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MULTI SCALE URBAN MODELLING TO IMPROVE THE RECOVERABILITY OF CITIES EXPOSED TO MULTIPLE NATURAL HAZARDS

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Abstract

A resilient urban system should be able to recover from a disaster as quickly and effectively as possible. The optimal time to begin planning and implementing recovery investments to improve the urban system's recoverability is before the disaster. Considering that usually there are insufficient resources to invest in all urban facilities and infrastructures, in this research, the concept of Minimum Urban System that assures the Safeguarding of the Settlement is developed. This concept refers to the "subset of assets" of the urban system to be preserved to ensure continuing recovery efforts after a disaster and must be determined in accordance with some defined criteria that indicate the relative socio-economic worth of the various assets and the significance of their contribution to the urban system's performance. When the urban system is exposed to multiple and potentially interacting (such as cascading, consecutive, compound, etc.) risks, the assets' contribution to the system's ability to deal with these complex multi-risk conditions needs to be considered and integrated into the minimum urban system determination.

In light of this, the goal of this work is to establish a methodological framework in three spatial scales (macro, meso and micro) to model the urban system, and identify its most crucial components - and their interdependencies - as the minimum urban system.

Keywords: Minimum Urban System, Safeguarding of the Settlement, Multi-risk, Disaster Recovery.

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1 INTRODUCTION

Recovery is defined by UNDRR [1] as “the restoring or improving of livelihoods and health, as well as economic, physical, social, cultural, and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and ‘build back better’, to avoid or reduce future disaster risk”. In line with this concept, several researchers indicated that to improve urban recoverability it is not only required to prepare recovery plans before the occurrence of the disaster but also to take some actions in pre-disaster time to make the system go through the recovery process in easier faster and efficient way [2]–[4].

Certain measures, like strengthening crucial infrastructures and structures, can make the system more recoverable from two perspectives. On the one hand, it would lessen the severity of the system’s failure right after the disaster occurred, increasing the system’s resistance. On the other hand, it would lead to the preservation of crucial structures that can help the recovery and emergency process after an event [5].

The Italian Civil Protection Department (CPD) has established certain Limit Conditions (LC) for urban areas, which serve as specific targets for disaster management planning [6]. These LCs are conceptual thresholds that relate various degrees of physical and functional damage to the urban system and its components, focusing on the seismic risk. The urban system may lose some degrees of functionality if any of these thresholds are surpassed as a result of a disaster.

While for the emergency limit condition (ELC) the CDP already proposed a well-defined procedure for assessing the functionality of some essential components of the urban system ([6], [7]), for other limit conditions these standardized procedures are not yet available. The definition of the ‘Limit Condition for Safeguarding the Existence of the Settlement’ (hereinafter as SLC) following the occurrence of a disaster is the main focus of this paper. A first attempt to outline an operational procedure to quantitively assess the SLC condition considering the seismic risk has been proposed in [8].

SLC pertains to the limit condition that allows an urban system to:

1. provide emergency management services in the aftermath of the disaster;
2. initiate the recovery process using its own primary functions, i.e., the system should have the capacity to leverage its existing infrastructure and resources to restore critical services and infrastructure in the affected areas;
3. restore other important urban functions in an efficient manner.

In general, fulfillment of the SLC requirement presupposes satisfaction of the ELC. It indicates that surpassing ELC, the vital physical assets necessary for providing emergency management services, have already been functional. Nevertheless, the connection amongst ELC and SLC assets has to be taken into account.

Considering the length of the recovery process, which might take years or decades [9], [10], SLC definition cannot disregard socio-economic issues. Otherwise, the recovery process would finally create a settlement that is not resilient, with social fragmentation and unusable living circumstances, even though the settlement would be physically rebuilt at the end of the recovery [11], [12]. In this context, it could be claimed that characterizing the SLC necessitates multidisciplinary analysis and evaluation of a community's economic, social, cultural, and identity aspects.

Because of the limited resources to invest in all urban facilities and infrastructures, a minimum urban system must be preserved to ensure the SLC after a disaster. This research aims to contribute to the identification of physical elements in an urban system that after a disaster, can ensure meeting the SLC condition. These elements are identified considering: (i) multiple **functions** (e.g., economic, education, health, etc.); (ii) the potential interactions and **interdependencies** among them as well as the overall **functionality** of the system; (iii) a multi-hazard risk perspective.

