Nhess-2020-12: Towards Resilient Vital Infrastructure Systems: Challenges, Opportunities, and Future Research Agenda (Mehvar et al.)

Reply to the comments from Referee #1

We appreciate the referee #1 for the very constructive feedback and detailed comments provided, which helped us to greatly improve the manuscript. We have responded to the comments and we will modify the manuscript in accordance to the received suggestions and comments. Our responses are given in blue. For all modifications affected the manuscript, line numbers are given in our responses, referring to the revised version of the manuscript when selecting ''All Markup'' in the track changes menu.

Comments:

The article aims to compile all relevant literature regarding resilience assessment and quantification of vital infrastructure systems (VIS). It points out quite extensively how is this literature specific for the different types of VIS and how every resilience conceptualization originates tensions when designing such infrastructure. It certainly represents a valuable document for people interested in resilience definition and quantification of VIS. While I would like to acknowledge that this manuscript has quite some potential it is difficult to read, and it certainly has a promising title which to my point of view does not reflect in the content. My two main criticisms for this manuscript are:

1. It gives high importance to the collection if interviews in the methodological section and yet it never points out opinions, agreements or even discuss the view of the interviewees. If you remove the promise of using interviews from the text it would not make a change in the paper. This also makes it a bit confusing to understand as the it is not clear if the paper structure is a literature review as sometimes it seems to be written as an opinion paper.

Response: In response to this comment, we would like to clarify that most of the inputs that are derived from the interviews are the ones that have been collected from the interviews conducted with the co-authors of this paper who are specialized in a wide range of different fields related to the four selected infrastructure sectors. Therefore, most of the non-literature based materials included in this paper are the authors' views. We did not cite the collected opinions in the paper, however, we included these views in agreement of (or in contradiction with) the literature based inputs. For example, in sections 4 where conceptual tensions are discussed, we analysed different opinions regarding the risk and resilience concepts (line 481), which come from the views of the interviewees. Other examples of such analysis/reflections included in this paper are as below:

- Line 404: Opinions of interviewees regarding resilience and justice issue
- Line 464: Opinions of the interviewees on ''Unit of analysis''
- Line 542: Agreements between the literature inputs and opinions from the interviewees on cascading effects of failure
- Line 568: Agreements between the literature and views of the interviewees on over-confidence in the robustness of systems
- Line 573: Controversies within social and technical aspects which are derived from the interviews

- Line 603: Agreements between the opinions of the interviewees and literature on how multi-functionality of infrastructures may lead to an increase in the resilience of the system
- Line 610: Integration of the literature-based inputs with the opinions of the interviewees regarding the long time scale of action to build resilience
- Line 625: Agreements between the literature and authors' opinions on the role of trust between stakeholders for making resilience-oriented decision making
- Line 679: Agreements between opinions and literature on the importance of using system of system approach in designing resilient infrastructures
- Line 703: Opinions of the interviewees in agreement with the recent studies regarding the emerging techniques in pre/post disaster anticipation/identification
- Line 741: Presented examples of ''Building with Nature'' by the interviewees which are supported with the literature as referred
- Lines 889, 895, 921: Cognitive approach; team reflection, knowledge-sharing; and human-centred design, respectively, as presented approaches/measures by the interviewees supported by the literature

Notably, this paper is primarily based on the inputs from the literature, and review is the largest contribution in this paper, therefore we structured it as a 'review' paper. This implies that the reflected opinions of the co-authors have been used mainly as the inspiration for the paper and we did not aim to necessarily confront them with the literature. However, these interviews provided supplement source of inputs, which are in support or in contradiction with the literature-based materials. In addition, we would like to highlight that due to the large extent of the paper, which extensively included several concepts and approaches, more elaborations on the provided claims and opinions are excluded in this review. We believe that such an integration of the contradictory and compatible opinions/claims with the literature-based inputs would help readers to better understand the concepts, challenges, and measures in applying the resilience concept to VIS.

To clarify this issue in the paper, and to avoid any likely confusion on the type of paper as mentioned by the reviewer, we excluded the terms 'interview' and 'state of the art' in the methodology section, and only presented the 'literature review' as the main source of inputs and the methodology used in this paper. By excluding the term 'interview', we did not make any change in the content of the paper, and we keep all the opinions and discussions as they have been already reflected, representing the paper as a 'review paper', which is enriched by relevant discussions and opinions of the authors on each concept/approach.

2. It supports the author's claims based on multiple resilience concepts which require to be defined beforehand so that the reader understands and follows the story. Defining the concepts before elaborating on them is almost a rule in resilience literature as Engineering, ecological and socioecological resilience views use similar terminology with different meaning. Furthermore, resilience concept definitions almost define quantification indicators of resilience in each context. This is very important as resilience thinking is contextual and discipline biased.

