moreover, each link has a cost associated with each resource transported through this link. The network we used is presented in Figure 3.

The cost in this section is understood as a generic unit used to measure the cost of transportation and obtaining original resources. This cost is used to identify the flow of goods and resources between the nodes. Therefore, the costs in the system are associated only with transportation links and with original creation of raw materials, whenever it is performed. The production processes do not generate any costs. However, they require other resources.

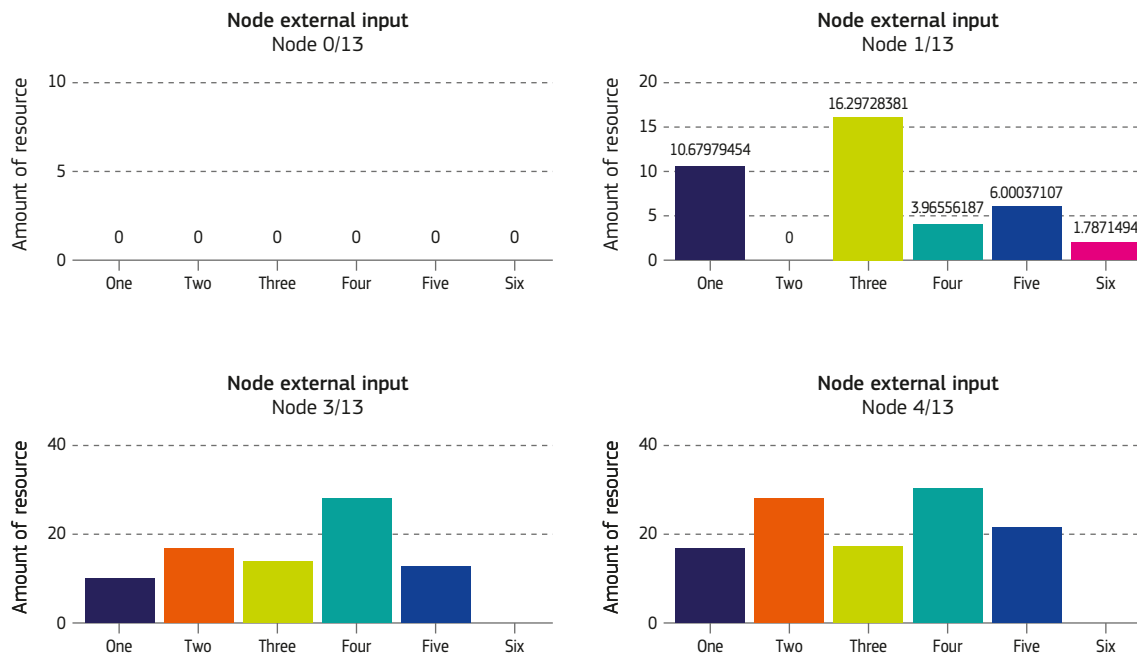
We perform a real-time monitoring of the system, and we visualize the results in real-time, so that we can perform assessment of how the flow of goods is changing when the properties of the system change. The sample of this monitoring system is shown on Figure 4.

Figure 3. A topology and outline of the network used in the application that developed. The network consists of 5 production units and 9 demand nodes. It contains edges with costs assigned to each edge.



Iterating through the balancing algorithm is used to balance the network. The algorithm is iterated at least the number of twice the longest path through the graph times to ensure that the network is completely balanced. Subsequently, this method of balancing can be used iteratively itself too, after changes or modifications to the network occur such as changes in the costs of transportation or in the production processes, to simulate the disruption or recovery of the system, or to observe how the system performs as changes in demand occur.

Figure 4. An example of real-time monitoring of the performance of the simulation system. We can see external inputs of each node shown for each resource on a bar graph.

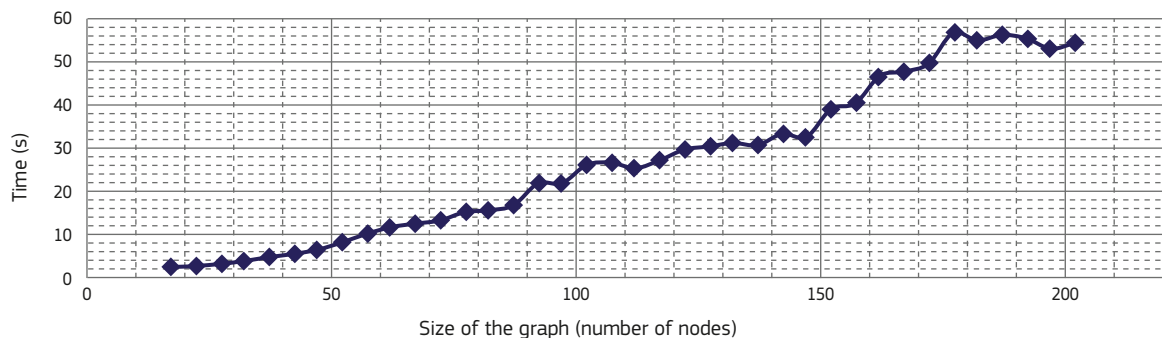


Source: CanvasJS.com

The simulation was developed in Python using *igraph* library to simulate the networks, and *numpy* to perform linear algebra operations. Furthermore, we used *CanvasJS* library to visualize the flows of goods and services at each node.

We have evaluated the speed of the network and for the network of 5 production units and 9 demand units presented in this section run over 100 iterations the average time of 100 runs is 12.3 seconds. The time varies with the number of iterations linearly, and with the number of units as shown on Figure 5. We believe this speed to be sufficiently fast for the simulation of infrastructure system interactions with the flow of goods and services simulation.

Figure 5. Time for the execution of the simulation varied with the size of the graph. This data was obtained for running the simulation with 10 iterations for each graph size. We can see that the time varies linearly with the size of the graph and that up to 100 nodes, the time is below 2s per iteration.



The data and information, which the simulation system can produce is the external demand of each production unit, the external supply of each production unit, and the internal production of each production unit. The internal production means the production of resources that is consumed by the same node to produce other goods and services. Therefore, it is the production that happens within the same unit without any need for transportation whatsoever. The relationship between these three metrics is shown on Figure 6.

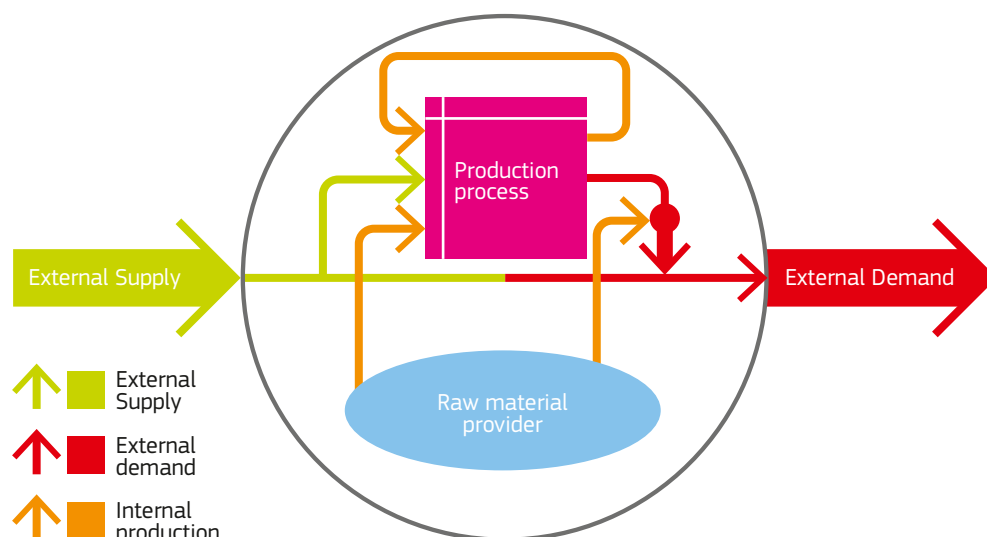
4. Conclusions and future work

In this paper, we have described a framework to model flow of goods and services between businesses, households, and infrastructures systems. To do this, we constructed agents using input-output model to represent production process of each individual processing unit. We joined these agents with the use of transportation links in a network to obtain a system-of-systems simulation, where the flow of goods and services is simulated.

The model developed can be used to better predict the behavior of systems following disruptions. Having developed the simulation framework, we can introduce disruptions and investigate how these disruptions propagate throughout the systems. Additionally, we can see whether the system can survive the disruptions, this is whether demands can still be fulfilled, and what is the cost of these disruptions.

Moreover, the simulation presented could aid with devising the best ways to organize the flow of goods and services in a network of businesses and households. These could be achieved through arranging alternative topologies and properties of the network, and assessing which of these are less costly using the framework described in this paper. This is a unique solution and contribution that could help to better design supply chains and infrastructure systems in various geographical areas, but also in sociotechnical settings.

Figure 6. Relationships between external supply, internal production and external supply values in a producing agent. External supply is what is input into an agent from the outside. External demand is the total that it outputs. Internal production is what is produced inside the agent.



There exist works on modeling of individual infrastructure systems. Moreover, Rinaldi, Peerenboom & Kelly (2001) describe and discuss interdependencies of systems, and show how interdependencies can be thought of as flows. However, they stop short of developing the actual models of infrastructure systems impacting societal entities. Similarly, Furuta et al. (2016) present a framework for modeling a network of infrastructure systems in a system-

of-systems model approach. Nevertheless, there is much less research available on how infrastructure systems impact businesses and households. These interdependencies between infrastructure systems and other societal units are understudied. In this paper, we provide a method for researching these interdependencies.

The use of input-output model in various settings is well documented in research, and has been described and applied to many fields. It has been applied to production of resources by geographical area in economies (Isard, 1951). Also, the input-output model has been utilized in supply chain management modeling (Wang, Sun, Tian & Yu 2011). Similarly, it has been applied to life-cycle assessment in wood production in a forestry setting, to describe model of what resources are needed to produce quantities of wood in particular types of forests (Heinimann, 2012). These papers describe input-output model in various settings from the economic perspective. However, the input-output model has never been applied to dynamic infrastructure systems modeling scenarios, what we achieve in this paper.

Acknowledgement

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Identifying and Quantifying the Resilience Dividend using Computable General Equilibrium Models: A Methodological Overview

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Abstract

This paper introduces the concept of accounting for the net co-benefits (the resilience dividend) associated with community-level resilience planning. Two solutions to the same resilience issue may often have different associated co-benefits that accrue on a day-to-day basis even if a disruptive event has not yet occurred. Thus, assessing potential community resilience projects requires taking (positive or negative) co-benefits (i.e., the resilience dividend) into account. Without including positive (negative) co-benefits, the total value of a resilience project may be underestimated (overestimated). But to date, quantification of the net co-benefits of resilience planning is not often addressed in the literature, as it is not a straight-forward task. We overview a methodology developed using spatial computable general equilibrium (SCGE) models to quantify and assess the distributional effects of the resilience dividend arising from a proposed resilience plan. In turn, such assessments can be used in benefit-cost analyses (BCAs) and other economic project assessments when comparing among potential resilience projects. Economically, good decision-making requires prioritizing feasible projects with the greatest overall net-benefit to the community. We provide a way for co-benefits to be quantified and subsequently accounted for in formal assessment by communities choosing among resilience plans.

