Response to Referee #1

We wish to thank the Referee for his/her time and effort reviewing the manuscript. We greatly appreciate the constructive comments and suggestions, which we have carefully addressed in this response. Where applicable, changes are proposed to the manuscript accordingly (and marked up for clarity). Following the guidelines of the NHESS Editorial Board, the revised manuscript was not prepared at this point.

Natural hazard risk of complex systems part I introduces graph theory into risk analysis to promote a paradigm shift from reductive to holistic approaches to risk assessment and assess the risk of complex systems. Through a review of graph theory as it relates to risk, including issues of exposure, vulnerability, and resilience, and the development of an illustrative case, the authors show how network analysis can be employed to assess complex interdependent systems. The authors' main argument is that current risk assessment approaches fail to capture complex interactions between systems as a whole, and that network analysis techniques can be used to capture that complexity.

The authors are correct that current risk assessments are often reductionist and fail to account for interconnections and the properties of the system as a whole. Readers will also benefit from this topic given the prevalence of risk analysis that take a reductionist perspective.

- However, there is a significant body of work using graph theory for risk analysis. A large literature builds on Rinaldi et al. (2001) to use graph theory to assess critical infrastructure risks, interdependencies, and cascades (Lewis 2014; Setola et al. 2016), and another focuses on the systemic risks in financial systems (Summer 2013). Instead of focusing primarily on the connections between physical structures of infrastructure, another body of work focuses on the interconnections between hazards or hazards and vulnerabilities showing how risks can propagate and cascade (Clark- Ginsberg 2017; Gill and Malamud 2014).

Graph Theory is a well-established branch of mathematics. As such, it has been used to address a wide number of problems in many different fields, where risk analysis is included. However, risk analysis is, in itself, a very large field. Natural hazard risk, despite falling under the 'risk analysis' umbrella, requires its own specific modelling approaches, which are necessarily different from other types of risk, such as financial contagion in banking systems (as covered by Summer (2013) mentioned by the Referee), or others like car accidents, disease, conflict, to name a few. As this paper focuses of natural hazard risk, we have engaged with literature primarily from this field, where the application of Graph Theory is much sparser. We agree that some of the references mentioned here by the Referee are relevant in this context, and were missing from the original manuscript. Accordingly, in the revised manuscript we will add Clark-Ginsberg *et al.* (2018) at L423, Lewis (2014) and Setola *et al.* (2016) at L91.

- This literature (and the broader qualitative literature on networks of risk) identifies several challenges with using network analysis for risk. Chief among them is how to account for the multi-level, open-ended nature of systems in graph based approaches. For instance, Schulman and Roe (2016) and other high reliability theorists point out that infrastructure systems are vastly more complex than modelers make them out to be, with substantial coupling across components that is difficult to discern. Clark- Ginsberg et al. (2018) applies these insights to argue that network bases approaches of open-ended systems can never be complete and require careful decisions on how to delimit boundaries and describe networks. The authors allude to the idea of system incompleteness when discussing the nestled nature of power infrastructure, but then purport to offer a complete network (p6), which is not possible given the open-ended nature of risk.

We agree that the issue of modelling open-ended systems is central in any study of networks, and that this aspect was not sufficiently discussed in the original manuscript. For this reason, following the suggested reference, we propose adding the following paragraph to the Discussion section (L423) in the revised manuscript:

> "Despite the improvements in risk assessment within this systems perspective, Clark-Ginsberg *et al.* (2018) highlights that there are "questions about the validity of such assessment" regarding the ontological foundations of networked risk, the non-linearity and emergent phenomena that characterize system phenomena. The emergence of the risk system demonstrates that the risk will never be completely knowable, and for this reason the "unknown unknowns" are an inseparable part of a risk networks; in fact, the boundary definition of open systems are by nature artificial."