Response: This comment has been addressed throughout the article (as described in our responses to your 'detailed comments') by including definitions of concepts before each claim is presented. Examples of corresponding changes are briefly as follows:

- Introduction: lines 66 - 72: Including the definition of 'systems resilience'
- Introduction: lines 74 - 89: Clarification on the definitions of the concepts: 'Engineering resilience' vs 'Ecological resilience', 'Resilience engineering' vs 'Engineering resilience'
- Section 3: line 166: Moving the definition of VIS to the beginning of the section

- Section 3.1: lines 199 - 204: Clarification on the terms: shocks, pressures, stresses, causes
- Section 3.2: lines 222 - 226: Adding the definitions of the terms 'capacity', and 'performance'
- Section 3.3: line 292 - 306: Definition of the 'resilience engineering' concept
- Section 4: Deleting Table 1 & moving the concepts/definitions (4.1) to the beginning of the section
- Section 4.1 (f): line 477 - 480: Adding the definition of 'risk' at the beginning of the sub-section

With respect to the second comment regarding the quantification indicators of resilience, we mainly focused on recovery aspect, and indicated potential indicators for it, as recovery is the important aspect represented in the resilience engineering definition provided in this article. These indicators include e.g., lines 584 & 1085: recovery speed; line 722: residual functionality; line 731: recovery patterns; line 1094: complete and partial recovery; line 1098: recovery rates across communities. However, quantifying these indicators and elaboration on them is beyond the scope of this article.

For this reason and other pointed out afterwards I suggest to accept the manuscript after major revisions as I still think it will be a good contribution for the field but significant editing and clarification work is required. Another small suggestion is that there are too many subheadings in the paper which have almost now relevant formation which makes it difficult to follow and long to read. This may be synthesized making the paper a bit more clear.

Response: The reason of having many sub-headings is that we extensively included important resilience-related concepts applied for VIS and analysis of similarities and contradictions between these concepts which are mostly distinct from each other. However, we did our best to synthesize them as much as possible. For example, table 1 with all its headings has been removed; 'risk assessment' has been merged to the engineering-based method (e); 'diversification' and 'de-centralization' have been merged to the heading 'redundancy creation' as one sub-heading (line 796).

Major comments:

The resilience definition is always determined by the system definition. The system is related to the field of study. I suggest this is a simple method to define resilience of a system. First define the system then elaborate of its resilience definition. Not the other way around.

Response: Thank you for your suggestion. Addressing this comment, we moved the definition of VIS to the beginning of section 3 (line 166). Therefore, we renamed the title of this section to ''Definition of VIS, design approaches, and concept of resilience engineering''. In this way, the section now starts with the definition of VIS including inter/cross sectoral dependencies; shocks and pressures affecting them; current design approaches; and conceptualization of resilience engineering within VIS, respectively.

The paper reads more like a review paper in which is never clear how the interviews contrast the literature or support the claims. It's said that interviews where held but it seems that no analysis was done over them.

Response: This comment has been addressed in the first page of this document.

Analysis of resilience should be framed under an specific resilience optic, heuristic or discipline, e.g. engineering resilience, ecological resilience, socio-ecological resilience or the case specific structural resilience etc. It also poses contradictory statements about concepts and method presented as non-engineering ones which are not true.

Response: We did analysis of resilience specifically under the ''resilience engineering'' concept, and throughout the article, VIS resilience is considered based on resilience of its social, ecological, and technical sub-systems as explicitly mentioned in e.g., section 3.

With respect to your second comment, contradictions and debates mentioned especially in sections 4 and 5 have been intentionally included, since one of the aims of this review is to shed light on these contradictions reflected in resilience literature (as we called tensions) and common discourses around them. Risk versus resilience is one of the examples for these contradictions, which are often subject to different interpretations.

In my opinion (which may be very subjective), the tittle (…. , and future research agenda) suggest that the authors will point out or give directions towards knowledge gaps and future research, but the section intended for this does not contain enough information regarding these matters. This section is more written like a recommendations section that points the things that resilience is doing wrong rather than what is envisioned by the authors as the required research agenda. In simple words, if the tittle promises something but does not deliver what it promises, it just becomes 'Scientific click bait'.

Response: We believe that section 6 (mainly derived from the identified gaps in the literature) provides the future research developments required in designing resilient VIS indicating where the research in this field is heading to. For example, these directions include:

- Further assessment of the integration between socio-ecological-technical aspects of infrastructures
- Understanding the complex cascading effects of failures and disturbances among the network of infrastructures
- Development of integrated approaches (e.g., system of system) for improving resilience of the large scale VIS
- More emphasis on the recovery process in designing and decision making procedures and understanding the most significant responsible parameters to inform the success of recovery
- More emphasis on the role of regular maintenance and understanding the performance of the current infrastructure systems
- Emphasis on how to make the obtained data useful in identifying the factors that create different recovery characteristics, e g., by developing couple image-based recovery assessment with macro-economic agent-based modelling

Authors tend to elaborate over concepts and definitions (e.g. Shock, pressure, hazard, Failure, system failure) which have not been previously defined and later on they explain some of them. The order follows, first you cite the concept, then you define what it means it and later elaborate. Few examples of what I'm saying are:

Line 82: Where did you explain the concept of engineering resilience.

Line 232: Which are the resilience levels? Concept introduced but no explanation given before.

Response: This comment has been addressed for each concept/term as described in our responses to the 'detailed' comments below. Addressing the above-mentioned questions: the resilience engineering concept has been defined first, and then elaborated in section 3.3 lines 292 - 306. Regarding the second question, analysis of resilience level including its definition, determinative factors, etc is not in the scope of this study. By 'resilience level' we mean how much a sub-system can be resilient (do not mean to a *specific level* indeed). Therefore, we removed ''level'' in the corresponding lines to avoid this unclarity.