Keywords

community resilience, adaptation, mitigation, community planning, macroeconomics

1. Introduction

The number of observed large-scale disruptive natural events is rising – by about five percent a year since 1960 (Schultz and Elliott 2013). Kunreuther and Michel-Kerjan (2009) note that costs of natural disaster-related losses jumped from \$93.3 billion in the 1960s to \$ 778.3 billion in the 1990s. Strömberg (2007) notes that population growth (meaning more people encounter disasters) explains only about half of this increase. After all, there has also been a marked reduction in lives lost due to natural disasters.⁴⁰ An important

⁴⁰ From 1900 to 2003, 62 million deaths resulted from natural disasters throughout the world. But 85 percent of those deaths occurred between 1900 and 1950 (Bandyk 2010).



factor in the increased number of reported disasters is likely better reporting and more responsive aid organizations as well as changing climatic trends.

As weather-related covariate risks and the associated costs of losses increase in the future, households and businesses need resilient strategies and coping mechanisms that reduce the effects of such disasters, in terms of intensity and economic losses. Generally, as assets vulnerable to natural disasters increase in value, so do costs of protecting these assets and infrastructure through insurance and/or other means of planning. Thus, the concept of choosing resilience plans that encompass co-benefits to the community on a day-to-day basis in the absence of a disaster event has garnered increased interest recently (e.g., Rodin 2014). Accounting for the net co-benefits (i.e., the “resilience dividend”) of a resilience project can often produce a convincing business case for undertaking the project. This is especially pertinent when the return on investment may be much lower if a disaster does not take place during the time frame of the analysis. Fung and Helgeson (2017) define the “resilience dividend as the net benefit (or cost) that accrues, from investments aimed at increasing resilience, in the absence of a disruptive incident over the planning horizon,” and provide a comprehensive overview of the resilience dividend as a useful metric for community resilience planning and reviews measurement and assessment efforts.

This paper provides an overview of the importance of accounting for the net co-benefits of resilience planning and explores a novel approach to quantifying the resilience dividend. The methodological approach introduced uses a spatial computable general equilibrium (SCGE) model of the community being assessed for resilience planning to identify co-benefits (co-costs).

The remainder of this paper is organized as follows. Section 2 provides context by reviewing the literature and some approaches that strive to quantify the resilience dividend, which to date has been largely dealt with through qualitative case studies (Rodin 2014). The section highlights the importance of considering the economic flows from the resilience dividend in a dynamic, quantifiable manner. Section 3 provides an overview of CGE and SCGE modelling. Section 4 provides a detailed discussion of data required to use SCGE models with special focus on the characteristics of a CGE model designed to trace co-benefit-related flows and distributional effects. It discusses the complex nature of obtaining data for CGE models and the accompanying social accounting matrix (SAM). This section offers insight as to the ideal

data versus data that is sufficient in most cases. Section 5 takes the data discussion towards methodological implementation. Finally, Section 6 highlights next steps and future work to develop a full case study based on the SCGE net co-benefits methodology introduced in this paper.

2. Background and Motivation

2.1. The importance of considering resilience-related co-benefits

Economic valuation techniques, such as benefit-cost analyses (BCAs) for community resilience planning alternatives, are often not a straightforward process. In nearly all cases, measuring the economic impact associated with resilience planning requires a better understanding of the costs and indirect losses⁴¹ to maintain a full accounting of the major cost elements. On the loss side, an understanding of the cascading indirect losses is critical to true valuation of losses stemming from a natural disaster. Furthermore, quantifying and accounting for uncertainty in estimates related to these costs and losses is complicated due to the nature of disaster events and the uncertainty surrounding their occurrence and effects. Finally, measuring net co-benefits (i.e., the resilience dividend) is needed to articulate the business case for resilience planning. Often plans that could alleviate vulnerability to a large-scale disruptive event, but are not called into action due to the absence of the event (in a given time frame), are perceived as a poor investment. Consideration of co-benefits (co-costs) is generally good practice,⁴² as the impacts of these values can be pivotal in identification of the most effective and efficient resilience plan.

When quantification of co-benefits is possible, they should be folded into the net-present valuation (NPV) of resilience plans (see Gilbert et al. (2016) and Helgeson et al. (2017)). Yet, much like cascading indirect losses, there are likely cascading and wide-spread effects of identified co-benefits. Thus, the use of computable general equilibrium (CGE) models that employ actual economic data from a community to estimate how an economy might react to changes in policy, technology, or other resilience planning initiatives allow for a better understanding of distributive effects of net co-benefits. Specifically, spatial computable general equilibrium (SCGE) models can be employed to indicate the distinction of flows throughout different areas of a community, which may be more or less vulnerable to and affected by a disruptive event. CGE and SCGE models are overviewed in Section 3.

2.2. Defining and quantifying the resilience dividend – overview

To date, the literature is largely dominated by definitional discussions and qualitative assessments of co-benefits (co-costs) and the resilience dividend using case study examples (e.g., Rodin 2014). In a review of the literature, Fung and Helgeson (2017) found that co-benefits fall into three broad categories: 1. Objective-based, 2. Intent-based, and 3. Externality-based.⁴³ The objective-based definition of co-benefits fits well into the methodology overviewed in this paper. Objective-based definitions regard co-benefits as benefits to secondary objectives of a policy (ibid.). For instance, changed zoning in a community may have a primary objective of shifting commerce away from the flood zone, while secondary objectives may include stimulating economic growth in an area of town that becomes favorable for re-locating businesses.

As noted in Fung and Helgeson (2017), research on the co-benefits of climate change mitigation and adaptation is substantial, while co-benefits in the context of resilience planning is still relatively nascent.

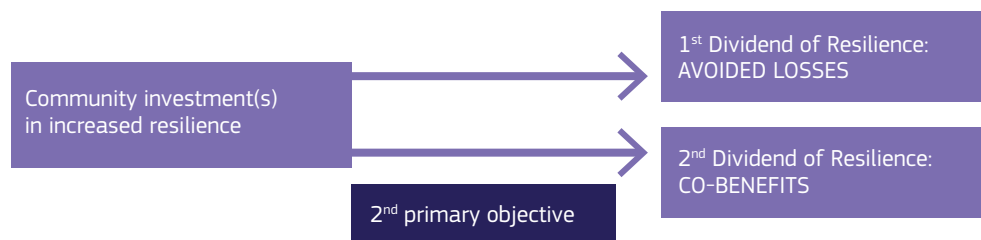
⁴¹ To date, direct losses tend to be better documented.

⁴² See Gilbert et al. (2016) and Helgeson et al. (2017)

⁴³ Externalities are defined by benefits (costs) that accrue to third parties. As such we treat them fundamentally different from values that are encompassed by the resilience dividend. For a discussion of externalities versus non-disaster related benefits (i.e., the resilience dividend), see Gilbert et al. (2016) and Helgeson et al. (2017).

Much of the literature on co-benefits of resilience planning is centered upon the developing country context. Furthermore, there appears to be relatively few scholarly works that deal with quantification, opposed to qualitative assessment, of co-benefits. This is understandable, as much of the work that explicitly encourages quantification of co-benefits when possible is based upon ex ante analysis, such as BCA, to determine effective investment decisions across a suite of options. In an ex ante BCA it is naturally complicated to capture full valuation of co-benefits, which often are apparent only after a plan is put in place. In other words, some co-benefits of significant value may not be readily obvious during the planning phase without a larger scale model that can incorporate spatial and/or distributive effects. But quantifying the full co-benefits ex post is not a simple task – modeling the economy is complex, it is likely very unclear how the co-benefits flow through the economy, and since the decision was already made, stakeholders may be less inclined to spend money and other resources on studying the issue.

Figure 1. Conception of the resilience dividend as net co-benefits used in this paper and upon which the proposed methodology is based.



A series of World Bank reports have presented the resilience dividend as arising from a “Triple Dividend of Resilience” as largely relevant to disaster risk management (DRM) (e.g., Tanner et al. 2015, Tanner et al. 2016, Mechler et al. 2016). This triple bottom line consists of: 1. avoided or reduced losses, in the event of a disruptive event occurring; 2. increased economic resilience from reduced disaster risk; and 3. co-benefits for development. Elements one and two make up the first dividend of resilience, while the third element makes up the second as shown in Figure 1. Though these three “dividend” sources do not map perfectly onto the developed country context, the prevailing message is that budgeting for contingent liabilities such as disaster risk, especially ex ante a disruptive event, is nearly impossible without accounting for the resilience dividend.

A recent RAND report (Bond et al. 2017) describes a Resilience Dividend Valuation Model (RDVM) and its application to six case studies in the developing country context. It should be kept in mind that Bond et al. (2017) define the resilience dividend as “the difference in net benefits from a project developed with a resilience lens versus one that is not.” This definition is much broader than the definition we use (Fung and Helgeson 2017), which is concerned with net benefits above and beyond benefits expected to accrue directly to the goal of resilience to a disruptive event.

The RDVM largely looks at the resilience dividend as the positive net benefits generated between a resilience project and a business as usual (BAU) counterfactual. The elements of the RDVM are largely based on typical meso- and macro-economic elements within a production-oriented framework: 1. Capital stocks/assets, 2. Production functions and allocation mechanisms (i.e., institutions), 3. Social welfare function, 4. Shocks and stressors (both ex ante and ex post), and 5. Project interventions (based on resilience).

Of the six case studies considered in the RAND Report, three are ex ante and three are ex post assessments. Three of these six case studies resulted in no quantifiable resilience dividend assessment (two ex post and one ex ante) and three result in a partial quantitative assessment of the resilience dividend (two ex ante and one ex post). In many cases the lack of a full quantitative resilience dividend analysis is discussed in the context of too little data

being available through pre-existing documentation and data.⁴⁴ Another challenge discussed is that only one state of the world is observed—the counterfactual is unobservable—it is then difficult to rely on observations made with or without a resilience intervention (i.e., plan) in place (ex ante or ex post).

The systems model approach we propose for assessing the resilience dividend is typically based at the meso-level of a community's economy and allows us to make assessments of the resilience dividend and the associated indirect flows throughout the economy. Many of the elements discussed in the RDVM in terms of a production-oriented framework are reflected in the SCGE model approach we describe in this paper. In our approach, we can theoretically obtain community-level data for any US-based community that may be engaged in resilience planning and assess ex ante potential resilience dividends as well as ex post performance. There are limitations inherent in this approach; this is especially the case for micro-level economic activity, at the household, opposed to community levels. This approach is a first step toward creating dynamic quantitative valuation of the resilience dividend and distributive effects.

3. Computable General Equilibrium Models – Introduction and Overview

3.1. CGE General Details and History

The characteristics of CGE models make them a reasonable choice for exploring the effect of large disruptive events on a community's economic activity as well as effects of resilience planning. This section provides a general outline of CGE and SCGE models. Specific use of an SCGE model and the relative data requirements is discussed in Section 4 of this paper.

There are two major reasons for exploring the use of CGE models to quantify the resilience dividend. The first being that while qualitative results are useful, understanding the relative effects in magnitude of a shock and the associated resilience plan as well as the resilience dividend is important. The second being that solid micro-foundations enhance our understanding of resilience planning and how a resilience dividend affects consumers, producers, and government in an economy. Overall, the aim of the CGE model approach is to convert the abstract representation of the community's economy into a realistic, solvable approximation to assess direct and indirect benefits of resilience planning. In turn, these assessments can help inform values used for co-benefits (co-costs) of resilience planning in (ex ante) BCA during planning phases.

Input-output (I-O) analysis (Leontief 1941) has been used for assessing the impact of a change in the demand conditions for a given sector of the economy.⁴⁵ I-O models/coefficients assume constant returns-to-scale for associated production functions and prices are also assumed to remain constant. Extension of the I-O model to a social accounting matrix (SAM) framework is performed by partitioning the accounts into endogenous and exogenous accounts. Sadoulet and de Janvry (1995) note that endogenous accounts are those for which changes in the level of expenditure directly follow any change in income, while exogenous accounts are those for which we assume that the expenditures are set independently of income.

