

Dear ESD Editors:

Attached is the revised version of our manuscript entitled “Linking Resilience and Robustness and Uncovering their Trade-offs in Coupled Infrastructure Systems” (formerly entitled “How robust is your system resilience?”) in which we have incorporated and addressed the comments and concerns raised by the two reviewers. We wish to thank the editor and the two referees for the constructive comments which improve the manuscript and provide useful ideas for future work.

Our detailed responses to the referees’ comments are below, in a blue font. We wish to highlight some major changes here.

- As explained in our online discussion post, we have added Chitsomanus P. Muneepakul as an author due to her contribution on the new definition of robustness.
- We, naturally, replaced all the results based the old definition of robustness with those based on the new definition.
- One of Referee #2’s suggestions prompted a discussion among the authors, which resulted in the title being changed to “Linking Resilience and Robustness and Uncovering their Trade-offs in Coupled Infrastructure Systems.”
- We followed the suggestion by Referee #1 and included a figure from Muneepakul and Andries (2017) in the Appendix. This inclusion makes the present work more self-contained.
- Throughout the manuscript, we have revised the language to be more careful and precise in using such terms as “disturbance,” “uncertainty,” “scenario” and “setting.”

Our point-by-point responses to other comments are listed below. With these revisions, we believe the manuscript is much improved and now ready for publication. We again thank the editor and reviewers for their constructive and useful comments. Please do not hesitate to let me know if you have questions.

Sincerely,

Mehran Homayounfar

On behalf of all authors

Response to Referee #1

This is an original research article that proposes two novel metrics of robustness and resilience. The authors identify a continual challenge with robustness and resilience: both these properties may require contextualization. That is, how is robust and/or resilient X to Y. Here, the authors evaluate the relationship between their two novel measures of robustness and resilience.

Specifically, they explore trade-offs. So not just how does X or Y change as a consequence of changing inputs or assumptions. This has the potential for some significant impact. The authors in the original submission argue that robustness is the more straightforward property to measure.

Since submission the authors have effectively submitted a correction in that they have identified a limitation - or at least undesirable property – of their definition of robustness. Consequently, I am not able to evaluate the quantitative elements of the manuscript. Instead, I consider some general then specific points.

General comments

- 1- The work is based on a previously published model. To aid the reader in understanding the model I would suggest reproducing Figure 1 from Muneepeerakul, R. and Anderies, J.M., 2017. Strategic behaviors and governance challenges in social-ecological systems. *Earth's Future*.

Response 1-1. Thank you for this suggestion. We have now included Figure 2 from Muneepeerakul and Anderies (2017), which is more explicitly connected to the equations, in Appendix.

- 2- P7 L4 “She may also be concerned about other system properties, e.g., productivity, user participation, etc. As more dimensions are considered, the set of Pareto- optimal policies grow. In the same spirit as that of the work done here, these other dimensions should be defined rigorously.”

This is not a criticism of the manuscript, more of a general observation: defining and including other properties and so adding other dimensions introduces the potential of adding very different measures to the framework. The problem of evaluating “apples to pears”. But beyond that there will be unavoidable normative inputs. As the authors note “she may also be concerned about other systems properties”. How much which will she concerned? What respective weightings would be given to such concerns? Given freedom to weight different factors, there are potentially a very large number of Pareto-optimal solutions. The authors propose a way to transparently link potentially different properties within a single (or at least well defined) CIS. Explicitly identifying trade-offs is a potentially valuable approach. Rather than address this at the end of the paper Discussion and conclusions, perhaps it could be worked into the paper’s main set of motivations?

Response 1-2. We share the reviewer’s perspective that indeed considering resilience and robustness together is like comparing apples to pears. This is why our analysis stops at the Pareto frontier—without giving relative weights to either property. In other words, we simply present a fundamental tradeoff between two very different properties, and it is up to the policy maker who “gives weights”—either explicitly by giving numeric weights to these properties or implicitly/subconsciously by the act of selecting a policy. If the weights are given, this problem will reduce to an optimization problem, and the rich nature of tradeoffs would be lost or at least overshadowed. As the reviewer pointed out, it is the tradeoffs that we wish to highlight. In fact, we already included the need to identify such tradeoffs as one of our motivations for this study (P2, L6).

- 3- P7L7 “In the present study, the governance structure, represented by a policy (a combination of C and y), is fixed. A natural next step is to explore if a policy is allowed to change, how

one may improve the resilience and robustness of a CIS and/or alter the nature of their tradeoff.”

This is another potential valuable contribution. If one possible impact of this work is to inform policy, then there needs to be an ability to evaluate changes and adaptations of policy in the light of new knowledge. How robustness and resilience changes over time as a consequence of changing policy is a very important research question. I think the authors could argue that in the absence of transparent measure and metrics, attempts to explore adaptive policy may be importantly limited.

Response 1-3. Thank you very much for this comment. We have inserted a sentence along the suggested line into the Discussion (P8, L20).

