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Building Resilient Cities: A Simulation-Based Scenario Assessment Methodology for the Integration of DRR and CCA in a Multi-Scale Design Perspective.

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Abstract

Resilience of the built environment and communities to natural and man-made hazards is consolidating worldwide as a key requirement in the field of urban planning and building design, and there is an increasing awareness that Sustainable Development Goals and priorities of the Sendai Framework cannot be achieved without a comprehensive approach able to promote the effective implementation of DRR and CCA measures within regeneration processes at various scales. In this sense, an "all-hazards" approach, addressing multiple risk conditions (including Natech and cascading effects) and integrating DRR and CCA design strategies, show a highly cost-effective potential, maximizing the effect of complementary measures and optimizing mitigation/adaptation design techniques within a multi-scale (building/neighbourhood/city) resilience perspective, delivering at the same time socio-economic benefits linked to the improvement of urban spaces' liveability and environmental quality. Vulnerability and impact assessment represent an essential component of a simulation-based methodology aimed at increasing the potential for use of scientific results by decision-makers, through multi-hazard and dynamic impact scenarios combined with cost-benefit and multi-criteria analyses to assess the effectiveness of alternative options. The paper presents the methodological approach developed at PLINIVS Study Centre and the experimental applications implemented within recent EU and National projects, such as H2020-ESPREssO and SIMMCITIES_NA.

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1. Integrating DRR and CCA: an emerging opportunity

Disaster Risk Reduction and Climate Change Adaptation are consolidating worldwide as an important requirement for sustainable development. Economic losses from natural hazards have increased almost 10 times during the past 40 years [1], with 10 billion yearly losses only in the EU context, and there is an increasing awareness that the ambitious objectives set with the Sustainable Development Goals, the New Urban Agenda, cannot be achieved without taking into account the risk of natural hazards and their impacts in a changing climate perspective, in line with the priorities of the Sendai Framework. Policies and measures need to be implemented to build disaster resilient societies and communities, with the aim of reducing the risk-proneness while ensuring that development efforts and urbanization trends do not increase the vulnerability to hazards but instead include actions to consciously reduce such vulnerability. A comprehensive set of studies outlined a variety of approaches to manage risks, highlighting how facing hazards only coping with emergency situations is becoming an increasingly ineffective and economically unsustainable solution [2], [3], [4], [5], [6]. Resilience-based planning and design actions, aimed at the protection of built environment, ensuring safety of population and economies, had proven to be cost-effective if compared to the huge expenses to be faced for restoring normal conditions after a disaster [7].

Built environment, and specifically urban areas represent the key issue for reducing risk for population and economies towards multiple sources of hazards. Most of the population growth of the last decade has been in fact concentrated in the metropolitan urban and suburban areas, already characterized by high levels of exposure and vulnerability, where the increased human pressure, in the absence of effective mitigation policies, has contributed to aggravate the risk factors and the energy/environmental weight of existing building stock.

Climate Change Mitigation actions, addressing reduction of CO2 emissions of built environment, have taken benefit from a well established framework of building codes and regulations, incentives for public and private investments set up in the last decades, especially within EU countries and US, thus allowing an increase of national retrofitting programs. Adaptation efforts, aimed at reducing the vulnerability of communities to the inevitable impacts of climate change both in terms of extreme events – whose frequency and intensity is expected to grow in the future – and slow onset changes – able to significantly shift the “ordinary” climate conditions in a given area or region – are taking advantage in recent years of a huge global effort in terms of funding and regulations to support large investments, often on a reactive basis following the occurrence of extreme events, such as Sandy storm and the “Rebuild by Design” initiative in New York, or the recognition of variation in their return periods as in the case of the floods in northern Europe and the implementation of local actions (e.g. the “Copenhagen Cloudburst Management Plan” or the “Rotterdam Climate Initiative”). The Paris Agreement and the establishment of the Green Climate Fund should consolidate in the upcoming years the stability of climate actions on a global scale.