Detailed comments:

Figure 1: Depending on the resilience context, system and discipline Shocks and pressures can be the same or different components of the system disturbances. Furthermore, literaute sometime mixes pressures and stresses. For example, shocks are instantaneous disturbances like floods and earthquakes whereas pressures can be long term characteristics of the system like population growth or climate change. If you are going to use both (shocks and pressures), please define what is a shock and what is a pressure or if they represent the same thing as it remains a big question along the whole paper? Also, try to include the stress definition for clarity as some of the claims are supported by stresses as well. please see : Shocks: Zseleczky, L. & Yosef, S. 2014. Are Shocks Really Increasing? A selective review of the global frequency, severity, scope and impact of five types of shocks. 2020 Conference Paper 5. May 2014. Washington, D.C.: IFPRI. Stresses (pressures) Bujones A., Jaskiewicz, K., Linakis, L. & McGirr, M. 2013. A Framework for Analyzing Resilience In Fragile and Conflict-Affected Situations. USAID Final Report. Columbia University SIPA 2013. Mock, N., Béné, C., Constas, M. & Frankenberger, T. 2015. Systems Cluster Paper: Systems analysis in the context of resilience. For discussion at the meeting on Resilience Measurement Technical Briefings. Resilience Measurement Technical Working Group. Rome: FSIN.

Response: With respect to the definitions of shocks and pressures, we used the both terms throughout the article, meaning that these two sources of disturbances are distinguished in this review. This has been shortly reflected already in the article, e.g., lines 46 and 942. However, for more clarification we added the following explanation (including the definition of stresses), in the lines 199 - 204:

‘‘Infrastructures are affected by many unexpected and sudden shocks, as well as pressures caused by different natural or human-induced sources. In this article, shocks are referred to as suddenly and instantaneously occurring disturbances, while pressures affect the system resilience in a long-term (e.g., climate change, population growth, etc.). The long-term pressures are also called ‘’Stresses’’ in some literature (e.g., Bujones et al., 2013). Hallegatte et al. (2019) classified these causes (here as referred to as sources of disturbances) into four categories …’’

Line 362: What is a favorable system regime?

Response: The word ‘‘favourable’’ is replaced by ‘‘desirable’’, as the authors mean a ‘‘desirable’’ system with greater production of services to societies (line 443).

The main comment after finishing the paper is that it is missing clear definitions of what the authors want to attribute to VIS resilience or want to deliver as their own definition VIS resilience (see first paragraph of section 3.3 for example). So, I strongly suggest to either explain what the authors understand themselves as VIS resilience since the early start of the paper of the paper to make the scope of the paper clearer. Also, I suggest moving section 3.3 towards the beginning of the paper. I also feel that the confusion of which type of paper in which type of paper is this manuscript is what makes the paper so long to read and makes it lose its powerful message.

Response: We thank the reviewer for these suggestions and we clarified this issue with following explanations and changes we have made:

Structure of the section 3 has been changed. Now it starts with definition of the VIS systems, and its resilience, including elaboration on inter/cross sectoral dependencies that exist in VIS. Then we identified different shocks & pressures affecting the infrastructures (section 3.1), followed by two distinct approaches in designing VIS (section 3.2). The latter (capacity-oriented approach) provides a foundation and basis for

the main part of this section, which defines the concept of resilience engineering within VIS (section 3.3, lines 292-306).

Section 3.3 provides the literature-based background on the conceptualization of the resilience engineering for VIS, and then we presented our own definition grounded on the five mentioned principles required to call a system resilient (line 295). Thus, *first* paragraph in section 3 explores the origin and existing definitions in literature, followed by the *second* and *third* paragraphs providing an overview of the current approaches for assessment of VIS resilience and interplays between different social, ecological, and technical resilience perspectives. *Fourth* paragraph (lines 292-306) explicitly present what the authors want to deliver as their own definition of resilience engineering concept and its application for VIS.

However, integration of the inputs from the literature review, and our own definition in this section might be the reason of this unclarity to reviewer. To avoid this, we distinguished between these two sources of inputs, by first presenting literature based materials, and then the adopted concept by the authors. This clarification has been done by the following changes:

- Adding the paragraph ‘‘In this article, we define VIS as...’’ in the line 166
- Editing the text: line 177-179 (‘‘we also highlight a cross sectoral dependency between different types of VIS (see Figure 2) in addition to the relations between the socio-ecological-technical sub-systems’’)
- Adding ‘‘Reviewing the literature shows that …’’ at the beginning of the section 3.3 (line 247)
- Deleting the lines 257-266 and moving them further to the lines 292-301

In the introduction is clear that Ecological and Engineering resilience distinction is made but I think you are missing to include analysis of systems resilience. A systems resilience analysis is related but not the same thing as a structural engineering resilience analysis. Sometimes they are not even methodologically connected. See you own citation of Hosseini (2016). He clarifies the definition of engineering resilience.