Specific comments

1- “The concepts of “resilience” and “robustness” have grown considerably in popularity as desirable properties for a wide range of systems. Terms like “resilient communities” and “robust cities” have been used more frequently in public discourse.”

This requires some evidential support. I also note that some of the key literature is potentially missing. For example, for a discussion on resilience on social-ecological systems, I would expect a reference to material such as Folke, C., 2006. Resilience: The emergence of a perspective for social-ecological systems analyses. *Global environmental change*, 16(3), pp.253-267. This would help address the first point as this article alone has been cited over 4300 times. Also, more recent work may be required. Holling (1973) is used to initially define resilience. The literature review stops at around 2006/7. Much work has been done since then. Another Folke paper for example: Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T. and Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and society*, 15(4).

Response 1b-1. The suggested references and several additional ones are now cited. Thank you for your suggestions.

2- P1 l29 “Robustness may very well be a desirable property of a system, but it seems to come with a price.”

The article is importantly about trade-offs. Perhaps also useful to simply point out that this may be an example of no free lunch? Wolpert, D.H. and Macready, W.G., 1997. No free lunch theorems for optimization. *IEEE transactions on evolutionary computation*, 1(1), pp.67-82.

Response 1b-2. Thank you for this suggestion. The suggested reference is now cited.

3- P2 footnote - I would propose this text is integrated into the main text. Clearly and consistently define all terms.

Response 1b-3. The text has been moved into the main text (P2, L22).

4- P2 L16 SES is not defined.

Response 1b-4. It is now defined. Thanks for catching this.

5- P3 L7 typo: “(cite report of engineers)”

Response 1b-5. Properly cited now. P3, L14.

6- P4 l14 “Routh-Horowitz” this is either a typo “Routh-Hurwitz” or the authors are referring to some other work. In either event, a citation is required here.

Response 1b-6. The spelling is corrected, and relevant references cited. P4-L30.

7- Caption text for Figure1 and Figure 2 require explanation of star symbol.

Response 1b-7. The figure captions now include “the black star in panels (a), (b), and (c) indicate the policy with the highest R_{PPC} , $R_{Stability}$, and R_{System} , respectively.”

8- Figure 4 red dots are very hard to see. Also bear in mind that RGB colour blindness may mean it is not possible to discern the difference between the red and blue.

Response 1b-8. This figure does not need to be in color. We have replaced the red dots with bigger, black dots, and the blue dots with smaller, gray dots.

Response to Referee #2

The present manuscript focuses on the relevant concepts of 'robustness' and 'resilience'. The authors revisit the concepts and aim for their proper quantification as well as study the connections between them. In doing so, they present an analytical framework based on a stylized dynamical model [proposed by Muneepeerakul and Andries (2017)] that realizes a conceptual framework for socio-ecological systems [coupled infrastructure systems (CISs)] to formulate the setting for their proposals and analyses presented in the manuscript.

The authors set forth the boundaries of conditions for the sustainable operation of the aforementioned system. The system may collapse by crossing one of the two boundaries relating to: - a scenario where there is an over-arching requirement of investment for maintaining the infrastructure, such that there is not enough revenue from the system. In this case, the system may be abandoned for an alternative one, - a scenario where the non-trivial equilibrium state of the system is unstable representing unsustainable maintenance of public infrastructure.

The authors define the measures of robustness and resilience relating to the above boundaries and study the connections between these measures. This reveals certain trade-offs between robustness and resilience of the system, which they relate to choices of certain policies implemented by social agents (e.g., taxation and investment in public infrastructure), internal stresses and external disturbances of the dynamical model considered.

The scope and results of the manuscript are potentially interesting and motivating. The authors hint at the potential implications of their results in 'understanding the interplay between social

dynamics and planetary boundaries', whereby crossing the latter may drive the system to undesirable regimes. In this regard, the trade-off between robustness and resilience of a system can be particularly useful for assisting decision makers in governing and/or managing CISs. However, the presentation of the results in the manuscript needs improvement. In my opinion, the article is still premature for publication, but may definitely be considered after an appropriate revision. Also, the authors themselves have realized that variance (as used in the present version of the manuscript) is not an apt measure of robustness since it weighs above mean and below mean values of resilience equally. Thus, further discussion may be postponed until the revised results are presented in the subsequent version of the manuscript. Specific comments:

- 1- The authors may consider rephrasing the title to: 'Robustness and Resilience - Quantification, Connections and Trade-offs' to have it more precise and well-rounded.

Response 2-1. We have taken the Referee's suggestion into account and modified our title to "Linking Resilience and Robustness and Uncovering their Trade-offs in Coupled Infrastructure Systems."

- 2- Page 2, line number 13: At this point, the authors may add references to more latest approaches in this direction (in addition to the suggestions by Anonymous Referee #1), such as that taken by - Mitra et al. (2015), An integrative quantifier of multistability in complex systems based on ecological resilience, *Scientific Reports*, 5, 16196.