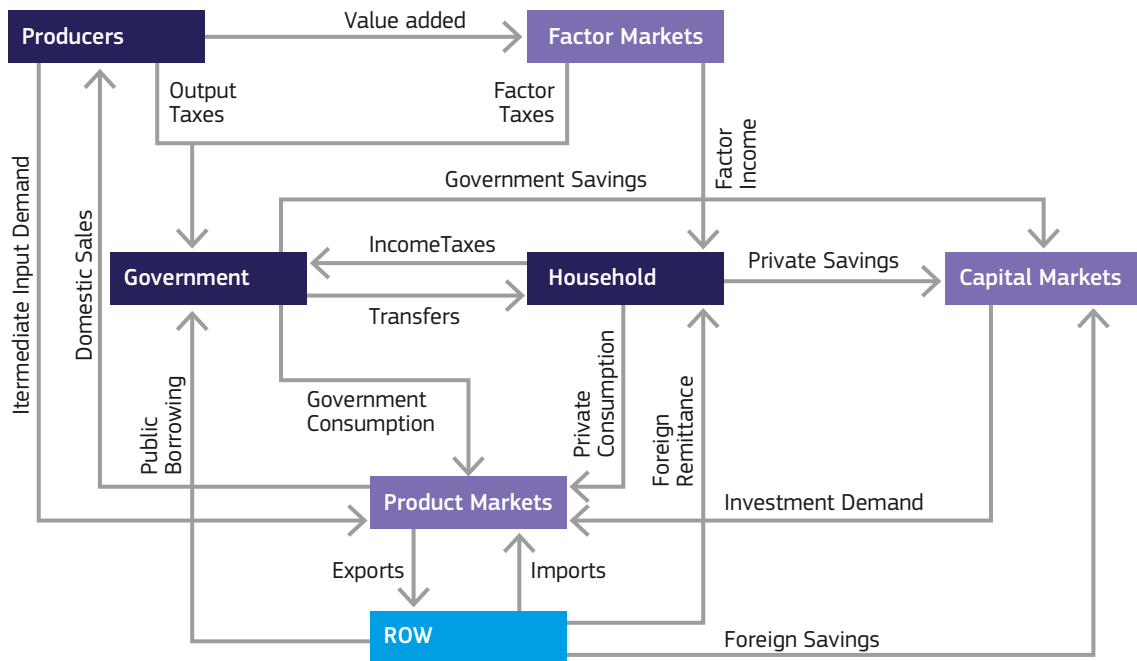
The CGE model encompasses both the I-O and SAM frameworks; this occurs because demand and supply of commodities and factors are assumed to be dependent on prices. Figure 2 provides a schematic overview of the typical elements of a CGE model. A CGE model simulates the working of a market economy in which prices and quantities adjust to clear all markets. For example, households maximize their welfare, the government is assumed to have a balanced budget, and resources are limited and costly. Effectively, a CGE model

⁴⁴ This data was not necessarily collected initially for use with the RDVM in most cases (Bond et al. 2017).

⁴⁵ See Section 4.7 for further discussion.

specifies expected behavior of optimizing consumers and producers, as well as including community government (e.g., taxes) as an agent to capture transactions in circular flow of income (Robinson et al. 1990).⁴⁶

Figure 2. Schematic of main components in a CGE model. Note that ROW refers to the “Rest of the World”, that is the aggregation of all economic transactions between the selected region under consideration and those not within the selected region.



3.2. Comparative-Static or Dynamic CGE Models?

Many CGE models are comparative-static; they are used to model the reactions of the economy at only one point in time. In such cases, the model is interpreted as demonstrating the reaction of the economy in a future period to one (or more) external shocks, policy changes, and/or resilience planning efforts—in our application, the resilience dividend. That is, the results show the difference (usually reported in percent change form) between two alternative future states (with and without the resilience plan in place). The process of adjustment to the new equilibrium is not explicitly represented in such a model, as the temporal element of a CGE model is not well defined. But it is possible to distinguish between short-run and long-run equilibria (e.g., looking at whether capital stocks are allowed to adjust in a given run of the model).

By contrast, dynamic CGE models (e.g., Pereira and Shove 1988) explicitly trace each variable through time—often at annual intervals. These models are more (temporally) realistic than comparative-static models; however, the data requirements are greater and they are generally more challenging to construct and solve. Furthermore, in the case of resilience planning which already encompasses a great deal of uncertainty, they require that future estimations are made for all exogenous variables—not just those affected by the shock,

⁴⁶ The CGE model takes a Walrasian neoclassical general equilibrium approach—the main equations that need to maintain equilibrium are derived from constrained optimization of the neoclassical production and consumption functions. Producers operate at a level as to maximize profits (minimize costs). Production factors – labor, capital, and land – are paid in accordance with their respective marginal productivities. Consumers are assumed to be subject to budget constraints, but otherwise maximize their utility. At equilibrium, the model solution at equilibrium provides a set of prices to clear commodity and factor markets within the modelled community's economy (see Bandara 1991).

policy change, and/or resilience plan. Furthermore, consistency problems may arise because variables that change from one equilibrium period to the next may not be consistent with each other in the fixed period of change.

Thus, we propose using a comparative-static model set-up. In some cases, the data required for the CGE assessment of the resilience dividend (see Section 4) will be available in different years. Thus, creating a CGE model for a period before the resilience plan integration and another CGE model following the integration may be a realistic way to provide a dynamic understanding of the resilience dividend.⁴⁷

3.3. Spatial CGE Models

SCGE models deal with distributive effects in a manner that makes a great deal of sense when dealing with resilience planning against large-scale shocks (e.g., natural disasters). To date, SCGE models have been used to assess economic impacts of infrastructure investments and policies, especially in the area of transportation (e.g., Ivanova et al. 2007 and Miyagi et al. 2006). Multi-regional input-output models are the closest relatives to SCGE models, but they are not able to fully capture price and quantity effects as they do not allow for substitution effects.

Thus, SCGE models are a natural fit for exploring the resilience dividend and the geographic distribution of the relative effects. In our discussion of data requirements and setting up the resilience dividend assessment we assume use of SCGE modelling.⁴⁸ Section 4 describes the specific data required to create a SCGE model to quantify the resilience dividend and determine distributive effects.

4. Data Required

4.1. Social Accounting Matrix (SAM)

The primary goal of data collection is to develop the social accounting matrix (SAM). A SAM can generally be described as “an organized matrix representation of all transactions and transfers between different production activities, factors of production, and institutions ... within the economy and with respect to the rest of the world” (Hirway et al. 2008). In short, it quantifies all cash flows between pertinent actors within an economy. The SAM serves as the core of the CGE analysis, as it defines the base relationships between sectors, households, labor markets, and other key actors in the economy that the CGE model uses to determine the impacts of policies and shocks. The World Bank (Round 2003) notes that there are three key features to a SAM: 1) they are square matrices, 2) they are comprehensive, including all economic activities of the system, and 3) they are flexible in how they may be disaggregated and what parts of the economic system are emphasized. The following sections provide available sources for acquiring the data needed to build a SAM based on the method for constructing a spatial SAM and CGE model developed in Cutler et al. (2017). The subsequent data sources are not the only ones available, but are more commonly used than others or are most capable of filling data needs. There is a comprehensive discussion of methods for SAMs and CGE models in Cutler et al. (2017). Example applications and case studies using CGE modeling can be found in Cutler et al. (2017) and Schwarm and Cutler (2003).

⁴⁷ This solution implies a retroactive study opposed to a perspective study in which the outcomes of the economy after the resilience plan is enacted is completely unknown.

⁴⁸ For more on SCGE, see Bröcker and Korzhenevych (2011).

4.2. Quarterly Census of Employment and Wages (QCEW) data

4.2.1. Summary

The quarterly census of employment and wages (QCEW) is a Bureau of Labor and Statistics (BLS) program that reports the quarterly count of employment and wages for employers, broken down at the industry (defined by the North American Industry and Classification System (NAICS) code) level and geographically at the county, Metropolitan Statistical Area (MSA), state, and national levels. The QCEW covers roughly 95 % of all U.S. jobs (BLS Website). This data is an excellent source to determine wage payments, employment, and number of firms by industry.

4.2.2. Challenges

Because the data contains commercially identifiable information (CII) and, potentially, personally identifiable information (PII), firm-level QCEW data is not publicly available and must be requested through an appropriate state or federal government agency. This process can be time consuming and may require payment to cover the cost of labor. There are also restrictions on how it can be used and reported, namely steps must be taken to mask any CII or PII. This is typically done through ensuring a minimum number of firms in each industry and making sure that no single industry has a large percentage of its data coming from one firm, regardless of how many firms are in the industry.

While one of the best sources of data for building a SAM, there are other ways to obtain the same information, though the data will typically be pre-aggregated to address CII and PII concerns and thus, less refined. The advantage of obtaining firm-level data is that a researcher can customize how the data is aggregated. In particular, the data can be aggregated with respect to sectors defined by the researcher, potentially breaking these out spatially using the establishment address. See Section 5.1 for more details.

4.3. LEHD Origin-Destination Employment Statistics (LODES) data

The Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES) data collected by the Center for Economic Studies at the US Census Bureau details employers, their employees, and the flow of jobs over time and space. This data allows for the mapping of labor flows between regions within and beyond the scope of a given CGE model. This data can be especially useful in modeling the commuting patterns of employees in and out of town as well as movement between a city's districts. The value of this data is in its ability to specify the transportation needs of the community under analysis and evaluate how that community would be impacted by various disaster scenarios or other shocks. For instance, the severity (measured in economic damages) of a hazard event that results in a bridge closure is likely to be informed by the extent to which the local community relies on that piece of infrastructure to commute to work or flee the ill-effects of the hazard in question.

4.4. Public Use Microdata Sample (PUMS) data

4.4.1. Summary

Public use microdata sample (PUMS) data is collected by the U.S. Census Bureau and reported at various intervals. The dataset relies on the use of American Community Survey (ACS) data. Unlike the decennial census, ACS surveys are yearly and not nationwide. Roughly one in thirty-eight households are invited to take the survey every year (U.S. Census Bureau 2017). The data collected in the ACS is very similar to the data collected during the decennial census. The household income distribution can be obtained from this dataset at varying geographic levels ranging from as large as the United States, down to ZIP code tabulated areas. The primary data set of interest from the PUMS data is the employment by sector and the aggregated wage payments by sector. These allow the SAM to differentiate between different labor groups.

4.4.2. Challenges

Access to individual level data is not available without the permission of the U.S. Census Bureau due to the large amount of PII and its access and use is subject to severe restrictions. At present, getting access to Census data requires showing that the use of the data would benefit the U.S. Census Bureau in some way. This is not necessarily easy to prove and, even if access is given, may take a significant amount of time to obtain. If obtained, restrictions on use, where and how the data can be accessed, and how data can be reported add further barriers to use. The publicly available data through the ACS website comes with no restrictions, but is pre-aggregated in a way that may not match one-to-one with the way industries are defined in other datasets. This issue may or may not be important depending on how industries are aggregated in the SAM, but nevertheless it is the most readily available data. The use of microsample data means the given value is extrapolated from the subset of U.S. homes that took part in the survey. If the desired year happens to coincide with a decennial census, then the use of decennial census data is possible.