Disaster Risk Reduction of geophysical hazards, such as seismic mitigation measures, despite being a much more consolidated field of study and long since integrated into ordinary design and construction practice, seems not to benefit of the improvement of international cooperation as in the case of climate initiatives. The uneven distribution worldwide of risk proneness conditions make this issue much more relevant at regional/country than global scale, if we exclude the efforts in terms of emergency management and humanitarian assistance. Even in this case, however, the global picture allows to identify some relevant issues that highlight the opportunity for a common action. The differences in terms of impact observed in relation to recent events worldwide (Italy 2009, 2012 and 2016; Japan 2011; Nepal 2015, Ecuador 2016) helps to identify the main challenges for DRR: Italy’s case emphasize the complexity of DRR measures that need to be adapted to a territory extensively characterized by historical settlements and heritage sites; Japan’s case highlight the issue of the “induced risk”, resulting from Natech and cascading effects, as major concern when the mitigation of buildings and infrastructure to geophysical hazards represents a widespread, consolidated and effective practice throughout the country; Nepal’s and Ecuador’s cases show how in absence of well structured existing policies and legislation for risk reduction, the huge impact from geophysical hazards and the complexity of reconstruction actions make developing countries even more vulnerable to climate extremes, thus suggesting the opportunity of integrated measures supported by the international community.

2. All-hazards modelling and adaptive mitigation: innovative research and policy perspectives in Europe

The following sections outline the methodological approach developed at PLINIVS Study Centre and the experimental applications implemented within recent EU and National projects, such as H2020-ESPREssO and SIMMCITIES_NA, aimed at building a strategic vision to foster a holistic and resilience-based "all-hazards" approach within risk assessment, policy making, planning and urban design. Such vision needs to be structured in relation to the main recognized challenges, identified as main barriers to implementation.

The ESPREssO project, funded within the European Programme Horizon2020, has identified in this sense three key challenges which represent emerging priorities for research, policy and practices in the field of DRR and CCA:

- Integrating Climate Change Adaptation and Disaster Risk Reduction
- Integrating Science and Legal/Policy issues in DRR
- Improving national regulations to prepare for trans-boundary crises

2.1. Integrating Climate Change Adaptation and Disaster Risk Reduction

The different backgrounds of Disaster Risk and Climate Change domains – the first emerging from risk sciences and emergency management fields, the latter from earth sciences and only recently recognized as a global challenge affecting society as a whole – limit so far the establishment of an integrated methodological and operational approach to DRR and CCA in a multi-risk modelling and design-oriented perspective. Europe, through its regulatory and funding initiatives at Community level, as well as committed partner within UN governance and policy actions, is providing a promising effort in bridging the two perspectives, despite still suffering of an "implementation gap", due to observed bias between a sufficient knowledge base and the insufficient take up by authorities, in some cases linked to the uncertainties in climate change scenarios and the lack of coordination between different governance levels and funding sources at national and international level. Synergies between CCA and DRR are emphasized in all the main strategies and agreements at EU level (e.g. EU Adaptation Strategy; EU Cohesion policy; Danube, Baltic, Alpine Macro-regional strategies). Such synergies reflect a common goal: reducing the impacts of extreme events and increasing resilience to disasters, particularly among vulnerable populations. Clear benefits of linking and integrating the knowledge base, as well as policies and practices, emerge in this perspective.

DRR and CCA are considered as cross-cutting fields across EU governance structures devoted to Cooperation and Development (DG-DEVCO), Environment (DG-ENV), Civil Protection and Humanitarian Aid (DG-ECHO), and this implies the need to identify synergies and integration opportunities in relation to land use, urban development, social issues, environmental protection, emergency planning and response. At the same time, the link with global processes and their implementation is at the base of the European policy, and this implies the need to build coherence around risk-informed approaches developed through international cooperation (Sendai Framework for DRR; Paris Agreement on Climate; 2030 Agenda for Sustainable Development; New Urban Agenda). In this sense, the outcomes of 2017 European Forum for DRR promoted by UNISDR reflect the alignment between EU and UN positions towards the objective of strengthening DRR and CCA integration. It is emphasized that multi-hazard, multi-scale, multi-functional DRR and CCA measures should be implemented, by enabling bottom-up and inclusive approaches to planning and implementation. This can only be achieved through a multi-stakeholder participation in risk assessment, DRR and CCA planning and implementation, in order to identify cost-effective and sustainable solutions and foster effective partnerships between public authorities, private sector and civil society. On top of such participatory strategies, a greater political commitment to catalyze investment and action on DRR+CCA plans is needed, also to improve legislation and regulations to underpin investments and ensure compliance. Such an approach is considered the best option to mitigate the abovementioned "implementation gaps" [8].