Response: Addressing this comment, we included the definition and analysis of system resilience derived from Henry and Ramirez-Marquez (2012), and Hosseini et al. (2016). This has been briefly added in the introduction, lines 66-72 as below:

‘‘For example, Henry and Ramirez-Marquez (2012) described system resilience as ‘‘how the system delivery function changes due to a disruptive event and how the system bounces back from such distress state into normalcy’’. Hosseini et al. (2016) stated that depending on which type of domains are considered (i.e., organizational, social, economic, and engineering), system resilience traditionally concentrate on the inherent ability of systems to absorb a disruptive effect to their performances, with more recent focuses on recovery aspects.’’

Line 53: “Estimates show that disruptive impacts on people cost at least $90 billion per year (Koks et al., 2019; Nicolas et al., 2019).” Please geo-reference this statement like “90 billion per year in European countries or in Delta regions” as it is highly unlikely that this value is the same all over the world.

Response: This has not been geo-referenced in the cited reference. Therefore, we removed this statement, and kept the following sentence (line 54) referring to the direct damage of natural hazards to infrastructure in low and middle income countries.

Line 55: What does it mean direct damage of Natural Hazards? Is it structural damage? or is it operational damage? Or incurred losses due to disruption?

Response: This refers to the damage to the assets, not to the infrastructure services. The statement (line 55) has been edited as below:

‘‘In low and middle income countries, direct damage of natural hazards to infrastructure assets within transport and energy systems is estimated …’’.

Lines 61-to 63: Please check sentence as grammar is sloppy.

Response: Addressing this comment, the sentence (lines 61-63) has been edited as below:

‘‘Over the past decades, the focus of resilience studies has shifted from single assets to systems (i.e., natural, social, technical). In recent resilience related literature, more emphasis is laid on coupled socio-ecological and socio-technical systems (Galderisi, 2018).’’

Line 66 to 68: What does the classic distinction claim from Holling (1996) in short? Why is it important to cite this author if his claim cannot be confronted with the subsequent claims citation from Hickford (2018) and Hollnagel (2006) which you DID explain in short?

Response: Addressing this comment, the following sentence has been added in lines 76-79:

‘‘According to Holling (1996), engineering resilience concentrates on stability near an equilibrium steady state, in which resistance to disturbances and speed of return to the equilibrium are centred in this definition. While, ecological resilience emphasizes conditions far from any equilibrium state in which a system can change into another regime of behaviour due to instability.’’

Line 80-81: I Do agree that only few studies present actual assessments of infrastructure resilience but if they are only few why you don’t cite them?

Response: New citations have been added in lines 101-102: (e.g., Donovan and Work, 2017; Panteli et al., 2017; Argyroudis et al., 2019).

Line 82: Where did you explain the concept of engineering resilience (this ia also linked to the general comments)? Otherwise is difficult to understand why it is difficult to apply.

Response: Thank you for highlighting this important point. As mentioned in the abstract and introduction sections, this review is based on the concept of ‘‘resilience engineering’’ within VIS. Therefore, throughout the manuscript we refer to this concept, and present the challenges and opportunities for designing resilient VIS within this concept. Although in some literature both concepts of ‘‘resilience engineering’’, and ‘‘engineering resilience’’ are defined and interpreted as similar engineering disciplines (e.g., Yodo and Wang, 2016), in this article we differentiate these two terms. Considering the origin of these two concepts, ‘‘resilience engineering’’ focuses mainly on the system’s ability to bounce back to a steady state after a disturbance (Davoudi et al., 2012; Kim and Lim, 2016), while ‘‘engineering resilience’’ mainly refers to the traditional view of system safety to withstand the failure possibility (Steen and Aven, 2011; Dekker et al., 2008). In addition, the engineering resilience definition by Holling (1996) has also been added in the previous paragraph (line 76).

Addressing this comment, the above-mentioned distinction has been added in the introduction, lines 82-89.

Line 106: I this a literature review type of paper or a state-of-the-art kind of paper? These are two different types of manuscript and therefore they should be written in different ways. To my view, is a mix of both and I personally don’t see the added value. I suggest to adapt the paper into a state of the art type of paper as the main claim of it is that until now, applying the resilience concept to VIS is difficult and this paper tries to organize this and from there it identifies new challenges and opportunities in resilience research of VIS.

Response: This comment has been addressed in the first page of this document.

Lines 118 to 119: Which are the four selected infrastructure systems? Please list them. I'm aware that you listed them in line 41 a 109 is not clear if they are standard or you chose them for the study. Is it correct to say that VIS are more than the four listed?

Response: The four selected VIS have been listed as suggested (line 141). There are different classifications for vital (critical) infrastructures (e.g., public health, emergency services, chemical sector, critical manufacturing sector, defense industrial base sector, financial services sector, food and agriculture sector, nuclear reactors, etc.). So, they are not standard. In this study we limited them to the four selected sectors.

Paragraph 117 to 126: Is it correct to attribute all 30,000 documents for example to resilience related documents? Or does this mean that your search query words were found in 30,000 documents?

Response: As mentioned in the line 144, application of these criteria (searched keywords) resulted in finding more than 30,000 documents, meaning that we found more than 30,000 documents in which these keywords are appeared.

Line 143: I'm not sure if the word "infrastructures" is correctly used in this sentence as infrastructure is already a plural. Please double check.

Response: Infrastructure is a singular word. Infrastructures is the plural form of infrastructure (https://en.wiktionary.org/wiki/infrastructure).

Lines 143-to 144: Are shocks and causes the same thing? Please unify terms to make it clearer.