We believe this issue should also be discussed in Section 2.2.1 (Network Conceptualization), and therefore propose to add the following sentence (L237):

> "In defining the topology, it is crucial to define the level of analysis details coherently with the scope and scale, both for the selection of elements and for the relationship between elements that need to be considered. In the case of a very high detail for example, a node of the graph could represent a single person within a population, and in the case of a lower resolution, it could represent a large group of people with a specific common characteristic, such as living

in the same block or having the same hobby. In the case of analyses at a coarser level, an entire network (e.g. electric power system) can be modelled as a single node of another larger network (e.g. national power system). The definition of the topology structure of the graph also identifies immediately the system boundaries (e.g. which hospitals to be considered in the analysis: only the potential flood area, the ones in the district or in the region?). Up to which extent it is necessary to consider elements as nodes of the graph? The topology definition is a necessary step to perform the computational analysis and introduces approximations of the open systems that need to be acknowledged."

- This literature shows how graph theory can be used for representing complex issues of risk in a holistic way and also provides a grounding in some of the challenges associated with the topic. The authors need to clearly state how their work contributes to this literature.

As stated in the first comment, it is true that Graph Theory has been used to model risk in different fields, and it is also true that some literature proposes the use of Graph Theory specifically to model natural hazard risk of specific types of systems (most often infrastructures, such as Dueñas-Osorio et al. (2004). However, to the best of our knowledge, the application of Graph Theory for broader disaster risk reduction and collective risk assessment purposes, as proposed in the article, is new.

As we aimed to describe in the Introduction, the common practice in the field of natural hazard risk is to adopt reductionist methods, which focus on exposed elements individually and therefore neglect a very significant parcel of the actual impacts. This is very clearly an under-explored area in catastrophe risk modelling, and one where more research work is warranted. As such, we are firmly convinced that this work makes a relevant contribution to the field.

However, we agree that the original manuscript fails to unequivocally identify this gap through a well-structured literature review, and therefore also fails to clearly position itself among that literature. While the introduction of the original manuscript aimed to achieve this, it probably did so in an insufficiently organized and incomplete manner. We therefore propose to restructure it by splitting it into three subsections and expanding certain parts, as described below:

1. Introduction

1.1 Collective Disaster Risk Assessment: traditional approaches

This subsection provides a brief contextualization of current practice and limitations in disaster risk assessments, making use of key references. Here we propose to add a relevant reference related to multi-hazard risk Zscheischler *et al.* (2018), as suggested by Referee #2 (L59).

1.2 Modelling natural hazard risk in complex systems: state of the art and limitations

This subsection introduces the need for holistic approaches that are able to handle the complexity of contemporary society. This is in contrast with the reductionist approaches presented in subsection 1.1, which only partially contribute to the assessment of the total impact, because they do not consider the connections between the exposed elements. The literature in this subsection aims to give an overview of the state of art and limitations of existing models to study complex systems. We propose to improve it by adding the suggested references listed here:

L70: Lhomme et al. (2013) showed that the "*city has to be considered as an entity composed by different elements and not merely as a set of concrete buildings.*"

L73: "The reductionist approach, in which the "risks are an additive product of their constituent parts" (Clark-Ginsberg *et al.*, 2018), contrasts with the complex nature of disasters."

We then show how the networks are treated in the infrastructure sectors, one of the sectors that traditionally address the complexity of interdependency. This brings to the concept of systemic vulnerability typical of cascading failures in the network, for which we also propose to add two suggested references Lewis (2014) and Setola *et al.* (2016) at L91. Subsection 1.2 ends with the presentation of the system of systems perspective.

1.3 Positioning and aims

The main difference between the original and the revised manuscript will be this subsection, where we wish to clarify:

(1) where our work is positioned in the recent theoretical framework covered by the proposed literature;

(2) the misunderstanding about the use of the network-based analysis: we do not analyse systems already organized as a network (e.g. electric power network), but we instead employ the network to represent a complex system such as an urban environment, and use Graph Theory as a diagnosis tool.

To achieve this, we propose adding the following:

"~~Although t~~The aspects of complexity and interdependency have been investigated by various models of critical infrastructure as a single system, or as systems of ~~systems,~~ systems, which are networks by construction (e.g. drainage system). However, there is still a gap in current practice when it comes to modelling~~we would like to further explore~~ the complexity of interconnections between ~~the~~ individual ~~exposed~~ elements that do not explicitly constitute a network, which tend to be neglected by traditional reductionist risk assessments.~~ and their interconnections,~~ Therefore, in this manuscript we propose an approach to model such interconnections and ~~and propose an approach to~~ develop a more holistic collective risk assessments.

