Questions for resilience assessment

S. Neda Naghshbandi[1], Liz Varga[12], Thomas Dolan[13]

[1] Department of Civil, Environmental and Geomatic Engineering, University College London

[2] Corresponding author l.varga@ucl.ac.uk

[3] UKCRIC Co-ordination Node

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Contents

1 Introduction

This report was produced on behalf of University College London[1] (UCL) for the National Infrastructure Commission[2] (NIC). It was commissioned by the NIC as part of a special study on infrastructure resilience

The following report addressed the need to provide a refined set of hypotheses and questions to enable resilience assessment.

A number of stages were followed, centred on expert appraisal, which culminated in a set of categorised questions and a revised list of hypotheses.

The stages are described in the following sections:

1. Preparation
2. Expert review
3. Analysis and categorisation

2 Preparation

The preparation stage followed the steps outlined below:

Step 1. NIC Problem Definition Report.

The NIC problem definition report specified eight baseline hypotheses and 25 supporting questions as the focus for the study (these are provided in full as Appendix A.)

Step 2. Initial UCL Review of Problem Definition Report.

Prior to undertaking literature review the UCL team reviewed the eight baseline hypotheses and 25 supporting questions specified in the problem definition report. Eight additional questions were proposed, four minor changes to question wording requested, and a minor change to one of the hypotheses suggested by the UCL team. These additions and changes are shown in Appendix A using purple text.

Step 3. Literature Review.

A review of academic and grey literature was undertaken with three main objectives: a) to validate the eight baseline hypotheses and 33 supporting questions (Appendix A) and; b) to identify additional supporting questions for the 8 baseline hypotheses; c) to identify clarifications, as appropriate, to enhance the wording of the baseline hypotheses without changing hypotheses content. Significantly, no additional hypotheses were added following the literature review because that had not been an objective of the literature review,

Full details of the literature review are set out in section 2.1 below. A summary Table of literature review findings is presented in Appendix B. This table does two things: a) links supporting questions to relevant sources identified in the literature review and; b) proposes (in orange text) 19 additional supporting questions drawn from specific literature sources.

Step 4. Expert Workshop Preparation.

The final stage of preparation was to format the 8 baseline hypotheses and 52 supporting questions for use in an expert stakeholder event. The eight hypotheses are shown in Table 1 and are presented alongside the full set of 52 supporting questions in Appendix C.

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[1] https://www.ucl.ac.uk/
[2] https://www.nic.org.uk/

The wording of the eight hypotheses validated from the literature review was used for the stakeholder event. As mentioned, this did not substantially change from the original wording and is reported below:

Table 1. Baseline Hypotheses for Expert Workshop

Baseline Hypothesis for Expert Workshop

- H1 More resilient infrastructure systems would make a greater contribution to the Commission's objectives

- H2: Resilience of infrastructure systems is not dynamically optimal for both regulated and publicly owned sectors.

- H3: We don't know about the risks (black swans), including future changes.

- H4: We don't identify the "right" interventions

- H5: There is a lack of coordination.

- H6: Stakeholders are not satisfied with the current level of infrastructure resilience.

- H7: Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability).

- H8: The relative resilience of different parts of the system is different

2.1   Literature search

A partial Systematic Literature Review (SLR) was the method used to validate the original hypotheses and supporting questions. The methodology involved finding relevant academic and grey literatures on the Scopus database, itself a collection of article references. Time constraints limited the depth and breadth of the SLR, hence our description as 'partial'.

Keywords were determined based on the research team's past experience of SLR, knowledge of resilience, and the project scope defined by the NIC. Two search strings based on the study objectives were used to search the Scopus database on 28 March 2019. The searches were structured with the aim of identifying literature that provides a systemic view rather than a specific sector or service or hazard orientation research. The first search identified 11 papers, 5 of which were assessed by the research team as being relevant to the scope of the study. The second search, was broader in scope. It identified 144 total results, 13 of which have been identified as relevant to the scope of the study.