In the interests of improving the recoverability of the urban system in multi-risk conditions, we explicitly provide here a multi-scale urban modeling framework that can become the basis for an optimization model for investing in these crucial physical elements.

2 THE MINIMUM URBAN SYSTEM IN A MULTI RISK ENVIRONMENT

In the work illustrated in [8], the physical elements that in an urban system can ensure continuing recovery efforts after a disaster and therefore meeting the SLC represent the so-called 'Minimum Urban System that assures the Safeguarding of the Settlement' (SLC_{MIN}). According to [8], the SLC_{MIN} must be determined in accordance with some defined criteria that indicate the relative socio-economic worth of the various assets and the significance of their contribution to the urban system's performance and probable damage that might imposed on the system as consequence of natural hazard event.

As aforementioned, the SLC_{MIN} introduced in [12] focuses only on seismic risk. Nevertheless, when the urban system is exposed to multiple risks, the circumstance will become more complicated. In this condition the physical assets' contribution to the system's ability to deal with multi-risk situations of any kind (such as cascading, consecutive, compound, etc.) is a critical aspect that should be considered in the minimum urban system determination.

Based on the hazards that pose a threat, certain physical elements and assets can be vital across all phases of the risk management cycle, from prevention and preparedness to emergency and recovery. However, the present research primarily emphasizes on enhancing the recoverability of urban systems. Therefore, identifying the relevant hazard scenarios and theirs impact can aid in determining critical physical components that can facilitate the recovery process while simultaneously strengthening community resilience against potential multi-risk scenarios that may occur during recovery [13]. In this study, the two primary hazards considered for multi-risk condition analysis are earthquake and flood. The study also emphasizes buildings and urban forms (here and after called as 'strategic physical assets') in urban areas. Thus, even though there are other primary elements, including lifeline infrastructure, that can contribute to the SLC_{MIN}, examining them is outside the scope of the current study.

The recognition of the SLC_{MIN} from a multi-hazard perspective is performed applying the procedure described in Fig.1 In order to identify the strategic physical assets to ensure the urban system's functionality and socioeconomic livelihood, the following actions should be performed:

- Modelling of the urban system functions and physical assets.
- Identification of the strategic physical assets and recognition of their importance.
- Definition of multi-hazard disaster scenarios to test the performances of the different components and the overall system.
- Implementation of a multi-criteria optimisation to identify the subset of components belonging to the SLC_{MIN}, as a set of urban assets to invest on to improve the overall urban recoverability after disasters.

Hence, as a first stage, a thorough three-scale urban system modeling must be conducted with the goal of identifying the importance of the strategic physical assets in the urban area and measuring their importance in safeguarding the settlement. This step, which will be explored more in detail in Section 3, must be conducted with perspective on the role that each asset can play during the recovery time. More explicitly, to assess the significance of strategic physical assets, it is essential to consider their importance not only ex-ante (i.e., before a disaster occurs), but also in terms of expediting and enhancing the recovery process ex-post (i.e., in the aftermath of a disaster). As an example of these assets, we mention the open spaces, that are potential places for temporary shelters during the recovery.

The next stage is to conduct a multi-hazard risk impact assessment to understand how the various multi-hazard disaster scenarios will affect the identified strategic physical assets and the urban system. The relevant multi-hazard disaster scenarios should be selected considering the different hazards that can occur in the study area and their potential interaction mechanism, either at the hazard or at the impact level [14]. Different multi-hazard disaster scenarios can be relevant: those generated by multi-hazard events that coincide in time and space, such as a strong windstorm and coastal flooding caused by the same adverse weather; those that happen in a cascade, such as an earthquake triggering a landslide or a tsunami; or even independent hazard events happening in a sequence, as in the case of an earthquake and then a flood affecting the same urban area that is still recovering from the damage caused by the previous hazards. This last case is the most interesting from the recovery perspective, since it highlights the need for integrated multi-hazard recovery planning and ex-ante strengthening interventions, able to reduce potential asynergies between earthquake and flood disaster risk reduction actions.