Response 2-2. The suggested reference and additional ones are now cited. (P2, L18)

- 3- Page 3, line number 19: Why are these two conditions referred to as 'boundaries'? Please motivate or rephrase the terminology.

Response 2-3. The two conditions *dissect* the PIP decision space (i.e., the C - y plane) into different regions, namely the regions in which the coupled system can be sustained or collapses. Graphically, the two conditions are represented by curves that form the *boundaries* between the sustainable and collapse regions in the decision space.

- 4- Page 3, line number 25: Why only the distance to the boundaries is considered as an effective measure here? What about the overall dynamics of the system within the phase space, or what about engineering resilience?

Response 2-4. The Referee is right that there are different facets of resilience. Yes, the engineering resilience, or the recovery-based resilience, is another way that people think of resilience. In this study, we focus on the regime shift-based resilience (traditionally called ecological resilience) and its tradeoff with robustness, which we believe is novel and requires expositional clarity. Presenting several metrics of resilience, let alone studying their tradeoffs with perhaps different kinds of robustness, we fear, would make the arguments too confusing to follow and dilute the key messages we wish to convey. In any event, we have added text to clarify the scope of our work, i.e., the focus on the regime shift-based resilience. P3-L34.

5- Page 5, line number 17: What is the reasoning behind choosing the ranges of uncertainties in 'g' and 'w' that the authors have used in the manuscript, namely, [75, 125] and [0.75, 1.75] respectively? Please state, if there is any physical reasoning underlying the above choice in order to motivate the reader about the same.

Response 2-5. This is a theoretical study that highlights the interplay and tradeoff between resilience and robustness. The model is not based on any particular system, but rather a generic one. The ranges of g and w were simply chosen so that the ranges of results exhibit the pattern of the resilience-robustness tradeoff well. There was no physical reasoning behind the parameter ranges beyond that.

Technical comments:

1- Page 2, line number 16: Please abbreviate SESs prior to their use at this point and thereafter.

Response 2b-1. Done.

2- Page 3, line number 8: Please insert an appropriate reference here ;).

Response 2b-2. Properly cited now. P3-L14.

3- Page 3, line number 12: 'of' which 'the' key variables...

Response 2b-3. That clause has been removed.

4- Page 4, line number 14: Is the Routh-Hurwitz stability criterion being referred to here? If yes, the necessary correction should be made along with the inclusion of a reference in this regard.

Response 2b-4. The spelling is corrected, and relevant references cited. P4-L30.

5- Page 9, line number 14: The word 'brief' should read as 'briefly'.

Response 2b-5. Accordingly changed.

6- Page 9, line number 16: 'Eq's (1, 4 and 5)' should read as 'Eqs. (A1, A4 and A5)'.

Response 2b-6. Accordingly changed.

7- Page 9, line number 22: The comma after 'Muneepeerakul and Anderies' is unnecessary.

Response 2b-7. Removed. P11-L24.

8- Page 9, line number 25: The equation number '(A2)' should be indented properly within the same line.

Response 2b-8. Accordingly changed.

9- Page 10, line number 2: Which Fig. 1 do the authors refer to here - of the manuscript under consideration or that of Muneepeerakul and Andries (2017)?

Response 2b-9. A figure from Muneepeerakul and Andries (2017) has been included in the Appendix as Figure A1 and is now referred to properly.

10- Page 10, line number 3: 'The' should not be capitalized.

Response 2b-10. Accordingly changed.

11- Page 10, line number 13: 'Replicator' should not be capitalized.

Response 2b-11. Accordingly changed.

12- Page 10, line number 24: 'Eqs. 1, 4 and 5' should read as 'Eqs. (A1, A4 and A5)'.

Response 2b-12. Accordingly changed.

13- This is a general comment concerning all the figures presented in the manuscript. The resolution of all the figures has to be substantially improved in the revised version of the manuscript. The 'x' and 'y' labels of the figures should be made larger in certain figures as well as the sizes of the texts associated with the colour bars in certain figures where they appear.

Response 2b-13. We have replaced some of the figures with those of better quality.

14- Figure 1: What do the stars represent?

Response 2b-14. The figure captions now include "the black star in panels (a), (b), and (c) indicate the policy with the highest R_{PPC} , $R_{Stability}$, and R_{system} , respectively."

15- Figure 2: What do the colours in Figure 2(a) represent - the standard deviation (nmu_system)? Otherwise, how are the standard deviations in this figure represented?

Response 2b-15. The colors represent essentially the same information as the surface and contours: red means high resilience and dark blue means low resilience. There are no standard deviations in this figure: each point on the surface and contours represents the resilience metric of the fixed policy under a given social-ecological setting (formerly termed "scenario"—a combination of *fixed g* and *w*—which is determined by evaluating the deterministic dynamical system model.