4.5. County and City Assessor data

4.5.1. Summary

The development of a CGE model involves the construction of an accurate snapshot of a specific economy at a given point in time so that the resulting model may be calibrated to represent the community under investigation. One key component of the CGE model is the accurate representation of the value of land and capital within the regional economy. Estimates of household expenditures on various classes of housing services for disaggregated groups of households is also a key attribute of the regional economy that must be modeled with the greatest level of fidelity possible. City and County Assessors offices collect, maintain, and make available to the public this information on the building stock within their respective political boundaries.

4.5.2. Challenges

The challenges inherent in working with public data are generally present when working with property tax assessment data. While very accessible, property tax assessment data is freely available for many communities, usually through the county assessor's office, it can and often does entail typographical errors that complicate the matching of the built environment to the businesses and residences therein. Missing data can be a problem for some variables reported in the property tax assessment data. There is considerable variance in the degree of detail and historical support of reported data across communities. Data may be reported in a manner that is not consistent across all years of interest to a given project. The classification and categorization of the built environment may change over time as data systems are improved and expanded.

4.6. City Budgets and the Comprehensive Annual Financial Report (CAFR)

4.6.1. Summary

Comprehensive Annual Financial Reports (CAFR) are documents containing details of the financial state of a given governmental entity such as a state or municipality. These documents are useful resources for the determination of local government tax revenue, expenditures, and employment. The CAFR provides the information necessary to decompose employment and expenditures into constituent government "industries"; education, public health, public safety, park and recreation, and others. This information is critical to efforts to properly size and disaggregate the government sector within the CGE model. CAFRs tend to be different across communities; one constant tends to be that the CAFR provides an excellent source of tax revenue and expenditures. The CAFR can also be a reliable source of data on the expenditure of federal funds in the local economy. Within some CAFRs, there is a Schedule of Expenditure of Federal Awards which lists information for each federal grant

awarded to the city (or other government entity) organized by the granting agency and program title.⁴⁹ This is a useful source of information for corroborating the timing of federal assistance programs that target disaster response among other pressing community needs. While the data in the CAFR on federal assistance may not be sufficiently disaggregated to model at the establishment or industry level, it is useful for ensuring the magnitude of relevant programs.

4.6.2. Challenges

The CAFRs are data-rich documents, but they generally contain information that must be reformatted or reorganized if it is to be of further use to the CGE modeler. While there are standards of presentation and content associated with the CAFRs, the exact format of the reports can differ over time, complicating long-term trend analysis.⁵⁰ It is possible that the CAFR for any single year may include federal grants that are only present in that year. Care should be taken to avoid treating grant awards as recurring components of local government finance within the CGE model.

4.7. Bureau of Economic Analysis (BEA) data

4.7.1. Summary

Bureau of Economic Analysis (BEA) data is vital in building the SAM. The BEA data set provides the necessary tables to determine I-O coefficients and the values required to develop the relationship between investment and the stock of capital. The I-O data is generally taken at the national level and, in its raw form, gives the raw dollar amounts of input from each industry and the total output from each industry. These values can be used to determine I-O coefficients, which represent how much input each industry requires from every other industry in order to produce a dollar's worth of output. I-O coefficients define the flow of money between industries, and thus the linkages between industries necessary for the CGE model to determine how impacts on one industry flow to another.

The data for the investment capital linkage (CAPCOM) matrix comes from the BEA "Capital Flow" data. This data tracks the investment in new structures, equipment, and software by using industries. In essence, it measures how many commodities a specific industry purchases for investment from another industry. Like the I-O data, the CAPCOM tracks the interdependencies between industries; however, it focuses on new investments instead of required input. The raw data is taken from the I-O commodity categories (as opposed to the National Income and Product Account categories), which are in terms of producers' prices.

Other useful data from the BEA includes the BEA employment estimates and the BEA income estimate, which are available at varying geographical levels. While other datasets offer data on these values that are better suited for use in the SAM, the BEA estimates provide a useful check for their totals.

4.7.2. Challenges

As the BEA data is derived from multiple sources using CII, including the U.S. Census Bureau, all publicly available data is pre-aggregated, meaning industry classifications may not match one-to-one between other data sets. The more detailed underlying data is subject to the similar requirements for access, and restrictions on use, as mentioned for the ACS data.

⁴⁹ A CAFR may not include a Schedule of Expenditure of Federal Awards if the total amount of federal awards expenditures by a non-federal entity is less than \$750 000 dollars in the reporting year. Title 2 U. S. Code of Federal Regulations Part 200, Uniform administrative requirements, cost principles, and audit requirements for Federal awards provides the guidance on whether or not a CAFR must contain an audit of the expenditure of federal grant awards.

⁵⁰ Accounting and financial reporting standards for state and local governments are codified by the Government Accounting Standards Board (GASB).

4.8. Informal data from community leadership and agencies

4.8.1. Summary

Depending on the exact research question and scope of the resilience dividend, the community being studied itself may prove to be an invaluable source of information. In the context of resilience, local officials can offer a unique and comprehensive perspective on the impact of a natural disaster on the community. Conversations with the City Manager's Office, Emergency Management, and (public or private) Economic Development teams can reveal priorities with respect to both the immediate response to a disruptive event type faced by the community, as well as short- and long-term recovery efforts and community goals. For instance, while a researcher may be aware that a community is investing in flood resilience, it is not obvious to an outsider where and how a community is investing its resources. Moreover, community officials can help a researcher compile a more complete picture of funding sources, both private and public.

Conversations with community officials can also provide perspective on local economic trends and goals, both irrespective of the potential disaster and specific to the disaster occurrence. While official data may suggest that manufacturing is an important sector to a community, the community itself may emphasize information technology as a growing sector being targeted with economic incentives such as tax breaks. Moreover, the community can provide insight into regional trends. For instance, business improvement districts may be integral to long-term community resilience. Certain neighborhoods may be of particular interest to a community (e.g., revitalization of downtown commerce). Such trends may inform the modeling step, in terms of how a researcher defines the productive sectors—especially spatially—and consequently the aggregation of official data for constructing the SAM.

4.8.2. Challenges

While the information gathered from conversations with community officials comes from authoritative sources, the “data” collected is informal. Incorporating the array of information into constructing a CGE model is less about collecting input data and more about guiding research direction. The biggest challenge arises from knowing what to ask. As an outsider, a researcher may have preconceived notions of what issues matters most, and community officials may be more than happy to answer questions about such issues. It is important to remember that what matters most to a community may differ from what a researcher thinks matters most. Gaining an understanding for a community's priorities can provide the proper context for analyzing a community with a CGE model. Moreover, it is important to keep in mind that not all communities may be organized enough to provide the necessary data, and some may be reluctant to the idea of providing the information. Even when community officials are willing to share information, they may be constrained by regulations, budget, or time.

4.9. Third Party data

4.9.1. Summary

If other data sources are not viable for use in the SAM, third party data may also be used. Third party datasets typically will provide the requested data aggregated as requested for a fee. Impact Analysis for Planning (IMPLAN) data (IMPLAN Group LLC) is a commonly used third party dataset derived for economic analysis. Their data includes premade SAMs at the national, state, and county level that can be augmented by the user with different data or relationships (RESI 2006). Other datasets are available, for example Thomson Reuters (Thomson Reuters 2015) and FactSet (FactSet 2017).

4.9.2. Challenges

Due to the proprietary nature of third party datasets, it is impossible to know all of the details of how the data were developed. While companies do describe processes and underlying sources, they invariably do not include everything in order to preserve any business advantages they might possess. The data also must be purchased and the fees may be prohibitive depending on the nature of the analysis and the party or parties required to purchase it. Care also must be taken to ensure that the data available from the third party is the actual data required.

4.10. Geographic Data

4.10.1. Summary

Economies have long been modeled as systems disembodied from their physical components. The increased adoption of geographic information systems (GIS) by firms and government entities allows for the spatial disaggregation of economic data with location records. Geographic data enables the introduction of explicit spatial considerations into the CGE model, which brings it towards an SCGE model. It is reasonable to assume that similar shocks may propagate through an economy in patterns that are informed by the topology of the built environment and regional geography. In many cases, data used for the CGE model includes spatial identifiers such as street address. GIS tools such as geocoders that produce longitude and latitude coordinates when fed address information, allow for the geolocation of individual business establishments and residences. In addition to matching firms and parcels, geocoding is instrumental to the process of defining the districts into which the local economy is divided. Once the geographic coordinates of each parcel are obtained, the parcels can be plotted and sorted into their districts using ArcGIS software. The importance of spatial linkages to overall impacts from a hazard may differ with the economy and hazard in question. There is a fundamental tradeoff between increased spatial disaggregation using GIS data and reduced complexity within the SAM. Establishing a distinct district for each establishment or residence would intractably complicate the SAM. Neglecting to incorporate any spatial information into the SAM may aggregate contravening trends, delivering results that mask important underlying trends in economic growth and hazard recovery.

4.10.2. Challenges

The fundamental challenge of working with GIS data is rooted in its variable quality and availability. GIS data may be missing for some public records and can be difficult to extract from data with messy variable coding. Improperly assigning establishments to the wrong district, as a result of bad address data, could impact the validity of a spatial CGE model. Different geocoding tools can produce geographic coordinates for the same record that disagree by small or large distances. The judgement calls that must be made to render this GIS data usable may ultimately be unjustifiable. Furthermore, GIS data can be inherently identifying when merged with other sources of data. Care must be taken when working with GIS data to avoid the unintended disclosure of CII and PII.

5. Methodology

5.1. Combining the Data

Combining the data from Section 4 into the SAM offers several benefits. First, in many cases it is often necessary. No single data set from Section 4 contains all of the required data for the SAM, with the possible exception of that provided by a third party vendor. Second, all of the data can be verified by the model builder. Moreover, each dataset can be verified independently by the model builder and better tailored to particular assumptions. Using third party data limits how much verification and customization is available for the analysis. Most

third-party datasets are heavily vetted; however, it can be beneficial to be able to check the underlying data. Third, working with the data directly can allow further insights outside the original scope of the model. Trends may appear in one dataset that wouldn't be visible in working with only the final SAM.

While there are benefits to using multiple sources of data, the use of the varied sources in Section 4 can create challenges when folding them into the final SAM. One example of this complication is attempting to derive the I-O and CAPCOM data at the PUMS sector level using the PUMS defined industry codes. The BEA and PUMS data sets are both based on NAICS codes; however, they aggregate those NAICS codes into larger industry categories that do not match one-to-one with each other. If the industries are broadly defined then this is not necessarily an issue. For instance, if manufacturing industry data is provided without disaggregation, then the industry codes from the PUMS data and BEA data, while different, still fall entirely within the larger aggregated manufacturing sector. If manufacturing industry data is disaggregated, then there is no guarantee that the each PUMS industry code will have a corresponding BEA code, or codes, that match in terms of NAICS codes covered. In such cases a fuzzy match is required which will possibly lead to a NAICS code from a sector not in a specific PUMS industry code being in the IO table for that PUMS industry code due to the inconsistency. The alternative version where a PUMS industry code loses a corresponding NAICS code is also possible.

Another challenge comes from datasets not necessarily covering the same geographical area. For instance, the smallest division of the county assessor may be at the city level, while the smallest division in the PUMS data may be at the MSA level. In such cases, it may be necessary to scale numbers up or down based on some distribution of relevant data, to get geographic areas to match up. An example of this would be scaling down MSA level data for industry specific employment by labor group down to the city level based on the known distribution of industry employment in the city.

Using different data sets means the totals for some values obtained for the same geographic area, such as total employment, should be the same (if all data were perfect), but end up being different between data sets. Such differences are to be expected between data sets, as differences in what is or is not included and methods may end up resulting in different estimates. Still, the CGE requires consistency between key values in order to balance the SAM and run analysis. Similar to the situation of differing geographic areas, scaling numbers up or down to match may be required. However, these differences between data sources under such circumstances should be relatively close. Otherwise, there may be an unaddressed issue with the data.