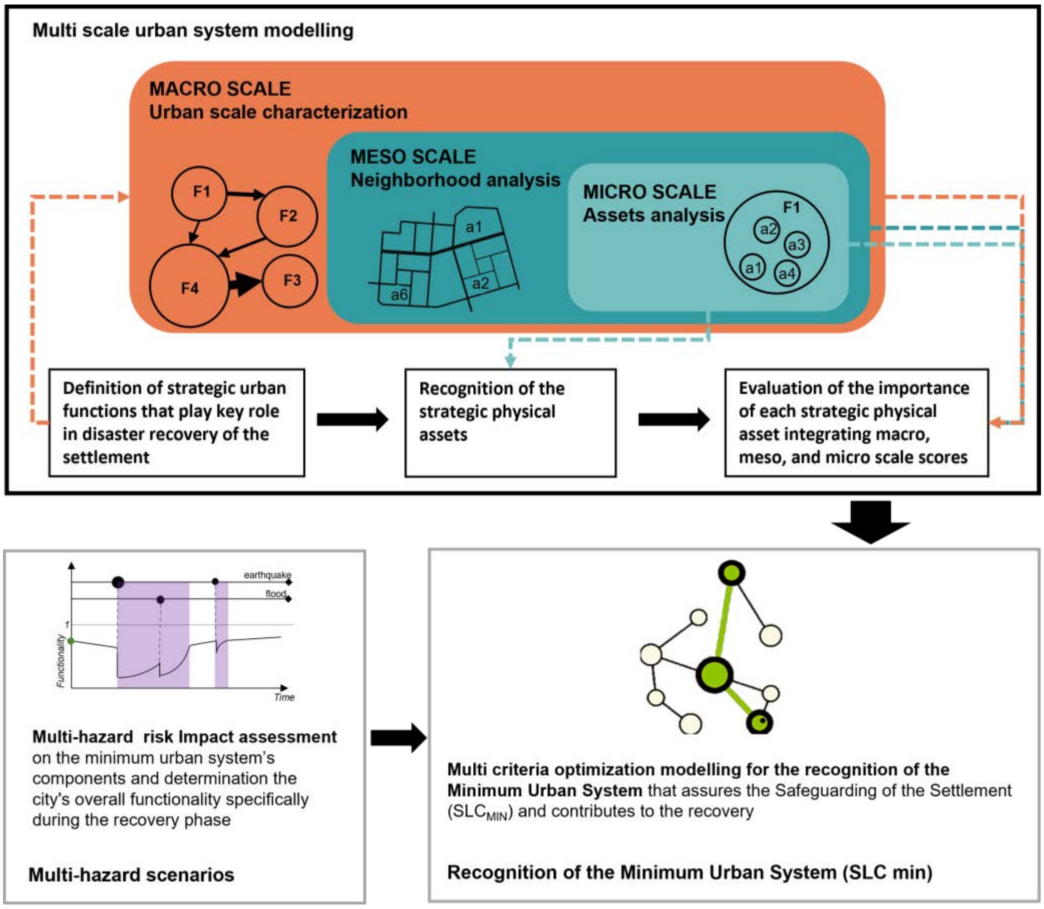

Figure 1: Overview of procedure for recognition of the Minimum Urban System that assures the Safeguarding of the Settlement in area exposed to multi hazard risk

As a main outcome from the multi-hazard risk impact assessment, the direct and indirect functional loss to each strategic physical asset and, consequently, to the overall urban system, will be obtained, also considering the effects of incremental damages and changes in the vulnerability of the damaged assets imposed by the multi-hazard risk scenarios.

Finally, the output of the multi scale urban system modelling and the multi hazard risk scenario assessment would be integrated in the last part of the procedure. The main aim of this last stage, denoted as 'Recognition of the SLC_{MIN}' in Figure 1, is to perform a multi criteria optimization model for deciding about direction investment on strengthening of the urban system. In other words, the strategic physical assets that worth more for the investments would be recognized according to their contribution to the SLC_{MIN} and their mutual impact on and of multi risk scenarios.

3 MULTI SCALE URBAN SYSTEM MODELLING

As mentioned in previous section as the first step of the procedure the system modeling must be conducted. For assessing the importance of different functions and their corresponded assets in the urban system a multi-scale methodological framework is presented in this section. The importance assessment of different urban system's physical elements should be assessed in different spatial scales for the following reasons:

1) ***As a socio-ecological system, the urban system is a system of systems*** **[15], [16]** ***where each lower-scale component could be viewed as a system in itself, made up of finer-scale components.*** Additionally, the urban system itself interacts with other systems at the same or higher scales, such as other cities or the state/region. This research ought to focus on the **micro-scale assets**, by taking into account their corresponded **functions** within the larger urban system. Nevertheless, without considering the role of each asset inside the systems and subsystems to which it belongs, the determination of its **function** and **importance** in the urban system would be inaccurate and inadequate [17].