This work proposes an approach to assess the interconnected risk (i.e. complex interaction between human, environment and technological systems) and a potential tool to model cascading risk (i.e. the results of escalation processes) and support more informed DRR decision making (Pescaroli and Alexander, 2018).

In particular, we understand that it is necessary to better analyse the interaction between these elements at risk and their influences on indirect impact assessment. The analyses of interaction and influence are assessed in this work by adopting the framework of Graph Theory, the branch of mathematics for the treatment of networks. Since its birth in 1736, Graph Theory has witnessed many exciting developments, and has been able to provide answers to a wide range of practical questions in many sectors (Boccaletti *et al.*, 2006). Given this context, this paper proposes an insight into collective risk assessment from an innovative holistic perspective.

The aims of this paper are: (…)"

- Because they do not engage with this literature, I do not believe there is enough for a standalone theoretical paper on their topic. Rather than publishing this as a separate piece, I recommend using this article as a basis the literature review/methodology of the empirical paper, which provides a useful contribution to the literature.

This article proposes the theoretical framework for a new approach to model collective risk of natural hazards in complex systems, such as urban environments. In order to do so, the introduction aims to engage with literature that is representative of the state of the art in this field, following the logical sequence described in the previous comment. Ultimately, the goal of the introduction is to provide a concise overview (i.e. brief but comprehensive), and then position this work among the existing body of literature.

We recognize that certain key references suggested by both Referees were missing, and following the very useful suggestions provided, we have expanded the introduction and added them. However, we would like to highlight that the goal of this article is *not* to provide an exhaustive literature review of the application of Graph Theory to risk analysis, or on collective risk assessments – these topics would likely require extensive review articles by themselves. As such, we believe that this does not justify the insufficiency of the article as a standalone theoretical paper, as the contents of the article go incontrovertibly beyond the literature review. Moreover, we believe that merging the two papers, even after a significant hypothetical reduction of both of them, would be harmful for their quality, and would still result in an excessively long manuscript. Finally, it is worth noting that the two papers may address different audiences: part I is targeted to a more general audience who may be interested in understanding the foundations of the approach, while part II points to technical experts and researchers who may want to implement this approach for their own practical applications. For these reasons, we believe that keeping the current structure with two companion papers is the optimal solution.

References

Boccaletti, Stefano, V. Latora, Y. Moreno, M. Chavez, and D. U. Hwang. 2006. "Complex Networks: Structure and Dynamics." *Physics Reports* 424(4–5):175–308.

Clark-Ginsberg, Aaron, Leili Abolhassani, and Elahe Azam Rahmati. 2018. "Comparing Networked and Linear Risk Assessments: From Theory to Evidence." *International Journal of Disaster Risk Reduction* 30(April):216–24. Retrieved (https://doi.org/10.1016/j.ijdrr.2018.04.031).

Dueñas-Osorio, Leonardo, James I. Craig, and Barry J. Goodno. 2004. "Probabilistic Response of Interdependent Infrastructure Networks." in *2nd annual meeting of the Asian-pacific network of centers for earthquake engineering research (ANCER)*. Honolulu, Hawaii. Retrieved (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.123.2036&rep=rep1&type=pdf).

Lewis, Ted G. 2014. *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*. John Wiley & Sons.

Lhomme, S., D. Serre, Y. Diab, and R. Laganier. 2013. "Analyzing Resilience of Urban Networks: A Preliminary Step towards More Flood Resilient Cities." *Natural Hazards and Earth System Science* 13(2):221–30.

Pescaroli, Gianluca and David Alexander. 2018. “Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework.” *Risk Analysis* 38(11):2245–57.

Setola, Roberto, Vittorio Rosato, Elias Kyriakides, and Erich Rome. 2016. *Managing the Complexity of Critical Infrastructures*. Springer Nature.

Summer, Martin. 2013. “Financial Contagion and Network Analysis.” *Annual Review of Financial Economics* 5:277–97.

Zscheischler, Jakob et al. 2018. “Future Climate Risk from Compound Events.” *Nature Climate Change* 8(6):469–77. Retrieved (http://dx.doi.org/10.1038/s41558-018-0156-3).