Search string 1:

TITLE ((infrastructure*) AND (national*) AND (resilien*))

Search string 2:

TITLE-ABS-KEY ((infrastructure*) AND (national*) AND (resilien*) AND (system*) AND (framework* OR question*)) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "DECI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "MATH") OR LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (LANGUAGE , "English")) with

3   Expert Review Workshop

A workshop for expert infrastructure practitioners (henceforth experts) was held on 3rd April 2019 with the primary purpose of validating the 8 Baseline hypotheses (Table 1) and 52 supporting questions (Appendix C) detailed in section 2.

However, before workshop attendees (henceforth experts) were provided with the hypotheses and question list, they were invited to capture and share their resilience insights and assumptions through a Free-listing exercise and plenary discussion.

3.1   Free-listing

In Free-listing an individual or group of people think of mental inventory of items within a disposed category (Quinlan M.B., 2017). It is a good way to explore common understanding: it exposes cultural "salience" of singular notions within groups, and variety in individuals' current knowledge opposite to groups. This semi-structured method can help to determine the scope of the domain while producing some vision about how the domain is structured.

For an effective Free-listing outcome, the UCL research team directed the research topic with some initial general questions. Participants received broad help to unpack mental subcategories. Researchers cross-checked Free-list feedbacks. With appropriate attention to detail, Free-listing accumulated high quality data. Among responses, some items will show up more frequently than others as they are more central to the perception than others. An important feature of Free-lists is that item occurrence frequency across people is relevant to its rank and both reflect the salience of an item (Sinha, R., 2003).

In the Free-listing exercise, experts were invited to reflect individually on the five questions in Table 2, and to write their answers on post-it notes (one answer per post-it note). The post-it notes produced were used to support all subsequent workshop stages.

Table 2. Knowing Resilience – Free-listing Exercise Questions

> Questions for Free-listing Session 1 – Knowing Resilience
>
> 1. Why should infrastructure services be resilient? (valuing resilience)
>
> 2. How resilient is/are the service/s relevant to your work? (measuring resilience)
>
> 3. Does it matter to what they are resilient? (hazards)
>
> 4. Do you know the key vulnerabilities? (vulnerability analysis)
>
> 5. Why is the business case for resilience difficult to make? (investment)

3.2   Plenary Discussion

For each of the five Free-listing exercise questions (Table 2), experts were invited during plenary discussion to share and discuss their comments with other experts. These were captured on flipcharts and have been checked for consistency with the post-it-notes (Appendix D).

3.3   Merge and reconcile

The eight hypotheses and 52 supporting questions were shared with experts at this stage in the workshop. Each Hypothesis and supporting question set were printed on a separate A3 sheet in the format shown in Appendix C. The 8 hypotheses were distributed across three groups as follows:

Group 1: Hypotheses 1, 6, 7

Group 2: Hypotheses 2, 5, 8

Group 3: Hypotheses 3, and 4

Experts were invited to compare and contrast their initial thoughts against a set of prepared questions and determine which to take forward. The points made (and available on post-it-notes) were merged and reconciled with the prepared hypotheses and questions. Differences were highlighted on A3 sheets (these have been recorded in Appendix E).

3.4   Critical appraisal

Experts were invited to work in pairs to critically appraise one of the baseline hypotheses that they had discussed during 3.3. The experts were specifically asked to propose improvements to the wording of the hypotheses and identify What needs improving to address each of the following issues for the hypothesis they were critiquing:

– Cognitive bias

– Inclusion (avoiding marginalization)

– Ambiguity

– Superiority/assumed narratives of "what's best"

– Challengeable/un-evidenced claims

– Is anything missing?

Comments were captured on the same A3 sheets used in part 3. Findings from 3.3 and 3.4 are presented in a series of tables in Appendix E.