Response: As mentioned in the corresponding line 199, and in the title of sub-section 3.1, infrastructures are affected by (i) shocks, and (ii) pressures. There are different causes (sources of disturbances) for the shocks and pressures as these causes are already classified to accidents, system failures, attacks, and natural hazards (lines 204-206). So, in this article, we consider a shock as an unforeseen and sudden disturbance affecting VIS, which is different than the cause of shock (sources of disturbances that can be natural & human induced). This has been clarified by some textual editions in lines 199-204 as below:

''Infrastructures are affected by many unexpected and sudden shocks, as well as pressures caused by different natural or human-induced sources. In this article, shocks are referred to as suddenly and instantaneously occurring disturbances, while pressures affect the system resilience in a long-term (e.g., climate change, population growth, etc.). The long-term pressures are also called ''Stresses'' in some literature (e.g., Bujones et al., 2013). Hallegatte et al. (2019) classified the causes (here as referred to as sources of disturbances) into four categories: ….''.

Line 143-144: What is the difference between accidents, system failures, attacks and hazards? Is an attack a type of hazard? Isn't a system failure the result of a shock? It seems that these definitions are mixing concepts like causes with effects. Please define terms before using them. This applies to the whole manuscript.

Response: There are different interpretations over these terms that are subjectively defined. As addressed in the previous response, in this article we clarified that: (i) shocks and pressures are types of disturbances (ii) causes are sources of these disturbances that can be either human or natural induced, classified by Hallegatte et al. (2019). Within this perspective, these causes are distinct as there are different sources of disturbances (e.g., systems & equipment in system failure, users in road accidents, human in attacks, natural phenomena in earthquake, flooding, etc).

Line 148: Climate change is not included in Natural hazards (just previous sentence item (4))?

Response: Climate change itself is not a natural hazard, rather it is a global pressure (as defined in lines 206-207) which is considered as one of the causes of natural hazards exacerbating them through its adverse impacts. For example, sea level rise causes coastal erosion, therefore, coastal erosion is the hazard, and climate change impact (sea level rise) is the cause of it. More examples: ocean warming results in marine biodiversity changes, and frequency and intensity of storms are changed due to climate change.

Line 153: Other examples of what? Cyber physical systems? Natural hazards? Or types of Infrastructure? What do you mean by discourse? A trend? and imposed (authoritarian) idea?

Response: The section 3.1 provides different examples of disturbances to infrastructure systems within different sectors. Here ‘‘other examples’’ refers to ‘‘examples of disturbances to infrastructure systems’’ (for clarification, this has been added in line 213). Discourse (line 226) refers to a debate and discussion in the literature.

Paragraph 161 to 173: Please explain what capacity is and what is performance are first and later elaborate on both.

Response: Capacity has broad definitions depending on within which context we define it. There is no unique definition for ‘performance’ as well. Addressing your comment, we added definitions of system’s capacity and system’s performance at the beginning of section 3.2 (lines 222-226) as below:

‘‘Considering a wide range of context-specific definitions for the two words ‘capacity’, and ‘performance’, here we define system’s capacity as the maximum capability, and amount that a system (i.e., VIS) can contain to sustain its services and productivity. System’s performance refers to the execution of different actions by a system aiming to produce its services.’’

Elaboration on both terms within VIS has been already done in lines 226-244.

Lines 176: What do you mean by dominant discourse? Is it a discourse or is an approach?

Response: Line 239: As reflected in Underwood and Waterson (2013), it is an approach which has become a ‘‘source of discussion/talk’’ (discourse) in the study of complex systems.

Section 3.3: Before elaborating on the resilience engineering concept please explain it.

Response: As addressed in your previous comment (page 4), resilience engineering concept has been defined and later elaborated within VIS in section 3.3, lines 292-306.

Line 190: what are the aspects? First list the aspects and then use the expression aspect.

Response: These aspects are further mentioned in the article (e.g., organisational, socio-ecological, and more others which we do not aim to explore all definitions as it has been done in many literature before). However, to better clarify, we removed the sentence in the line 253: ‘‘These definitions are varied, depending on which aspect of the infrastructure system is under consideration.’’, since this has been already reflected in the sentences afterwards.

Line 210 to 212: While self-organizing is in fact an important part of resilience of flood defense systems, defense level also highly determines the resilience of the system. Just compare the Netherlands to other deltaic systems. They have very robust selforganization and still their defense levels are very high due to risk inclusion. Please take a look at “Assessment of critical infrastructure resilience to flooding using a response curve approach – Murdock et al. 2018” for better insight.

Response: Yes, indeed. Thank you for your explanation, and suggested reference.

Line 223 to 224: This sentence is redundant. I suggest to change it "From a socioecological perspective, social and ecological systems are also interlinked systems". If they were not interlinked, why they will fit in the socio-ecological category?

Response: Addressing this comment, a textual edition has been done: ''From a socio-ecological perspective'' is removed in the line 286, and replaced at the end of sentence (line 290): ''referring to the *socio-ecological* perspective''.

Paragraph 229 to 237: This could be a good definition of what the vital infrastructure SYSTEM is for the authors. Word conglomeration is a bit confusing. What do you mean be conglomeration?

Response: We mean ''collection'' of different sub-systems. To avoid this confusion, 'collection' has been replaced (line 166).