Spatializing the SAM adds further complications. One issue that arises is the need to match industry level data to the spatialized components. This process is meant to allot the capital land value from the county property tax assessment data and the QCEW employment and wages to the appropriate industry sector. Matching on addresses is known to be a non-trivial task, as abbreviations, misspellings, date entry errors, and other consistency problems make getting the desired match difficult. Address standardization and fuzzy matching can alleviate this, but typically does not fully address the issue. The other complication with using the QCEW data in this context is that there are requirements on making sure all data is aggregated to the point that CII becomes masked. This is typically achieved by ensuring every industry has a minimum number of firms included to make it impossible to trace back the information to a specific firm. This means that industry sectors may need to be aggregated into larger sectors if they contain too few firms.

Spatialization also complicates the entry of sector related data into the SAM. Ordinarily, industries are assumed to be in the area of study and that is all. Spatialization divides industries into sub-regions of the study area. This means labor, households, capital value, and the I-O and CAPCOM tables need to reflect this division. For the I-O table, it can be done fairly simply if one assumes that the firms in any sub-region are essentially the same as the firms in the larger area. Under this assumption, all I-O coefficients are identical to the non-spatialized I-O table for every industry. Otherwise, effort must be put into understanding how firms differ in terms of inputs and outputs in each sub-region. The spatialized CAPCOM

can be obtained by determining a distribution of investments based on available data, for instance, the distribution of workers, firms, or wages for all sub-regions, and distributing them accordingly.

5.2. CGE Coverage of the Resilience Dividend

The ultimate goal of the proposed SCGE modeling method is to quantify the resilience dividend. Therefore, it is important to understand what the SCGE model can and cannot quantify. A CGE model provides distributional impacts of shocks, policy changes, and the current status of the region. Distributional impacts allow the analyst to understand not only the overarching net impacts, but to whom and where those impacts fall and are distributed. Large economic effects will be easily discerned and the impacts can be selected to see how different scenarios may have played out in the region. Any effects of resilience actions that have co-benefits can be modeled to identify how those co-benefits manifest themselves throughout the economy and where they go. Thus, the resilience dividend can be quantified as a grand total, as well as determining who gets these benefits and where they go spatially. SCGE models may not capture the entirety of the resilience dividend in many cases. Non-market benefits that never actually materialize as real cash flows are not necessarily captured. Minor impacts may also be lost as the overall economic conditions may overwhelm them.

5.3. Additional Considerations

There are additional considerations that are important when using a SCGE model to quantify the resilience dividend. There are limitations to the CGE approach and full assessment of the resilience dividend may be best achieved using CGE methods in tandem with other economic methods.

5.3.1. The use of two CGE models

One critique of CGE models is that they are unable to fully capture the dynamics of an economy's response to a shock. Whether a community responds in acute fashion or slowly over a longer time period can have a considerable influence on the impacts of a given shock. The speed and persistence of a shock may be more informative than its magnitude. An advantage of having cross-sectional and panel data for a community is that response trajectories generated without full time specification can be calibrated using trends observed in the temporal data. The speed of recovery is of interest to communities considering their various options. The use of multiple CGE models may facilitate the corroboration of findings across approaches. Furthermore, if static CGE models are built using different baseline years that coincide with periods before and after a hazard event of interest, it is possible to see how the economy's response to an unrelated shock has changed over time. Of course, care must be taken to avoid the Post hoc ergo propter hoc fallacy if one is to employ two CGE models timed to before and after a hazard event. It is quite possible that other important structural changes are occurring simultaneously with the hazard.

5.3.2. Net Present Value, The EDGeS Tool, and CGE

As the CGE methodology uses I-O data there is some debate as to how time plays in CGE models. I-O tables generally represent a snapshot in time. However, CGE models use them to obtain the equilibrium following shocks to a system. How long it takes to reach that equilibrium after a shock is not a simple question to answer. In that regard, the time varying nature of the transition period from base state to post-shock state is currently difficult to model.

On the other hand, if one views the post-resilience action equilibrium as the base state for one case and the pre-resilience equilibrium as the base state for another case, it is possible to use the Economic Decision Guide (EDG) (Gilbert et al. 2016) methodology to examine these options based on Net Present Value (NPV). If a shock representing a disaster of an

assumed magnitude is applied to both cases, the on-event indirect losses required using the EDG methodology can be obtained. Direct losses, such as structural losses, and response and recovery losses, such as temporary shelters, would need to be added in separately. The non-event related benefits can be estimated by examining the two cases' base states, with non-market benefits and externalities added separately from the CGE analysis, assuming these are not impacted by disaster related shock. The costs for each case should be known, thus all inputs required for the Economic Decision Guide Software (EDGeS) Tool (Helgeson et al. 2017) should be available.

6. Next Steps

The next step in this process is to complete an SCGE model based upon a community that has made changes based on resilience planning against a natural hazard event. A flooding event was chosen for the initial case study. Flood situations cannot be entirely prevented, but steps can generally be taken to prevent and minimize loss of property, interruption of business, and loss of life. Furthermore, floods are a leading cause of death from natural disasters in the United States. Flood-related fatalities are reported around 200 per year with about half caused directly by individuals attempting to drive through flood waters (Ashley and Ashley 2008).

Given the uncertain nature of most hazard events, in terms of timing, magnitude and path, we find flooding to be one disturbance event that may be more predictable than are other events, at least in terms of areas potentially affected (i.e., within a flood plain). Flood situations are variable and are often a by-product of other natural hazards, such as hurricanes. But there are instances when floods are standalone disturbance events (e.g., snowmelt, severe thunderstorms, prolonged rains) versus a bi-product or co-consequence of other disturbance events. In such cases of flood as a singular event, a geographic area in a given community may be affected more than other areas given soil, height above sea level, and flood protections. This is the case in general for Cedar Rapids, Iowa and the community's flooding events (p.c. S. Fowler, 13 March 2017).

We are in the process of finalizing the construction of the SAM for Cedar Rapids, Iowa with consideration for Linn County, Iowa. To date, we have collected detailed data for each category noted in Section 4 of this paper. This community made a number of deliberate choices in terms of zoning, retrofit construction, and new construction in the period since the major flood event of September 2008. Tate et al. (2016) assess the government buy-out process undertaken in Cedar Rapids. There are a number of additional projects that have now had time to mature since 2008, such as the revitalization of the downtown district and development of the McGrath Amphitheater (p.c. H. Stiffler 27 June 2017) that can be assessed using SCGE modeling to understand the full resilience dividend and distributional effects throughout the Cedar Rapids economy.

In turn, these findings may be compared to estimates of ROI and the NPV metrics calculated for the projects at the initial time of development and when the choice was made for which projects to take-on and further develop.

We are aware that the SCGE process is data-driven and unique to each community and its associated economy, the disturbances faced and the resilience options available (e.g., subject to budget constraints, social factors, etc.). It is clear that the SCGE resilience dividend quantification methods discussed in this paper may be better suited for the developed country context because of the extensive data requirements. Yet, once the methodology is demonstrated in a case study, it may be possible to assess the level of specificity required in the data to obtain meaningful estimates of the resilience dividend.

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A new approach to model the potential damage and physical impacts on the built environment after an earthquake

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Abstract

This paper presents a new approach to predict the potential damage and physical impacts of an earthquake on the built environment. A new methodology to the urbanized systems and large-scale simulations within a seismic scenario is explored, by evaluating multipurpose codes for numerical simulation. A 3-D building shape of a standard virtual city is developed for evaluating the seismic effects at increasing intensities. Four different building sectors that provide essential functions to a community, including housing, education, business, and public services are considered. Once the buildings are integrated into the city, parallel simulations are applied to compute the system functionality following a disruptive scenario. Tri-linear elasto-plastic backbone curve representative of global shear behavior of each building is estimated considering the dominant modal shapes and building irregularities. Monte Carlo Simulations (MCS) are applied to take into account the epistemic uncertainties associated with geometry and mechanical properties within the range of observations. For each set of buildings' data, the nonlinear dynamic analysis is performed through SAP2000 Application Programming Interface (API) in order to assess the dynamic response of the buildings in an organized and automatic fashion. Accordingly, the city is mapped into different zones representative to the possibility of having different levels of damage (complete, extensive, moderate, and slight). This methodology supports decision-makers to explore how their community will respond to a disruptive event, to develop different strategies for monitoring and control the emergency in urbanized areas, and to plan better resilience-building and evacuation strategies.

Keywords

community
disaster resilience,
virtual city, smart
city, evacuation,
monitoring

1. Introduction

According to the World Bank, disasters have killed 58,000 people on average each year and affected another 225 million people worldwide since 1990. The rising of global populations and the massive economic development in areas prone to disasters have increased the chance of catastrophic incidents, which leads to disruption of buildings and infrastructure. Over the years, community resilience has attracted tremendous attention due to the increasing number of natural and man-made disasters. The concept of resilience is multi-dimensional, and therefore involves various subjects of different disciplines. In engineering,



resilience is the ability to “withstand stress, survive, adapt, and bounce back from a crisis or disaster and rapidly move on”. It can also be defined as “the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize social disruption and mitigate the effectors of further earthquakes”. The absence of a concise and methodical approach makes it extremely difficult to evaluate resilience. This paper focuses on the resilience-based design and assessment of the residential buildings in a virtual city. The objective is to predict, with the set of physical simulation models, the potential damage and physical impacts of an earthquake and other hazards (natural disasters and man-made attacks) on the built environment. A virtual city consisting of different buildings categories and infrastructure was designed. Four building sectors that provide essential functions to a community including housing (residential building, hotel, shelter), education (school, university, library), business (shopping centers, retail stores, heavy industries), and public services (hospital, police station, churches, airport etc.) are considered. Five critical infrastructure systems supporting a community’s indispensable demands, i.e., water and waste water distribution system, gas networks, power grids, transportation and communication networks were also designed. Once the infrastructure was integrated into the city, parallel simulations were applied in order to compute their functionality when exposed to a disruptive scenario.

Given the large number of buildings in a city, the seismic simulation of the buildings cannot be easily implemented without huge computational effort. Thus, several numerical models have been proposed to simulate the seismic damage to buildings in the recent years. Basically, the simulation models are classified into a data-driven method and a physics-driven method. The first is based on statistical data obtained from previous earthquakes. The main limitation is due to the inadequacy and leakage of statistical data for any world areas. To overcome these intrinsic limitations, the physics-driven methods have been progressing in recent years. The building seismic damage is based on the structural analysis of an individual building subjected to a given seismic input. Given limited attribute data of each building and the large number of buildings in an urban area, the seismic response prediction model of buildings must be relatively simple to reduce the computational time requested by the analyses.