2.2. Integrating Science and Legal/Policy issues in DRR

To support the great potential of such declared strategic perspective, the scientific community is called to a coordinated effort aimed at producing innovative methods and tools for reliable risk and impact simulation, decision-support based on tailored cost-benefit and multi-criteria analyses, resilience-driven and multi-scale design.

In this sense, a collective effort is needed to take advantage of the most advanced science-based hazard/impact assessment methods, to streamline their contribution to the needed policy and legislation evolution. A common field of research and implementation needs to be targeted, based on identified priorities: a service-oriented thinking, aimed at maximising the usability and the user-tailoring of simulation models and tools developed by the scientific community, both to support technical policy improvements and specific actions' implementation; the exploitation of big data and satellite/remote sensing information, to improve high level assessment and identify priorities at international and regional scales; the quantitative assessment of losses (physical, functional and economic) and their propagation among different geographical areas, infrastructure networks and economic sectors.

Some main scientific gaps and needs are identified in this sense: 1) there is an increasing need of standardizing risk and impact modelling methodologies, at least at macro-regional/national scale [9], to take advantage of the potential integration of methods and tools developed by a variety of actors (governments, research centers, industry, SMEs, etc.) which would meet the need for a more useful, usable and evidence-based knowledge to inform resilient planning and emergency management (full DRM cycle approach); 2) operational and organizational modelling (and thus a stronger link with human behavioral aspects) represents a priority when assessing social and systemic, as well as service networks and critical infrastructures vulnerability, which is essential to properly model functional and economic losses (CIs still remain black boxes in this sense); 3) the need of producing time-dependent and multi-hazard vulnerability analyses of systems and their elements, so as reliable impact evaluation approaches, require a substantial methodological shift with respect to the conventional probabilistic simulation methods, often limited to hazard characterization and risk assessment, and thus with a limited application potential in a design-oriented perspective, where the quantification of potential losses and the benefits related to adaptation/mitigation measures is essential to define standards, protocols and guidelines [10]. Such innovative methodologies need to take into account e.g. the implication of cumulative damage from cascading effects, the dynamic variables related to space, time and human behavior, the effect of maintenance and retrofitting operations, the uncertainty and error propagation evaluations. Similarly, effective common methodologies for multi-sectorial resilience assessments are needed, with indicators and metrics strictly connected in terms of input/output to innovative impact simulation models, to provide decision-makers and end-users with actionable information to be incorporated in regulatory and policy improvements [11].

The main expected benefits arising from the opportunity of strong linkages between scientific research findings and regulatory/policy improvements in land use and emergency management can be resumed as follows:

- Identify high/low-impact areas for development planning (limit urban growth; manage densification patterns; identify mid- to long-term resilience pathways);
- Prioritize mitigation and adaptation actions in a multi-scale perspective (regional to local; city to neighbourhood; building to technical component);
- Allocate resources for emergency planning and management (through an accurate knowledge of the diverse potential losses in relation to the multi-hazard proneness of a given area)
- Enable distributed networks of cloud- and web-based services (allowing substantial economy for the end-users thanks to data sharing and custom-fit applications).

2.3. Improving national regulations to prepare for trans-boundary crises

Many of the recent geophysical and climate-related events, such as the Ejafjallajökull eruption in 2010, the Tōhoku earthquake in 2011 and the Danube floods in 2012-2013 (not to mention the migration flows and displacements triggered by climatic and or disaster risk conditions), highlighted how natural disasters often do not respect jurisdictional borders, and transboundary cooperation is needed both for what concerns adaption, mitigation and long-term preparedness efforts, both for emergency management and response coordination. The key issues related to transboundary crises need to be tackled at different levels:

- Interregional (single state) disasters: e.g. earthquakes (Centre Italy 2016);
- Interregional (multiple states) disasters: e.g. international river basins flood (Central Europe and Danube floods);
- Disasters with transboundary impacts: e.g. volcanic eruptions and ash fallout (Iceland 2010, Vesuvius and Campi Flegrei Emergency planning).