Level 232: Which are the resilience levels? Were they explained before?

Response: We mean how much a sub-system can be resilient (do not mean to a *specific level* indeed). Therefore, we removed ''level'' to avoid this unclarity.

Level 232: Again, you are elaborating an idea supported by the engineering concept which was not clearly defined or chosen. What is the definition of resilience engineering over which the paper should be evaluated on?

Response: This comment has been addressed by moving this idea (lines 301-306) after the resilience engineering definition.

234: instead of than "to"

Response: ''to'' has been replaced as suggested (line 303).

234: replace infrastructure systems by "VIS" otherwise it seems they are two different concepts.

Response: ''VIS'' has been replaced (line 303).

Figure 1. Where can I find a definition of shock and pressures to understand how they differ?

Response: We already added definition and clarified this in the lines 199-203 (also explained in response to your similar comment, page 8).

Line 245: Why inter-relation instead of relation? Are they reciprocal or not? Example: Power outage affect transport system implies that transport system affects power system? Damage in roads represents damage in flood protection system?

Response: Not all types of systems are reciprocal indeed; therefore, to address this comment, we replaced ''inter-relations'' with ''relations'' (line 178).

Line 245: Why inter-dependency instead of dependency? Are they reciprocal or not?

Response: Similar to the previous comment, this has been corrected too (line 177).

Line 270: I really like that you define them as "Conceptual Tensions"!

Line 272: Again, elaboration over the concept of resilience engineering which was never formally defined as the one the reader needs to use to understand the claims.

Response: This comment has been addressed before.

Table 1 is full of concepts which are not previously defined. For example, what is transformative capacity? What is bouncing back or bouncing forward? Please move table after definitions of section 4.1. Otherwise is difficult to understand the reasoning behind their location in triangle.

Response: Addressing this comment, a new section 4.3 has been added in line 651 (‘‘Relevance of the challenges to the VIS’s components’’), and figure 3 (now is modified based on the changes of headings) including its corresponding explanations have been removed from the beginning of section 4, and replaced under this added section 4.3 (lines 652-668). Since Table 1 is repetition of what has been titled and discussed in sections 4.1 and 4.2, we removed this Table from the article.

Paragraph Line 323 to 333: “calling communities or individual “resilient” may be an excuse of not changing”. Please connect these ideas to VIS.

Response: The whole paragraph refers to the VIS resilience with an emphasis on the social resilience of the systems. This has been reflected by adding ‘‘in such a context, which emphasizes on the social resilience of VIS’’ in line 412-413.

Paragraph Line 336 to 341: Note that resistance can be included in a systems resilience. If so, resistance of a system partly defines its resilience as it can decrease or increase the magnitude of the damage which will result in a lower resilience level to be required for the system.

Response: We agree with you that resistance of a system partly defines its resilience, in this way resilience and resistance are (partly) related concepts (as already referred in the 1st paragraph, lines 417-422), but the aim of this sub-section (Resilient versus robust systems) is to provide also contrary opinions that exist in the literature as referred here to as a conceptual tension.

Paragraph 343 to 354: Use adapt instead of responding as resisting can also be a way of response to a shock.

Response: The correction has been made, as suggested (line 426).

Line 354: Replace the last sentence part “that changes” to “that change” as is referring to the disturbances which is a plural noun.

Response: This has been corrected as suggested (line 435).

Line 358: replace by “Flexibility of the system allowing changes while controlling disruptions”.

Response: The comment has been addressed, as suggested (line 440).

Line 362: What is a favorable system regime?

Response: This comment has been already addressed as suggested (line 443). The authors mean a ‘‘desirable’’ system with greater production of services to societies.

Paragraph Lines 370 to 380: I personally think that the temporal and spatial scale is part of defining the system and its boundaries which will later shape its definition of resilience. What do you think? IS it valuable to elaborate on this? Are there any authors claiming this as well?

Response: In the literature, there are different ways to elaborate on this issue. Temporal and spatial scales of study are not necessarily defined within the system (resilience) definitions. In this article, we think that highlighting this as a challenge might better reflect the importance of this issue for designing resilient VIS. This has also been reflected as a challenging question in literature (line 453) pointing out to the proper time scale of action facing a disturbance, as well as answering the question of 'resilience for where' (line 461).

Paragraph 380 to 390: First define what do you mean by unit and the proceed to elaborate the idea. A suggestion for this could be by moving the first two sentences:

"Infrastructure systems as coupled socio-ecological-technical systems are designed and managed by different organizational levels. This different unit of analysis can and perhaps should be considered when analyzing the resilience of an infrastructure system." to the end of the paragraph.

Response: Thank you for your suggestion. We addressed this comment as you suggested (line 473).

Paragraph 392: What shall the reader understand as risk? Probability of a Hazard or Probability times the consequence? Magnitude of the damage? Casualties? Please define risk to be able to understand why it is different of similar to resilience concept.

Response: To address this comment, we added definition of 'risk' considered in this article, lines 477-480:

''Risk is widely defined in the literature as a combination of the occurrence of a disturbance, the exposure and vulnerability of a system within different context (e.g., Ness et al., 2007; Covello and Merkhoher, 2013; Oppenheimer et al., 2014). In this article, the concept of risk is defined as probability of occurrence of a disturbance (hazard) to VIS, times the consequences (damages) to the system.''