4   Analysis and categorisation

4.1   Review and Refine

Post Expert review, the research team used findings and recommendations from the expert review to redraft the questions and hypotheses, and identify additional questions (Appendix F).   The following principles were used:

Hypotheses must be falsifiable statements. This requires the hypotheses to have:

- clear wording
- single focus
- simplicity
- unambiguity
- not framed as questions

Questions should be

- simple
- unambiguous
- not leading
- single focus
- use as little technical jargon as possible

4.2 Grounded Research Analysis

The research team then clustered the revised questions using grounded research to examine each question in turn and classified it according to its primary motivations. This categorisation exercise allowed the removal of duplicate questions which emerged twice in the original expert review, and supported identification of six broad question categories:

1. Clarity in meeting NIC objectives
2. Value, benefits and perceptions
3. Planning and preparedness
4. Assessment/knowledge/measures for performance/efficiency and resilience
5. Skills and capabilities for implementing resilience
6. Strategies and inventions

Each of which is described below. The questions by categorisations can be found in Appendix G.

4.2.1 Clarity in meeting NIC objectives

The strategic objectives for the NIC and set by UK Government, are to support:

- sustainable economic growth across all regions of the UK
- improve competitiveness
- improve quality of life

It is, therefore, strategically important that there are clear lines of argumentation connecting the resilience of infrastructure services with NIC strategic objectives.

4.2.2 Value, benefits and perceptions

Public perceptions and expectations in terms of infrastructure resilience formed the next category. The questions extended to the value of resilience, the benefits of resilience, and tolerable reductions in services. Business and emergency responder needs and satisfaction were also considered.

4.2.3 Planning and preparedness (for disruption and recovery)

A number of questions related to planning, risk management, and emergency planning and response.

4.2.4 Assessment/knowledge/measures for performance/efficiency and resilience

A great number of questions concerned the knowledge and techniques available to measure the resilience of infrastructure services. There was significant discussion on the trade-off between performance/efficiency and resilience. Behavioural and sectoral differences are also highlighted.

Assessment is closely connected to the ability to make business cases for investment in resilience, and what should and should not be considered in evaluation of resilience.

4.2.5 Skills and capabilities for implementing resilience

Questions concerning capacity and capabilities, as well as the use of resources, are a distinct category.

4.2.6 Strategies and inventions

Strategies for implanting interventions, including mechanisms, standards, designs were included in the final category.

4.3 Gap Analysis

A gap analysis was undertaken between the questions listed Appendix G, and the original NIC Problem Definition document on 23rd April 2019. A number of key words, terms or concepts were identified as having been present in the original problem definition document, but absent from the questions presented in this spreadsheet. These were:

- Policy, regulation, governance
- Barriers to resilience
- Counterfactuals
- Opportunity cost / cost of inaction
- Long term perspectives
- Wider Frameworks for action
- Security

The gap analysis statement was created (Appendix H).

4.4   Reconcile Hypotheses with Question List

The final stage of analysis was to undertake an exercise to couple each question in the final list of 118 questions (Appendices G and H) with the most up-to-date iteration of the wording for the hypotheses supplied by the NIC on 24/04/2019 (Appendix I).

The objective of the reconciliation was to couple each question with one and only one of the hypotheses.

The reconciliation concluded that it was only possible to assign 71 of the 118 questions to the latest iteration of the hypotheses set. Meaning 47 of the questions collated through various stages of the research were not assigned to a hypothesis.

Based on this analysis, the research team proposed two complementary hypotheses to extend the scope of the initial hypotheses (Table 3). The final set of hypotheses and questions is reported in Appendix J.

Table 3. Complementary Hypotheses Proposal and Explanation

H4.4: We don't identify the "right" interventions for reasons other than those stated in hypotheses 4.1-4.3	Proposed to complement H4.1, H4.2, H4.3. It was proposed because 4.1, 4.2, 4.3 focus on the important topic of Identifying the right interventions, But do not cover all possible reasons for the failure to identify the right interventions.
H5.2: There is a lack coordination of interventions to improve the resilience of infrastructure services	Proposed either to replace and broaden H5 or to complement H5 as H5.2. It was proposed because the lack of coordination for improving the resilience of infrastructure services is an issue far wider than the coordination of investment.