Despite its fragmented socio-political identity, but at the same time thanks to the community status and the solidarity principles that link together 27 countries, Europe represents one of the most significant areas worldwide to experiment and test evolutionary approaches to national regulations based on trans-boundary priorities and implementation opportunities arising from the collaboration of many single countries in view of common objectives.

Some large ongoing EU projects, aimed at developing shared tools/services among member states, can strengthen the data/knowledge transfer and the coordination capability, especially needed in transboundary crises preparedness and management. Copernicus (Emergency Management & Climate Change Service) is enabling a pan-European access to advanced and high resolution satellite data; the ambitious Aristotle (All Risk Integrated System Towards Trans-boundary holistic Early-warning) aims at providing a nearly real time simulation system and rapid impact assessment to be used in the context of emergency management; GR2ASP (Geospatial Risk and Resilience Assessment Platform) is specifically focused on critical infrastructures' vulnerability, resilience and impact assessment, also taking into account network interdependencies and potential cascading effects.

An effective implementation of such tools would allow each single country to have access to the background knowledge and decision-support tools needed to streamline the national policies towards DRR and CCA objectives, improving the standardization of approaches and procedures, and thus simplifying also the procedures at EU level in financing transboundary adaptation and mitigation measures through the existing collaborative programmes (e.g. H2020; Life+), development and cohesion funds (e.g. ESF; ERDF).

From an emergency management perspective, another significant achievement in Europe is the 2013 EU Civil Protection legislation, currently in a process of updating to better answer to humanitarian aid needs related to the migration emergency. Significant implications are related to several areas related to transboundary issues, such as: National Civil Protections coordination around the Union Civil Protection Mechanism; humanitarian aid and NGOs cooperation; coordination of large investments programs for resilience and adaptation in neighboring countries; improvement of international (extra-EU) cooperation to tackle the aggravating impact factors of natural disasters due to specific context conditions, e.g. because of migrations, wars; pandemics; social inequities and injustice.

3. Methodology: Linking Simulation-Based Scenario Assessment and Multi-Scale Resilient Design

The position of the UNISDR EU Platform, expressed at the European Forum on Disaster Risk Reduction 2017 in Istanbul, reflects the consolidated and emerging challenges related to DRR and CCA, which connect the European science and policy innovation within a shared international perspective. A significant message is related to the need to drive/underpin decision-making strategies at local, national and international levels through science, evidence and knowledge. The need to provide effective multi-hazard assessments, paying attention to cascading effects, hybrid threats and their impacts on increasingly complex societies is explicitly recognized [12]. In this context, DRR and CCA synergies have to be stressed through a comprehensive all-hazards approach to identify trade-offs, co-benefits of integrated mitigation and adaptation measures, common resilience pathways and management approaches. Two key domains of research and implementation should drive the major advancements in terms of science-based regulation and policy: 1) Simulation-based impact quantification and assessments, targeting multi-hazard, natech and cascading effects conditions; 2) "Adaptive mitigation" design and "build back better" solutions, targeting resilience-based urban regeneration and building retrofitting scenarios.

Vulnerability and impact assessments (including simulation-based scenarios) represent an effective approach to make science understandable to decision makers and streamline national to local mitigation/adaptation actions, especially if integrated with effective tools for cost-benefit and multi-criteria analyses, tailored according end-users' needs, to assess the effectiveness of alternative options. Resilient land-use planning and building/open spaces design can indeed take advantage from simulation scenario analysis approaches, which allow the understanding of physical and economic impacts due to natural, technological or natech hazards.