2) ***Data for describing and characterizing the urban system and its subsystems are provided at various scales.*** For instance, **demographic data** is usually presented at the city scale. This information could be essential for determining the population's needs and requirements and, as a result, for identifying the **functions** and **assets** that are fulfilling those demands. On the other hand, for example a **school's enrollment statistics** are an **asset** scale data that may be crucial for assessing the significance of the institutions and furthermore of the overall local education system.

3) ***Urban assets and forms at various scales contribute to the urban area's recoverability.*** For example, open spaces, that are neighborhood scale features of the urban system, are important throughout the recovery process since they can be used as potential temporary housing place [18], [19].

As a result, the urban system modeling should be carried out at three different scales: **macro, meso,** and **micro**, using the indicators that characterize the city at each of these scales [20]**,** [21]. In order to effectively assess the relative importance of diverse assets in urban settings, a comprehensive analysis must be conducted across these three distinct scales, with the aim of integrating the results to achieve a holistic understanding of their importance. The schematic diagram depicted in Figure 2 illustrates the overarching framework and the interrelationship between the scales, as well as the outcomes from the analyses conducted at each scale.

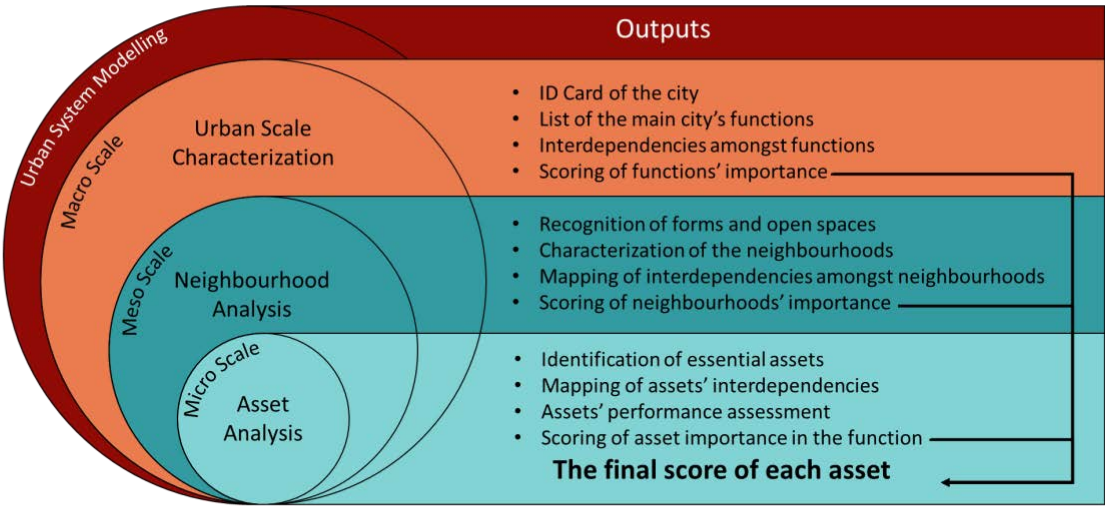

Figure 2: Overview of the proposed urban system modelling framework

The purpose of **macro scale** analysis is to characterize urban areas, which vary in their features based on capacities, shortages, settled population, and background. Different cities may have different functions and assets that are important to them, depending on their character. For example, some cities are primarily tourist destinations, while others are known for their religious or agricultural significance. Therefore, for instance the accommodation facilities might not have equal importance in these two types of cities. Accordingly, the role and importance of the different function and asset might differ in these different cities. As a result of macro scale analysis, the most important urban functions would be identified.

The primary goal at **meso scale** is to cluster urban areas into uniform districts that share the same characteristics and score them according to their importance in the recovery process. Different types of information, such as demography and socioeconomic dominant activities, should be considered in this clustering in addition to the physical data that have been gathered through the **macro** scale study. **Neighborhoods** may be the ideal unit to consider for this classification, although it should be noted that the final area selected may not correspond to neighborhood borders shown on administrative urban maps. In this research, the **neighborhood unit refers to the geographic region with a common physical and socioeconomic texture**.

Finally, the **micro scale** modelling aims at identifying the **essential assets** which contribute to the urban functions selected as a result of the **macro scale analysis**, mapping their interdependencies, evaluate their performances, and finally assign the score accordingly. For instance, after determining that schools are an essential asset in the education function, which has previously been defined as an important function as result of macro scale analysis, two schools would be compared, and each would receive a different score based on how many people they served, the size of their buildings, or any other metric that demonstrates how well they performed in the education system.