In this paper, a simplified and efficient physical approach is presented. Nonlinear response of an Multi Degree Of Freedom (MDOF) model of each building is obtained considering the

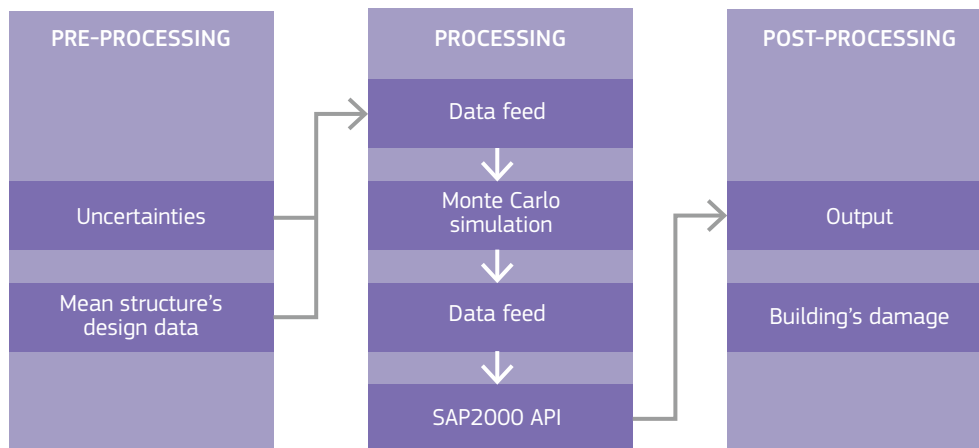
dominant modal shapes and irregularities. A trilinear backbone curve is used to simulate the building's seismic response. The elastic trend of this curve is assessed through a multi-modal approach. A nonlinear static procedure is carried out to evaluate the yield shear force, which is identified as the horizontal force causing the first plastic hinge in the weakest base column.

A collapse analysis is carried out for each building to assess the post-elastic building's behaviour. Considering a global collapse mechanism, the over strength factor is identified according to the geometry of the structural elements composing the building.

Furthermore, the epistemic uncertainties associated with geometry and mechanical properties within the range of observations are taken into account by performing MCS. At each step of MCS a set of parameters are assigned to each building and the associated backbone curve is obtained through an algorithm developed in MATLAB (MATLAB, 2012) by using parallel computing features. The SAP2000 (Computers & Structures, Inc.) application programming interface (API) is used to import, change the building's parameters at each step of the simulation, and perform nonlinear dynamic analysis with a given seismic input.

The SAP2000 advanced numerical modules permit efficient pre- and post-analysis computations. In fact, the automated post-processing analysis allows us to extract all the response parameters needed to estimate the level of damage for each building. The Figure 1 depicts the typical data flow using the SAP2000 API.

Figure 1. Data flow.



2. Buildings Database

The virtual city has been designed based on the buildings stock for the city of Turin, Italy. The virtual city has the area of 120.1 km² with the total population of 850,000. Four building sectors that provide essential functions to a community, including housing (residential building, hotel, shelter, etc.), education (school, university, library, etc.), business (shopping center, retail store, heavy industry, etc.), and public services (hospital, police station, church, airport, etc.) are considered.

Table 1 lists in detail the building sectors supporting the physical, economical, and social dimensions of the virtual city. In total, the virtual city has 30,122 buildings.

The plan dimensions of each building have been gathered through CADMAPPER file for the entire city of Turin. In addition, the numbers of story have been obtained by the shape-file of "Carta Tecnica Comunale (CTC)" of the city of Turin, available at the website <http://www.comune.torino.it/geoportale/>.

The building inventory of the city is based on the building typology concept already used in many European countries at national and regional levels. However, the lack of information about some buildings makes it difficult to have perfect knowledge of any individual building. For this reason, some building's attributes (e.g. year of construction, type of deck) have been assigned based on known data for the entire city. Six different categories of construction year have been utilized according to the main changing from standard Italian codes (Table 2).

Table 1. Number of buildings stock and map of the city.

Building	Residential	27 830	
	Mobile Home	62	
Hospital		17	
Fire Station		3	
Physical Infrastructure	Police Station	Carabinieri	18
		Polizia Municipale	11
		Questura	31
Educational		Elementary School	157
		Middle School	105
		High School	97
		University	70
Hotel		31	
Historical Building		951	
Castel and Palace		18	
Church		176	
Sport		265	
Cinema		48	
Museum		156	
Theater		38	
Library		15	
Economic Infrast.	Industrial Build.	Light	321
		Heavy	108
Commercial		Retail store	25
		Malls	12




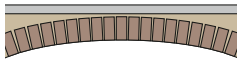
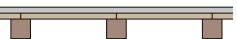

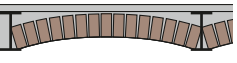
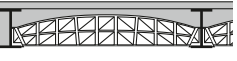
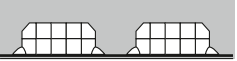

Table 2. Categories of year of construction.

I	II	III	IV	V	VI
< 1916	1916-1937	1938-1974	1975-1996	1996-2008	> 2008

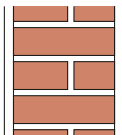
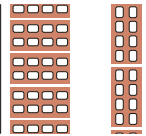
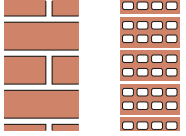
The numbers of buildings for each year of construction category have been assigned according to Cities on Power (CoP) European program research for the city of Turin (Fracastoro et al., 2013). Corrado et al. (2012) provided typical Italian building construction elements depending on the year of construction. Classification of building construction elements (e.g. deck, wall, etc.) plays a key role in the assessment of mass. Seven different typical deck and three typical external walls have been selected and distributed based on their year of construction (Figure 2).

All the buildings have been divided into groups based on material: concrete, masonry, and steel. Considering limited information in the building attribute data, an accurate determination of the nonlinear structural parameters is rather challenging. The major objectives of this work are to provide a simplified and accurate method for assessing the dynamic response of residential buildings in a generic built environment. For this purpose, the geometric characteristics of the structural elements (e.g. columns and beam sizes) have been defined in order to respect all the technical standards for a given year of construction and for a given seismic hazard scenario (medium or high level).

Figure 2. Typical Italian building's decks (a) and walls (b) used for residential occupancy in different years (Corrado et al., 2012).

	Description	Year
	Vault ceiling with solid bricks	< 1900
	Ceiling with wood beams and hollow bricks	< 1900
	Vault ceiling reinforced concrete	1900 - 1930
	Vault ceiling with bricks and steel beams	< 1930
	Vault ceiling with hollow bricks and steel beams	1910 - 1940
	Ceiling with reinforced bricks-concrete slab	> 1930
	Ceiling with reinforced bricks-concrete slab, low insulation	> 1976

(a)

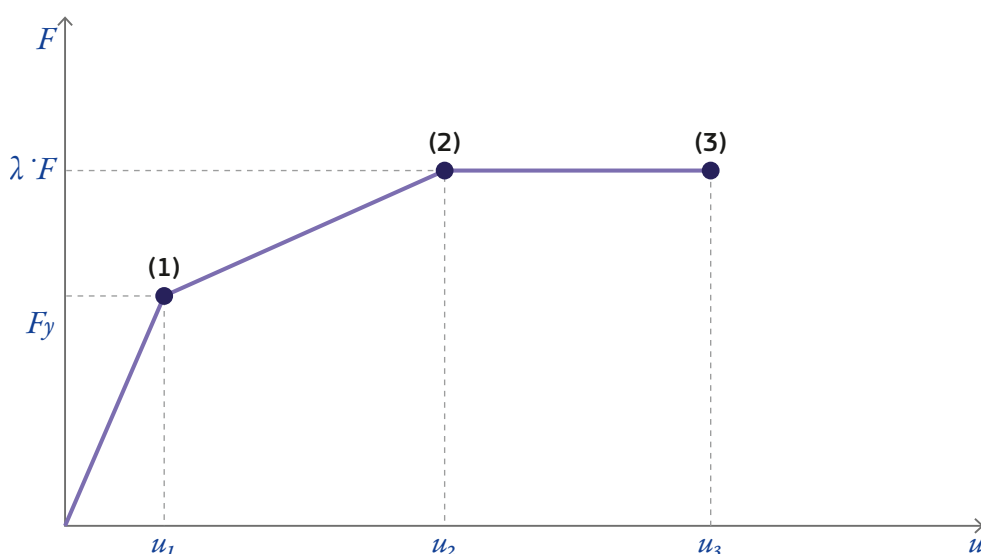
	Description	Year
	Solid brick masonry (25cm)	1900 - 1950
	Hollow wall bricks brick masonry (30cm)	> 1930
	Hollow wall bricks brick masonry with solid and hollow bricks (40cm)	

(b)

3. Nonlinear model

A large component to an urban environment is residential buildings. When a catastrophic event such as an earthquake occurs in a built environment, the consequential structural damage may cause high losses (casualties, repair costs, and repair time). Thus, a concise and methodical approach is needed to estimate the fragility of the building framework. Nonlinear MDOF shear model is able to satisfactorily capture the nonlinear properties of multi-story buildings, predict the Engineering Demand Parameters (EDPs), and assess a reasonable level of damage (Lu et al. 2014; Xu et al. 2014). In the proposed approach, the inter-story behavior of a regular building is simulated through a trilinear backbone curve (Figure 3). Many studies claimed that the trilinear backbone curve model can accurately represent the building's response in terms of inter-story (Vamvatsikos and Cornell 2005; Shi 2014).

Figure 3. Trilinear backbone curve.



The first point of the trilinear backbone curve (1) indicates the yield point ($\lambda \cdot F_y - u_1$) corresponding to the formation of the first plastic hinge in the weakest base column. After the yield point, the stiffness is significantly reduced until the next point (2), for which the maximum shear base capacity ($\lambda \cdot F_y$) is reached. The ultimate point (3) corresponds to the collapse of the building (complete damage). The evaluation of the shear base and top displacement parameters for each point is discussed in the following subsections.

The three main points of the curve are evaluated using a nonlinear static approach for a MDOF system. To achieve this goal, a MATLAB algorithm has been developed considering the uncertainties on the geometric and mechanical parameters used in the analyses. Variation of the parameters within an acceptable range is considered through an MCS obtaining a set of trilinear backbone curves for each building. The ranges of the main building's parameters are selected according to the knowledge level of the building. In addition, the deterioration of the mechanical properties (such as strength and elastic modulus of concrete) is taken into account through the aging equation proposed by Eurocode 2 (EC2, 2004) according to the year of construction. Once the Matlab algorithm evaluates the trilinear backbone curve at each step of MCS, the SAP2000 API is used to apply to all the buildings the data set obtained by the algorithm. This automated procedure is capable of reducing the computational time and analyze the dynamic responses dispersion caused by the data uncertainty. Therefore, the mean response and associated dispersion for each building within the virtual city can be estimated. This approach is suitable to allow a decision-maker the ability to explore how their community responds to a disruptive event and quantify the mean performance of buildings and their uncertainty in the dynamic response after a hazard.

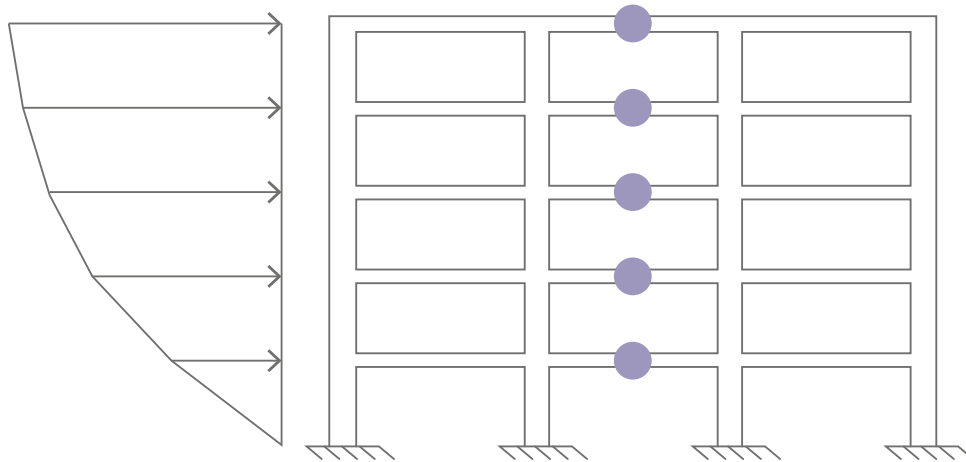
Assimilating the dynamic nonlinear response of a structural system to a unique backbone curve leads to analyze the building as a nonlinear equivalent Single Degree Of Freedom (SDOF) model. Considering an SDOF system allows for a reduction in the computational effort needed to assess the response of a large number of structures. Finally, due to limited amount of detailed building information about its dynamic behavior, the hysteresis is considered according to the Takeda model (Takeda et al., 1970) implemented in SAP2000.