5   Conclusions and next steps

There has been exhaustive iteration and validation of hypotheses and research questions, which has culminated in a well-defined and comprehensive set of hypotheses and questions, enabling the NIC to progress these toward developing potential frameworks to be tested in the main phase of the resilience study. These will be further validated by the NIC using the input from the ongoing consultation and research. This exercise was a collaborative effort between the NIC Secretariat, the project team and an external group of experts.

6   References

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Appendix A – Original Hypotheses and Questions

This appendix lists the eight baseline hypotheses and 25 linked questions specified in the original NIC problem definition report. Additionally, it presents in purple text eight additional supporting questions, four minor changes to question wording and one minor change to hypotheses wording suggested by the UCL team following initial review of the problem definition document.

Hypothesis 1: More resilient infrastructure systems would make a greater contribution to the Commission's objectives of supporting economic growth, increasing competitiveness and quality of life, now and in the future.

- How does infrastructure resilience (or the lack of) relates to competitiveness, economic growth and quality of life? (Logic chain)
- What are the current and future impacts of infrastructure resilience (or the lack of) on economic growth?
- What are the current and future impacts of infrastructure resilience (or the lack of) on competitiveness?
- What are the current and future impacts of infrastructure resilience (or the lack of) on quality of life? (E.g. flooding example)

Hypothesis 2: Resilience of infrastructure systems is not dynamically optimal for both regulated and publicly owned sectors.

- Are investments in infrastructure resilience below the optimum level? (e.g. drought and flooding)
- Are investments in infrastructure resilience above the optimum level?
- Are we not investing in the right things?

Hypothesis 3: We don't know about the risks (black swans), including future changes.

- Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?
- Can the likelihood and impact of risks be accurately measured given interdependent infrastructures?
- Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?

Hypothesis 4: We don't identify the "right" interventions because:

Hypothesis 4.1: Resilience is undervalued in many investment decisions.

- Why resilience is undervalued?
- How is resilience valued?
- Is resilience undervalued due to a regulatory or policy gap?
- Are we not accounting for interdependencies and/or cascading failures?
- Are we undervaluing benefits?
- Are valuing benefits conflated with the value of the services themselves?
- Can the value of benefits be couched in terms of acceptable (scale, scope, length) outages?
- Does efficiency (system cost optimisation) necessarily lead to a system less resilient to extremes?
- Can / how should we value adaptive capacity and optionality?

Hypothesis 4.2: Lack/wrong incentives.

- Are there barriers to strategic, cross-sectoral assessment and planning?
- Are decisions based on public perception, and is this leading to different risk acceptance (eg car vs air safety; natural vs man-made hazards) and often focusing on the short term?
- Political dimension?

Hypothesis 4.3: Capability.

- Is it always clear what the "right" interventions are?
- If the "right" interventions are identified, is there the capability and capacity to implement them?

Hypothesis 5: There is a lack coordination.

- Is lack of knowledge and communication about resilience of infrastructure hindering effective planning and response?

Hypothesis 6: Stakeholders are not satisfied with the current level of infrastructure resilience.

- Is the public receiving enough assurance or support to cope with disruptions?
- Is the public encouraged (or not discouraged) to have unrealistic expectations?
- Are emergency responders satisfied with the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?
- Are businesses satisfied with (or disproportionally impacted by) the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?

Hypothesis 7: Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability). There might be cases in which the resilience investments are disproportionately high compared with the probability of the events.

- Are investments intended to improve resilience unused?
- Can infrastructure operators rely on past experience of disruption events to assess occurrence probability?

Hypothesis 8: The relative resilience of different parts of the system is different (is it a bad thing?)