The experiences conducted in the last 25 years at PLINIVS Study Centre of University of Naples Federico II allowed the development several probabilistic simulation models to assess the impacts of natural hazards, taking into account the impact distribution in time and space and the cumulative damage produced by possible cascading effects, as well as a continuous data collection activity on built environment and population, at national and regional scale in Italy, that allowed building up a comprehensive GIS database, that includes population data, classification of different building typologies (detailed at the level of technical elements: structure, wall, roof, openings, etc.), features of transport networks and critical infrastructures. The database includes vulnerability classes of each element at risk considered (population, building components, transport network nodes, economy, etc.) with respect to the main hazards considered. The database is integrated into impact models, allowing to derive the expected impact of a given event on selected elements at risk (e.g. population, residential buildings, critical infrastructure, transport networks, etc.) with a detail of a 500x500m mesh at national level and 250x250m at regional level. The methodology applied within PLINIVS models (which includes Probabilistic dynamics modelling, Bayesian networks, Event tree analysis, Monte Carlo Method, fuzzy logics and error propagation calculation for uncertainties treatment) allows to determine realistic impacts on selected elements at risk, deriving hazard modelling information from specialized research institutions, such as, in Italy, the INGV for geophysical hazards, the National Weather Service for meteorological hazards and the CMCC for climate change projections.

The current development of vulnerability assessment and impact models is based on a constant evolution and integration within several research and innovation projects [13], [14], [15], [16], [9], [10], focusing on geophysical and climate-related hazards. The output of models, currently adopted by the Italian Department of Civil Protection for activities related to emergency management in the context of seismic crises and emergency planning for the volcanic areas of Vesuvius and Campi Flegrei, offers significant opportunities for the identification of alternative land-use planning and building retrofitting measures aimed at DRR and CCA, through the integration within robust multi-criteria and cost-benefit analyses tools to support decision-making process and funding programming, based on a reliable quantification of expected impacts. The evaluations criteria emphasize the benefits of mitigation/adaptation options not only after a hazard event occur, but also in "peace time", e.g. in relation to socio-economic benefits related to the improvement of energy efficiency and environmental quality of buildings and urban infrastructures. The methodology adopted for the development and application of PLINIVS tools and services allows a customization process based on specific needs of stakeholders and communities, which highlights the opportunities for action emerging at local level. Experiences conducted in South and Central America (Perù, Dominican Rep.), Europe and Middle East (Greece, Israel) show the exportability of models and tools in different territorial contexts, based on a service-based approach to data collection and models calibration. Such approach is consistent with many ongoing initiatives at EU level, aimed at integrating a variety of models and tools in a distributed and cloud-based network, able to exploit the capabilities offered by Copernicus datasets and tools and to integrate the available models and services. In this sense, the multi-hazard vulnerability framework developed at PLINIVS respond to the shortcomings for an operational use specifically identified, especially for the Copernicus Emergency Management Service (EMS), such as interoperability between scales, the incorporation of socio-economic, legal, cultural dimensions, compliance with international (e.g. UNISDR, IPCC) and European concepts (e.g. DG-ECHO, DG-RTD) to improve Risk & Recovery module of the Copernicus EMS [17]. The relevance of reliable impact simulation models and decision-support tools is strictly connected to the need of enabling a knowledge-exchange between scientific communities, governance institutions, industry and practitioners, and society, as all essential actors for the implementation of resilience pathways. In fact, even where scientific advancements resulted in an adequate improvement of the regulatory environment at national level to face risk factors connected to local conditions, the efforts in this direction did not produce a leverage effect in the construction sector for what concerns public/private investments and "safety oriented" building retrofitting or urban redevelopment programs.