3.1. Elastic parameters

Generally, the geometry of a residential building is mostly regular in plan and elevation, therefore the mass and stiffness can be assumed to be mostly uniformly distributed. In these cases, the evaluation of the response of MDOF system with a nonlinear static procedure is close to the real response of the structure.

Thus, a nonlinear static analysis is performed to assess the base shear and top displacement values corresponding to the formation of the first plastic hinge at the base level (yield point). In order to consider all Degrees Of Freedom (DOFs), the stiffness matrix of the structure is evaluated considering the building as a bending type system. Since the load patterns are applied on two main directions of the buildings, the modal characteristics are derived by considering the stiffness matrix in the two directions for a 2D system. Thereafter, the static condensation procedures are performed to reduce the number of DOFs to the translational DOFs. Moreover, the model assumes that the mass of each story is concentrated in the center of the mass on its elevation and represented by a mass point (Figure 4).

Figure 4. Concept of nonlinear MDOF system.



Equations (1) and (2) summarize the global stiffness and mass matrices of a MDOF model, respectively.

$$K = \begin{bmatrix} k_{11} & k_{12} & L & k_{1dof} \\ k_{21} & k_{22} & L & k_{2dof} \\ M & M & M & M \\ k_{dof1} & k_{dof2} & L & k_{dofdof} \end{bmatrix} \quad (1)$$

$$M = \begin{bmatrix} m_1 & 0 & L & 0 \\ 0 & m_2 & L & 0 \\ M & M & M & M \\ 0 & 0 & L & m_{dof} \end{bmatrix} \quad (2)$$

where *dof* represents the total number of DOFs.

The yielding base shear force is assessed by applying a monotonic load pattern on the building proportional to a given modal shape. A multi-modal approach is carried out to consider all the modal shape contributions, especially for buildings that have geometric irregularities (Equation (3)).

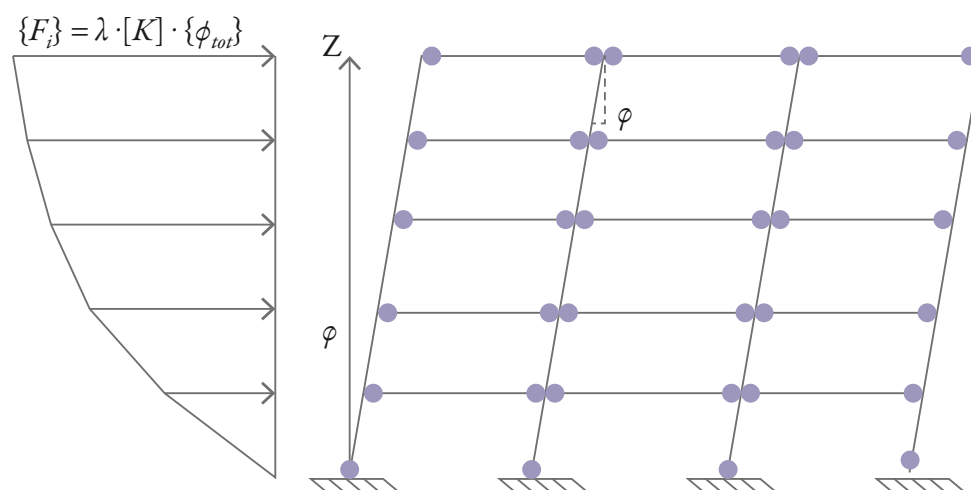
$$\Phi_{tot} = \sum_{i=1}^{dof} \{\Phi_i\} \cdot g_i \quad (3)$$

where Φ_{tot} is the modal shape considering all modal contributions (Φ_i). The modal participation factors are represented by the term g_i .

3.2. Post-elastic parameters

Once the structure reaches the yield point, the stiffness is significantly reduced until point (2) for which the maximum shear base capacity is reached. Thus the top shear base remains constant and the top displacement increases (perfectly plastic behavior) until the ultimate value. The maximum shear base capacity is estimated through the kinematic approach of the limit analysis (Greenberg-Prager theorem). The general global collapse mechanism of a frame subjected to a distribution of horizontal forces (proportional to a given modal shape) is considered (Figure 5).

Figure 5. Global collapse mechanism.



This approach leads to take into account the strength contribution of all the structural elements (beams and columns). According to the kinematic theorem of the limit analysis, the global over-strength factor (λ) is assessed by the ratio between the internal and external work of the structural system with equal columns and beams dimensions (Equation (4)).

$$\lambda = \frac{n_c \cdot M_{y,c} + 2 \cdot n_{span} \cdot dof \cdot M_{y,b}}{\sum_{i=1}^{dof} \{F_i\} \cdot \{z_i\}} \quad (4)$$

where $M_{y,c}$ and $M_{y,b}$ are the yielding bending moment for the columns and beams, respectively. The parameters n_c represents the number of columns, n_{span} indicates the number of spans in the considered direction, and dof is the number of master DOFs which corresponds to the story number of the building. The external work is given by the denominator expression and it is due to the horizontal load patterns $\{F_i\}$ multiplied by the distance between the considered story and the base at each elevation level $\{z_i\}$.

One of the limitations of this procedure consists of the load pattern's shape. In fact, the monotonic horizontal force distribution does not change its shape due to the progressive formation of the plastic hinges in the columns (non-adaptive approach). In addition, a global mechanism has been considered as representative of the collapse mechanism. This hypothesis is reasonable for regular buildings designed according to the seismic standard codes. When a building is not well designed or seismically retrofitted (such as an old building), the collapse can be caused by a local mechanism for which the over-strength factor assumes lower values. In these cases, the possible local mechanisms have to be identified and the over-strength factor will be assumed as the minimum values among all the defined factors.

Once the shear base capacity is determined, the top displacements corresponding to points (2) and (3) of the trilinear backbone curve (u_2 and u_3 in Figure 3) have to be assessed. Since the shear base capacity is previously evaluated, the definition of reduction factor (R_μ) can be used to calculate the displacement u_2 . The reduction factor accounts for ductility, over-strength, redundancy, and damping of a structural system (Equation (5)).

$$R_\mu(T, \mu, \xi) = \frac{F_{EL}(T, \xi)}{\lambda \cdot F_y(T, \mu, \xi)} \quad (5)$$

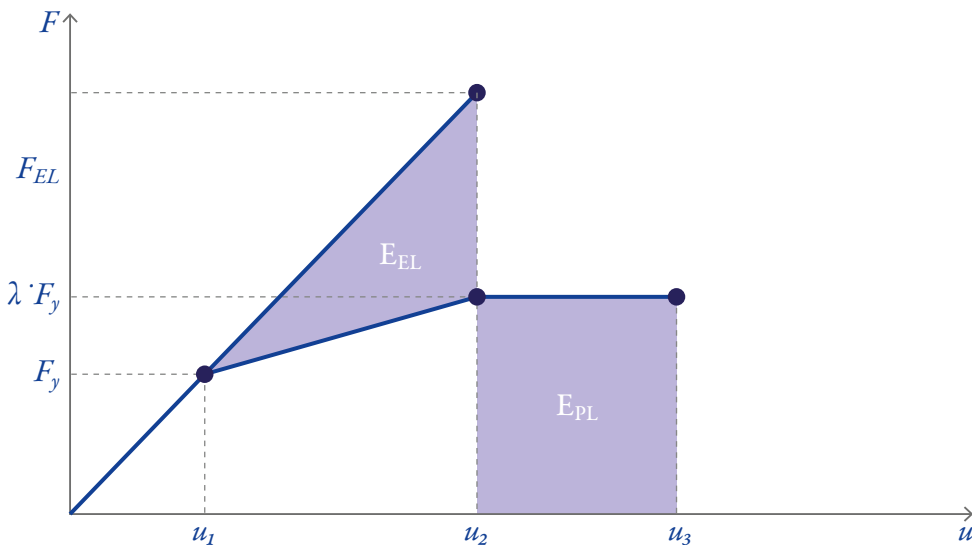
where $\lambda \cdot F_y$ is the maximum shear capacity and F_{EL} represents the equivalent elastic shear force. As mentioned previously, the reduction factors depend on ductility (μ), over-strength (λ), damping (ξ) and elastic building characteristics (such as period, T). Several mathematical formulations have been proposed for evaluating the reduction factor. One of the most used expressions is based on the equal energy rule (short period systems, $T < 0.5 s$) or equal displacement rule (long period systems, $T > 0.5 s$) (Equation (6)).

$$\begin{cases} R_\mu = \sqrt{2 \cdot \mu - 1} & (T < 0.5s) \\ R_\mu = \mu & (T > 0.5s) \end{cases} \quad (6)$$

The ductility parameters are expressed as a ratio between the ultimate displacement and the displacement for which the maximum shear capacity occurs. According to the proposed trilinear backbone curve, the ductility is given by the ratio between displacements u_2 and u_3 .

Furthermore, the ultimate top displacement is evaluated based on the equal energy theorem (Figure 6).

Figure 6. Equivalent elastic energy (E_{EL}) and elasto-plastic energy (F_{PL}) of the system.



According to the Figure 6, the energy balance between the equivalent elastic energy (E_{EL}) and elasto-plastic energy (E_{PL}) is reported in Equation (7).

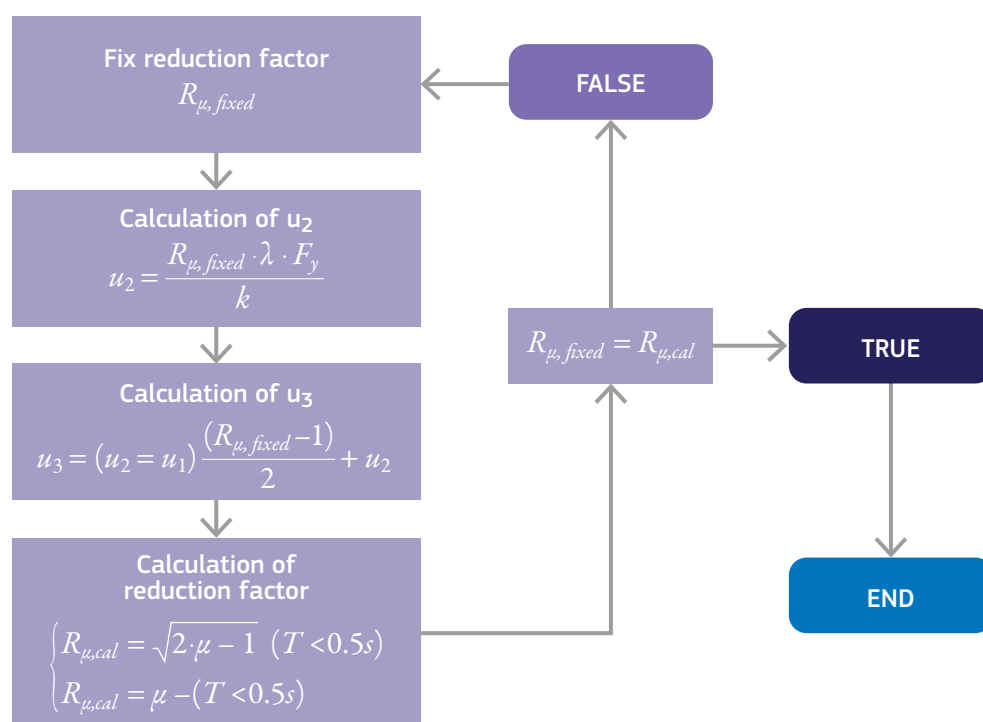
$$(u_2 - u_1) \cdot \frac{(R_\mu - 1)}{2} = (u_3 - u_2) \quad (7)$$

In the proposed approach, the two unknown displacement values are evaluated through an iterative procedure. The reduction factor value is fixed and then the displacement u_2 is assessed (Equation (8)).

$$u_2 = \frac{R_{\mu, fixed} \cdot \lambda \cdot F_y}{k} \quad (8)$$

where k is the stiffness of the system. According to Equation (7), the ultimate top displacement u_3 is evaluated and then the reduction factor is calculated by using Equation (6). This iterative procedure continues until the corresponding calculated reduction factor converges for given initial approximation (Figure 7).