- If different resilience frameworks are used by different parts of the system, then can the whole system's resilience be known?
- Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?

Appendix B – Hypotheses and Questions Validated Against Literature

This Appendix presents a summary table of literature review findings. Table 4 below:

- links supporting questions to relevant sources identified in the literature review and;
- proposes (in orange text) 19 additional supporting questions drawn from specific literature sources.

Table 4. Literature support for hypotheses and questions

Hypotheses and Supporting Questions	Literature Source
Hypothesis 1: More resilient infrastructure systems would make a greater contribution to the Commission's objectives of supporting economic growth, increasing competitiveness and quality of life, now and in the future.	
How does infrastructure resilience (or the lack of) relates to competitiveness, economic growth and quality of life? (Logic chain)	Mazur, C. et al (2019)
What are the current and future impacts of infrastructure resilience (or the lack of) on economic growth?	Harrop, W. and Matteson, A., (2015)
What are the current and future impacts of infrastructure resilience (or the lack of) on competitiveness?	
What are the current and future impacts of infrastructure resilience (or the lack of) on quality of life? (E.g. flooding example)	
What trade-offs are acceptable when operators must stop critical infrastructure services to prevent cascading effects?	Watanabe, K., (2018)
Do emergency plans assess BIA (Business Impact Analysis) and SIA (Social Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?	Watanabe, K., (2018)
Do we use appropriate ways of analysing national infrastructures? (e.g. complexity based methods)	Amin, S.M. and Horowitz, B.M., 2008 Harrop, W. and Matteson, A., (2015)
Hypothesis 2: Resilience of infrastructure systems is not dynamically optimal for both regulated and publicly owned sectors.	
Are investments in infrastructure resilience below the optimum level? (e.g. drought and flooding)	Mallett, W.J. et al (2011)
Are investments in infrastructure resilience above the optimum level?	
Are we not investing in the right things?	
Are investments targeted at the right part of the national infrastructure to prevent sustained and targeted attacks?	Harrop, W. and Matteson, A., (2015)
To optimise, what trade-off is needed between performance, cost (of investment in resilience) and risk?	Harrop, W. and Matteson, A., (2015)
Is there a way to know the most vulnerable structures? (e.g. to prioritise investment)?	Mallett, W.J. et al (2011)
How do we measure optimal resilience and the effectiveness of risk reduction?	Whelchel, A.W. et al (2018)

Hypothesis 3: We don't know about the risks (black swans), including future changes.	
Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?	
Can the likelihood and impact of risks be accurately measured given interdependent infrastructures?	Harrop, W. and Matteson, A., (2015)
Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?	Watanabe, K., (2018) Harrop, W. and Matteson, A., (2015)
Are a sufficiently wide range of responses available when there is limited information?	Watanabe, K., (2018)
Hypothesis 4: We don't identify the "right" interventions because:	
Hypothesis 4.1: Resilience is undervalued in many investment decisions.	Mallett, W.J. et al (2011)
Why is resilience is undervalued?	
How is resilience valued?	
Is resilience undervalued due to a regulatory or policy gap?	
Are we not accounting for interdependencies and/or cascading failures?	Watanabe, K., (2018)
Are we undervaluing benefits?	
Are valuing benefits conflated with the value of the services themselves?	
Can the value of benefits be couched in terms of acceptable (scale, scope, length) outages?	
Does efficiency (system cost optimisation) necessarily lead to a system less resilient to extremes?	
Can / how should we value adaptive capacity and optionality?	
Have we prioritised the right properties of resilient infrastructure (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?	Watanabe, K., (2018)
Hypothesis 4.2: Lack/wrong incentives.	
Are there barriers to strategic, cross-sectoral assessment and planning?	Watanabe, K., (2018)
Are decisions based on public perception, and is this leading to different risk acceptance (eg car vs air safety; natural vs man-made hazards) and often focusing on the short term?	
Political dimension?	
How can NIC manage conflicting stakeholder incentives so that resilience is assured?	Naghshbandi (thesis)
Hypothesis 4.3: Capability.	
Is it always clear what the "right" interventions are?	
If the "right" interventions are identified, is there the capability and capacity to implement them?	Mazur, C. et al (2019)
Do we need new capabilities (e.g. not just coping capability, adaptive capability, but others such as agile capability)?	TANDRI
Do we know all the skills we need to have adequate resilience capabilities?	Hannan, N.K., (2015)