One of the reasons of this difficulty to put into practice the important achievements in terms of strategic guidelines and technical rules comes from the low cost-benefit ratio of this kind of interventions. Even if is widely demonstrated that investments on mitigation measures (i.e. seismic retrofitting of buildings) allow to reduce recovery costs after the event until 75% [18], the real economic benefit is obtained only after the disastrous event is occurred and, until that moment, these kind of investments represent only an additional cost factor if compared with a "standard" refurbishment intervention. This is evident in the case of "High-Impact, Low-Frequency events" such as volcanic eruptions, where the potential economic benefits from mitigation measures can be huge, but the high implementation costs compared to the low probability of occurrence significantly reduce the attractiveness of this kind of investments. On the other side, actions aimed at improving energy efficiency of buildings and energy production from renewable sources (thus contributing to climate change mitigation if widespread on a mass scale) are characterized by a rising level of cost effectiveness. Innovative solutions for energy efficient building envelope and HVAC systems showed a constant reduction of payback times, also thanks to the growing push from construction industry and the development of "smart" and "green" technologies [10], [11]. At the same time, the attractiveness of adaptation measures is certainly not limited to the opportunity of climate vulnerability reduction, but more and more linked to the socio-economic co-benefits arising from their implementation, such as the increase in livability and environmental quality of urban areas following the application of ecosystem- or nature-based solutions. In this sense, a combined approach to geophysical and climate change induced hazards allows to improve cost effectiveness of retrofitting and redevelopment actions, introducing new perspectives for product and process technological innovation in the construction sector. There is in fact an increasing evidence of how impacts of natural hazards and the costs of the disasters can be reduced whether mitigation/adaptation measures are implemented within new construction or as retrofitting actions, through risk reduction and adaptation techniques addressing multiple hazard conditions [19], [20].

"Adaptive mitigation" [21] and "build back better" [22], are emerging as effective approaches able to drive scientific results and policy updates towards a holistic resilient design perspective. Through this approaches, built environment can become part of the solution rather than exacerbating the risk, by combining traditional hazard mitigation strategies (e.g. structural retrofitting of buildings and transport networks against earthquakes, protection of roofs against volcanic ash falls, environmental engineering solutions against landslides, smart design of ground floors in flood-prone areas), with measures for climate change mitigation (energy retrofitting and new zero-energy district for reducing CO2 emissions) and adaptation (blue/green infrastructures and Sustainable Urban Drainage Systems for adapting to impacts from precipitation extremes such as droughts and flash floods). Such a set of actions, having as object the built environment vulnerability reduction, should be incorporated into the different stages of planning, design and construction, developing an integrated "whole building approach" [23].

A variety of techniques are available to mitigate the effects of natural hazards on the built environment. Depending on the hazards identified, the location and construction type of a proposed building or facility, and the specific performance requirements for the building, the structure can be designed or retrofitted to resist to hazard-induced stressful conditions, such as dynamic overloads (earthquakes, volcanic eruptions, tornadoes, landslides). At the same time, specific building technologies for risk mitigation of non-structural elements, such as windows, balcony railings, electrical and mechanical systems, etc. must be taken into account, since in some cases they represent more than 70% of the value of a building. Regulations, codes, standards, technical requirements, performance indicators and best practices improvement represent needed governance and policy actions to guide building design strategies, though compliance with regulations in building design is not always sufficient to guarantee safety condition. Indeed, individual evaluation of the costs and benefits of specific hazard mitigation/adaptation alternatives can lead to effective strategies aimed at exceeding the minimum regulatory requirements. Additionally, special mitigation/adaptation requirements may be imposed by local regulation in response to site-specific hazards. Furthermore, when a change in use or occupancy occurs, it must be determined whether this change triggers other risk conditions, thus requiring additional mitigation measures.

4. Conclusions

Dealing with DRR and CCA in a design-oriented perspective entails the clear need of strengthening the collaboration between areas characterized by diverse research backgrounds, but all complementary to effectively contribute to identify answers and solutions adequate to the systemic complexity of the challenge. Cities can be conceived as complex systems resulting from the interaction of different subsystems: physical system, functional system and socio-economic system. Disaster Risk and Climate Change are producing increasing crises in each of these subsystems, with consequences to the society as whole. The challenge of bridging scientific research and technological innovation with transnational policies and operational practices needs to be supported by a multidisciplinary systemic approach to the transformation of the built environment, where architectural and urban disciplines, systems' engineering, social studies, earth sciences, IT and data visualization, probabilistic modelling and scenario analysis, are called to focus on identifying and communicating effective and adaptive solutions to the challenge of a sustainable growth in a globally connected world, dealing with increasingly complex disaster risk conditions aggravated by the inevitable climate change perspective.

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