Line 411: Moving close to the flood defenses will change the risk indeed but because the people are increasing the exposure. This will be according to the definition of Risk = Exposure X Vulnerability X Vulnerability. Please make sure that every assumption must be framed under a common understanding of the definition.

Response: We agree with your opinion. To address this comment and make it consistent with our risk definition, we did the below edition in lines 498-499:

''…. since they may allude people to move and live closer to the sea, increasing potential consequences (damages) to flooding, and thus, increasing the risk.''

Line 416: How is it possible to determine that the risk concept from people has a faster rate of change than climate and other ongoing pressures? BTW you are supporting this claim without explaining what you mean by pressures in the flood risk context.

Response: There are studies on how risk attitude changes over time. Such an analysis is beyond the scope of this study. We presented this claim as it 'may potentially' occur, given the very long term impacts of pressures such as climate change. Other ongoing pressures can also be e.g., popularity of the coastal areas to live, and thus growing pace of migration to the coastal cities (Small and Nicholls, 2003). This clarification has been done in lines 502-504.

Line 426: The claim that infrastructure is constructed to their minimum/limit capacity is wrong. In case of limit state design, the structure is designed so that the ultimate load can be withstand before failure (limit state). Structural design is mostly ruled by three main design philosophies: 1-Working stress: Structures are designed before the threshold were material present permanent deformations. 2-Ultimate Load: Structures are designed for estimated maximum loads affected by safety factors. This will not only allow to cope with

material uncertainty, but it will also allow to include increase in the working loads plus deterioration in time, e.g. increase in estimated traffic over a bridge. 3-Limit state: In the limit state, safety of the structure is determined by the ultimate load that a structure can bear either before loss of serviceability or before failure, e.g for service load design go until maximum tolerable deformations, erosion depth, initiation of cracks or amplitude of vibration (e.g. roads) whereas for limit state the design goes until, fatigue, permanent deformation and even collapse (e.g. dikes).

Response: The sub-section 'g' (Design with minimum/maximum capacity) has been removed from the article (lines 513-522).

Line 442: Please check in the whole document the proper use of the word infrastructure versus infrastructures.

Response: This has been checked throughout the article. In general, the word 'infrastructure' is used in plural form (infrastructures), unless we refer to a specific type of system for which we used it in a singular form (infrastructure).

Line 443: How can a limit the limits be defined if they represent two different things which are even measured in different conceptual and physical units?

Response: This claim is stated by Troccoli et al. (2014) in which climate data and its necessity for the energy sector has been studied. As mentioned before (b: Resilient versus robust systems), resistance and resilience in some literature are related concepts which have been comparatively analysed. Here we do not aim to explore how to cope with uncertainties associated with determination of resilience and resistance limits (or limits between them), but rather to emphasize the importance of climate data and understanding the current meteorological variables under climate change, which can be used to predict the impacts of extreme events and climate change impacts on infrastructures.

Paragraph Line 438 to 453: Seems to me after reading it that according to the content, the section and challenge should be referenced as data scarcity rather than predicting long term pressures.

Response: The section has been renamed to ''Data scarcity'' as suggested (line 524).

Paragraph Line 507 to 523: How can the multi-functionality decrease adaptability? Multi-functionality actually aims to increase adaptability. For example, MFFD's aim to make flood defenses livable and profitable. From a risk cost benefit perspective, MFFD's are attractive as they have an added value which increase their benefit term allowing them to have higher safety standards and consequently adapt better to unknown flood events. Increasing the dikes height not necessarily reduces the resilience of a system as once they are breached, they will reduce the magnitude of the shock for locations downstream of the breach. This means that this assumption is again dependent on the system's definition and boundaries.

Response: As stated in this section (lines 592-607), multi-functionality may decrease the adaptability, since multiple functions of a system are all difficult to change over a long time span, so the infrastructures' adaptabity to changes can be reduced since the system can not provide the similar functions and services as before, while adapting to the changes. On the other hand, we also mentioned that multi-functionality could also lead to more adaptability of the system if the system provide different un-intended functions (e.g., closure dikes in the NL, and MFFD program). In the latter case, multi-functionality increases the VIS resilience (which is in agreement with your comment). We hope this explanation clarifies what we meant in this section by the two confronted ideas regarding multi-functionality and resilience of VIS.

Paragraph Line 553 to 563: I suggest including macroeconomic unforeseen situations like Brexit or 9/11 which does not affect the infrastructure directly but still reduces their resilience due to their overuse or lack of maintenance and reduction of maintainer budget. E.g. Road bridges in Italy and railroads in the US.

Response: Very good point! We added your suggestion in lines 643-646 as copied below:

‘‘…and 4) macro-economic unforeseen situations caused by e.g., Brexit, or COVID-19 Virus pandemic which do not affect the infrastructures directly, but still may reduce their resilience due to their overuse or lack of maintenance and reduction of maintainer budget, etc.’’

Line 604: What do you mean by “A later correlation”? Correlation between observed recovery and what else?

Response: We mean a correlation observed in a latter study by Kerle et al. (2019b), (line 735).