Figure 7. Iterative procedure to evaluate the reduction factor.

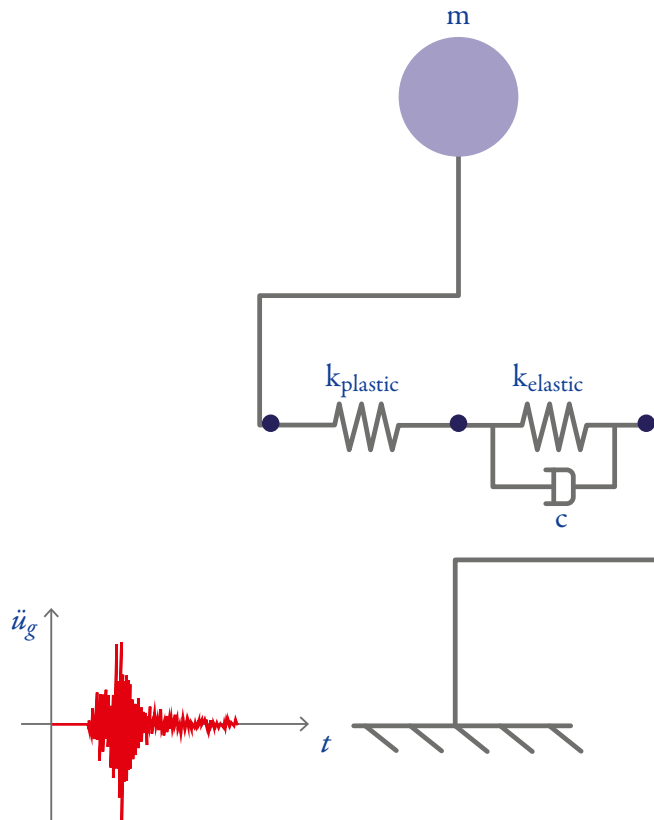


4. Analysis implementation and simulation

The proposed approach is capable of applying nonlinear time history analyses to a large number of buildings. The dynamic response of the structural system in a built environment takes into account a considerable amount of parameters. The building inventory, containing all the information (such as material, geometry and mechanical properties) has been developed and allocated on an external server. All this data are accessible by a MATLAB code organized in several functions that manage the seismic input definition, MCS for evaluation of the nonlinear parameters, and SAP2000 API actions. Due to the large number of variables and the time requested for processing, parallel algorithms running on multiple processors are developed with MATLAB. The global behavior of each building has been modeled by using multi-linear plastic link element available in SAP2000. The mechanical characteristics have

been defined automatically according to the obtained backbone curves from MCS. Figure 9 depicts the schematic model used for simulating the global shear capacity of each building. The equivalent damping coefficient has been assessed according to the Rayleigh formulation considering the first and second building's period as control periods.

Figure 8. Multi-linear plastic model.



4.1 Software architecture

The analysis flow is controlled through an interactive graphical user interface (GUI) that allows for selection of an earthquake scenario in the virtual city (magnitude and epicenter location). Furthermore, the acceleration time history can be selected and processed in both North-South (NS) and East-West (EW) directions. In order to take into account the deamplification of the seismic excitation with the epicenter distance, the shear wave velocity in the upper most 30 m (V_{S30}) for the city of Turin is included in the data. The V_{S30} map has been obtained via USGS website (USGS, 2013) at the link <http://earthquake.usgs.gov/hazards/apps/vs30/>. The Boore-Atkinson (Boore and Atkinson, 2008) attenuation law is used to estimate the attenuation of the time history's peaks. A Matlab function is provided for calculating distances between the selected epicenter and the center of the mass of each building. Moreover, the equivalent shear wave velocity is assessed according to the VS30 map, and considered in the attenuation model.

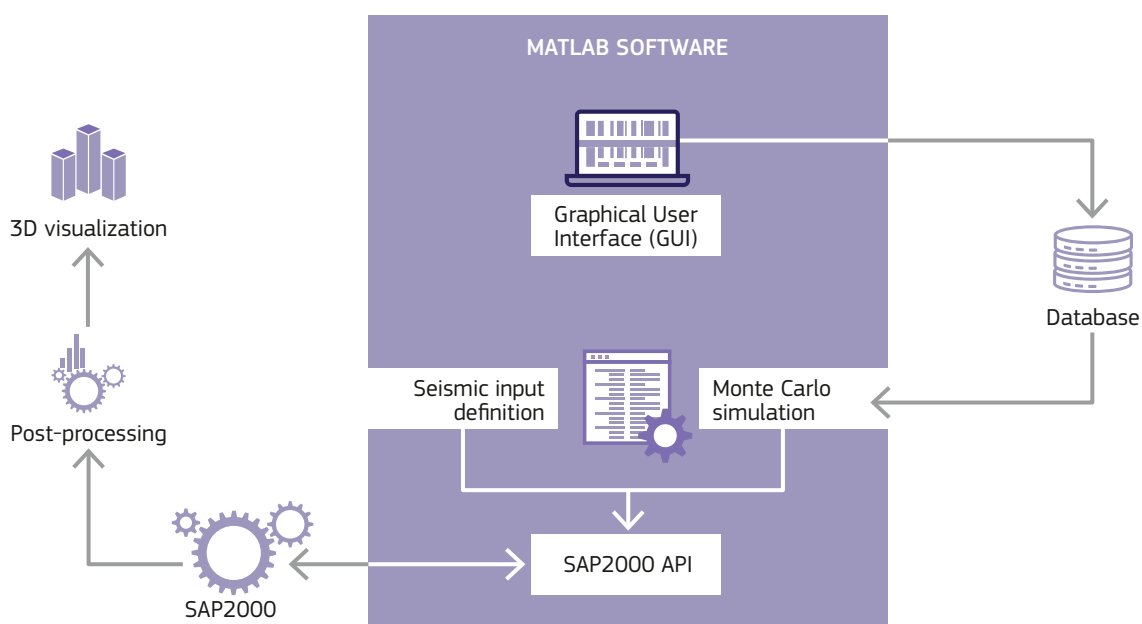
The main Matlab function controls the building's data flow, then the MCSs are carried out to evaluate the backbone curves for each building, considering the epistemic uncertainties in the input model parameters.

4.2. SAP2000 API

The SAP2000 Application Programming Interface (API) is a programming tool that offers efficient access to the analysis and design technology of the SAP2000 structural analysis software. A direct interaction with third-party applications is allowed during run-time analysis. The API software library provides access to a collection of objects and functions capable of remotely controlling the data exchange and setting data in SAP2000. Both pre- and post-processing procedures are managed by a Matlab language code which mainly provides the two-way data exchange. This procedure is capable of significantly reducing the time needed for data exchange, especially for large data models.

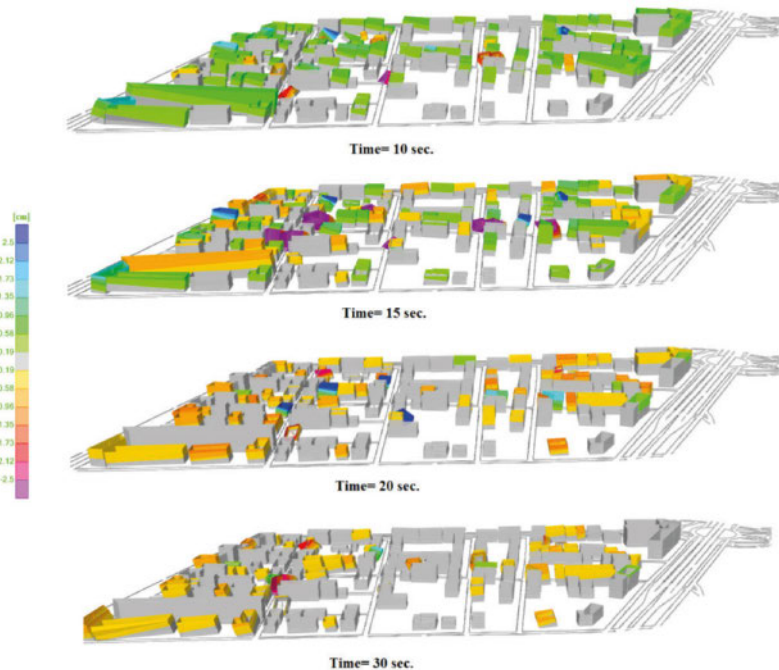
Once the Matlab functions assess the nonlinear parameters (trilinear backbone curve) and the processed seismic input, they are transferred to SAP2000 through API tool. Due to the limited amount of detailed building information, the hysteresis is considered according to the Takeda model. Thus, the nonlinear time history analyses are performed in the SAP2000 environment and the derived output is remotely controlled by Matlab. Figure 9 shows in detail the software data flow used in the simulations.

Figure 9. Software data flow.



According to the maximum drift, the structural damage is assessed for each building and the associated level of damage is evaluated (slight, moderate, extensive, complete). A 3D visualization tool is also provided which shows the dynamic response of the building within the virtual city. This visualization tool can be helpful for monitoring and evacuation management in smart cities.

The proposed methodology has been applied to the virtual city and the results, in terms of displacements, are shown for a part of the city in Figure 10. A time history recorded during the Central Italy earthquake (Norcia station, PGA=0.42 g), in both horizontal directions, has been used as earthquake scenario for the simulation. The predicted real time response of buildings can help decision makers to monitor and manage the resources during emergency situations.

Figure 10. Displacement contours at four different time steps.

5. Conclusions

This paper deals with the development of different strategies for monitoring and control the emergency in urbanized areas. A new approach to implement dynamic time history analyses in a built environment of a virtual city is proposed. The virtual city has been designed based on the buildings stock for the city of Turin, Italy. All the characteristics of each residential building have been collected and organized in a complete database. The dynamic structural response has been simulated through a trilinear backbone curve through a nonlinear static approach for a MDOF system. The uncertainties on the building geometric and mechanical parameters have been taken into account through a MCS. Furthermore, an accurate selection and evaluation of the seismic input has been proposed. The dynamic response of the built environment have been carried out by SAP2000 software.

A Matlab based software has been developed to control the input data and the SAP2000 workflow through its Application Programming Interface. The post-processing is remotely controlled by Matlab, and the buildings' damage level is estimated. Finally, a 3D visualization tool is also provided which shows the dynamic response of the building within the virtual city.

This procedure is capable to significantly reduce the time needed for data exchange especially for large data models. This methodology supports decision-maker to explore how their community responds to a disruptive event, quantify the performance of buildings following a hazard, and to plan the better resilience-building strategies to minimize the losses and recovery time.

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