A **final score** is assigned to each urban asset as a combination of the scores it receives from the analyses performed at the micro, meso and macro scale, which encompasses:

1) The importance of the **function** it serves, obtained from the **macro scale**.
2) The **neighborhood** where the asset is located in, obtained from the **meso scale**.
3) The degree of **performance** and importance in the function the asset has attained from the **micro scale** analysis.

4 DATA SOURCES

4.1 Input data for the urban system modelling

In order to conduct an effective analysis within the context of the explained framework and specially in the section of multi-scale urban system modelling (upper box in Fig. 1), data must be collected from a variety of sources, including:

a) **Local stakeholders' knowledge**. Engaging with stakeholders, such as community members, local businesses, and city officials, can provide valuable insight into the urban system and help identify key factors and issues that should be considered in the analysis. This information can be collected through **interviews, surveys, and focus groups**. The involvement of stakeholders is crucial for both macro and micro-scale analyses.

b) **Accessibile quantitative and qualitative dataste**. This can be obtained from official databases run by statistic administration and local authorities. This data can include **demographic information, land use, economic, transportation, and environmental data**, that can be available at different geographic scales (i.e., regional, municipal, sub-municipal) and might refer to different time periods. Geographic Information System (GIS) can be used to elaborate some of these data and develop maps that can help in visualizing and analysing the urban system. This can include maps of land use, transportation infrastructure, and environmental factors such as air quality and water resources.

c) **Cadastral maps and areal-imagery**. The analysis of available cadastral maps and areal-imagery (e.g., satellite optical imagery) can support in the **recognition of the urban forms and open spaces,** and in the clustering of the different forms at the neighbourhood (i.e., meso) scale.

Macro and micro-scale analyses are performed integrating local stakeholders' knowledge with quantitative and qualitative datasets.

The meso-scale analysis is primarily conducted through the processing of data and maps collected at the micro and macro scales. Data collected at the micro and macro scales are processed and projected in a map form, providing a clearer spatial representation of the urban assets. This spatial representation enables more informed decision-making regarding the importance and location of various urban assets.

4.2 Data sources for the multi-hazard risk assessment

The second main step of the framework, i.e. the 'Multi-hazard risk assessments' (lower-left box in Fig. 1) requires a comprehensive and large-scale analysis, making it advisable to employ proper multi-hazard exposure and physical vulnerability models.

Generally, the framework is compatible with multi-hazard analysis of any kind, but with current research's focus on enhancing the urban system's recoverability, cascading and independent consecutive events are prioritized. In cases where two or more hazards are examined, it is essential to consider their interaction at the vulnerability level, and selecting the most appropriate multi-hazard vulnerability models [22]. Specifically, multi-variate vulnerability functions can be applied to properly evaluate the effect of compound hazards acting on the same asset. While stage-state functions are preferable when it is required to evaluate incremental impacts of consecutive events on the functionality of urban system components.

To enable the application of multiple vulnerability functions, the components of the territorial system require to be characterized by applying a proper multi-hazard exposure taxonomy, such as the GED4ALL Global Exposure Taxonomy[23].

To perform the multi-hazard impact (or risk) assessment, the loss of functionality of various assets is evaluated combining the exposure and vulnerability models with a series of hazard scenarios, which properly describe the evolution of the different hazards in space and time [14], including information about hazard intensity. These hazard scenarios can be obtained either by applying hazard models or exploiting available hazard maps.

5 CONCLUSIONS

The main aim of the presented procedure is the selection of a subset of assets and functions that contribute to the recoverability of the urban system after the occurrence of a disaster, improving and enlarging the definition of the 'Minimum Urban System that assures the Safeguarding of the Settlement' from a multi risk perspective.

Stakeholders are the individuals who utilize, shape, and develop the facilities and buildings that are part of an urban system. therefor as developers and final users of the urban system their ideas can play crucial role in decision making process [24], [25] to make sure that the selections outcome is going towards benefit of the settled population in urban system.

Moreover, in selecting the main assets and evaluating the performance of certain urban assets in the selected functions, or demonstration of the interdependencies amongst functions and assets, specialized knowledge may be required. However, it may not be feasible for a research team to include experts in all domains related to the active function in the urban system. To benefit from the knowledge and expertise of various professionals across different realms, it is necessary to involve them in the decision-making process as required. Therefore, it is essential to set a participation mechanism and integrate their knowledge and preferences into the modelling of the urban system.

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