Line 619: Grey infrastructure is not necessarily more costly than green projects. Just look at the cost of the Sand Engine, Room for the river or Noordwaard wave attenuation willow. Depending on their function and importance, both gray and green solutions are often dimensioned based on risk-based cost benefit analysis which means that in principle their cost is optimal with respect to their benefits.

Response: To address this comment, we did a textual edition in the lines 750-756 as below:

‘‘Grey infrastructures have little flexibility to adapt to changes, or to transform to a new structure at a disruptive event. Depending on the function and importance, both grey and green solutions are often dimensioned based on risk-based cost benefit analysis, which means that in principle their cost is optimal with respect to their benefits. Nature-based solutions either by themselves or combined with grey infrastructures can provide a more sustained opportunity in increasing resilience of the infrastructures (Browder et al., 2019; Hallegatte et al., 2019).’’

Line 644: If I’m correct, the room for the river didn’t aim to widen the embankments but to widen the conveyance channels and flood plains and maybe strengthening the dikes but that does not mean making them wider either.

Response: The concept aims to accommodate more space for the rivers (through a set of measures) to enable to managing higher water levels during floods. For clarification, this concept has been rephrased in lines 778-779 as below:

‘‘… suggesting to lower and broaden the flood plain and create river diversions, widen the conveyance channels, and provide temporary water storage area, so there would be more room for rivers ....’’

Line 648 to 654: With Tough dikes are you referring to a “unbreachable dikes”? If so, this means that they are designed to withstand events with very large return period. Residual strength is related to the amount of un-accounted strength of conventional dikes for which the failure mechanisms DOES occur but still it does not translate instantaneously as a BREACH. Hence, there is a period in which the dike can withstand the water while being in failure state. Please rephrase it terms of failure mechanism, breach, and flooding. Also note that one thing is damage recovery of the flood defence system and another is recovery of the protected system from a resilience point of view (e.g. GDP, employment, etc).

Response: Tough dikes (taaie dijken in Dutch) does not refer to un-breachable dikes, rather they are types of dikes with high ‘elasticity’ characteristic, and ‘residual strength’, which doesn’t allow the entire structure for an instantaneous breach while the failure mechanism does occur, or when breaching occurs partially in some parts of the structure. So, as you mentioned, there is a period in which the dike can withstand the

water while being in failure state (with also partial breach). In response to your second point, here we mean damage recovery of the flood defence and its protected area from an engineering perspective (technical resilience of the system shown in Figure 1).

Paragraph 691: the first paragraph of the Other measures section is not really written for alternative measures but for ways of modeling and quantification of resilience. Check if it fits there or not.

Response: To address this comment, title of the section has been renamed to 'Modelling approaches and other alternative measures' in line 827.

Line 714: Systems thinking is by definition an Engineered approach and therefore tittle a) and heading 5.1.2 are contradictory. Ball and cup system heuristics (Holling, Walker, Foster, Carpenter , etc …) is a clear example of how the engineering resilience concept (inspired by engineering approach to design) is based on systems theory which is the basis for systems thinking. I suggest changing the 5.1.2 tittle to non-structural measures, but the question is if this fits the scope of your paper.

Response: Thank you for highlighting this point. Since the core of the article is based on the resilience engineering concept, we prefer to use the engineering label (title 5.1.2) for the technical-related content (e.g., nature based solutions, redundancy creation, etc.).

Addressing your comment on 'system thinking' as an engineered approach, the section (5.1.2 a) has been removed from non-engineering measures, and replaced in the section (5.1.1 a) as an engineering-based measure. Therefore, the section 'engineering-based measures' now starts with (a): System thinking - system of systems approach, followed by the rest (b: Emerging techniques…, etc.). Notably, corresponding to the changes in sub-headings of the section 5, the figure 4 has been modified in the article, page 23.

Line 758: risk assessment is a purely engineering way of designing and assessing. Fault trees and reliability theory are used in all engineering designs and safety assessments around the world.

Response: Addressing this comment, we merged the section 'risk assessment' to the engineering-based measures (e) as alternative measures (line 850-862).

Line 806: Recent literature is reviewed or literatures are reviewed. Choose one.

Response: In more general and commonly used contexts, the plural form will also be literature.

Line 835: remove 'a' so that '…, little appears' and add by in 'by using other measures'.

Response: The corrections have been made as suggested (line 984).

Lune 846: So, the experts provided relevant literature but not opinions? What is the goal of the interviews if the collected responses are not cited, contrasted or discussed in the paper?

Response: This comment has been addressed in the first page of this document.

Line 851: What is the impact of having inter-sectoral dependency? Note that the resilience concept agreement is contextual, system dependent and discipline oriented?

Response: We agree with the reviewer that resilience concept is contextual system dependent, and discipline oriented as we also specifically focused on resilience engineering discipline within VIS. The inter-sectoral dependency affect the resilience of the VIS as such that resilience of one sub-system depends on (or affects) resilience of the other one. To better clarify this, resilience of a particular VIS such as a railway system not only depends on the performance of the system and technical aspects (e.g., engineered

equipment), but also depends on the behaviour of users at the time of disruption and their influence on the resilience of the entire system. Resilience of the built environment in which the system functions and provides services also affects resilience of the entire VIS. Therefore, such an inter-sectoral dependency between resilience of social, technical, and ecological (environmental) sub-systems has an impact on the resilience of the VIS in a specific sector.