Can we learn from or collaborate with organisations that have experience and history in managing emergency situations?	Hannan, N.K., (2015)
Hypothesis 5: There is a lack coordination.	
Is lack of knowledge and communication about resilience of infrastructure hindering effective planning and response?	Harrop, W. and Matteson, A., (2015)
Is lack of coordination and trust between government and private sector providers hindering effective planning and response?	Watanabe, K., (2018)
Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?	Watanabe, K., (2018)
Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?	Harrop, W. and Matteson, A., (2015)
Hypothesis 6: Stakeholders are not satisfied with the current level of infrastructure resilience.	
Is the public receiving enough assurance or support to cope with disruptions?	
Is the public encouraged (or not discouraged) to have unrealistic expectations?	
Are emergency responders satisfied with the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?	
Are businesses satisfied with (or disproportionally impacted by) the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?	
What is the basic level of service that safeguards that stakeholders take for granted?	Harrop, W. and Matteson, A., (2015)
Do we have agreeable principles, standards, and designs for infrastructure resilience that meets stakeholders' needs?	Whelchel, A.W. et al (2018)
Is human thinking and action considered sufficiently in resilience assessment?	Amin, S.M. and Horowitz, B.M., 2008
Hypothesis 7: Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability). There might be cases in which the resilience investments are disproportionately high compared with the probability of the events. (tbc)	
Are investments intended to improve resilience unused?	
Can infrastructure operators rely on past experience of disruption events to assess occurrence probability?	
Hypothesis 8: The relative resilience of different parts of the system is different (is it a bad thing?)	
If different resilience frameworks are used by different parts of the system, then can the whole system's resilience be known?	Harrop, W. and Matteson, A., (2015)
Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?	

Appendix C – Hypotheses and Questions formatted for 03 Apr 2019 workshop

This Appendix states the 8 hypotheses and 52 supporting questions used for the Expert workshop on 3rd April 2019

Hypothesis 1: More resilient infrastructure systems would make a greater contribution to the Commission's objectives of supporting economic growth, increasing competitiveness and quality of life, now and in the future.

Questions to demonstrate hypothesis 1:

1.1 How does infrastructure resilience (or the lack of) relates to competitiveness, economic growth and quality of life? (Logic chain)

1.2 What are the current and future impacts of infrastructure resilience (or the lack of) on economic growth?

1.3 What are the current and future impacts of infrastructure resilience (or the lack of) on competitiveness?

1.4 What are the current and future impacts of infrastructure resilience (or the lack of) on quality of life? (E.g. flooding example)

1.5 What trade-offs are acceptable when operators must stop critical infrastructure services to prevent cascading effects?

1.6 Do emergency plans assess BIA (Business Impact Analysis) and SIA (Social Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?

1.7 Do we use appropriate ways of analysing national infrastructures? (e.g. complexity based methods)

Hypothesis 2: Resilience of infrastructure systems is not dynamically optimal for both regulated and publicly owned sectors.

Questions to demonstrate hypothesis 2:

2.1 Are investments in infrastructure resilience below the optimum level? (e.g. drought and flooding)

2.2 Are investments in infrastructure resilience above the optimum level?

2.3 Are we not investing in the right things?

2.4 Are investments targeted at the right part of the national infrastructure to prevent sustained and targeted attacks?

2.5 To optimise, what trade-off is needed between performance, cost (of investment in resilience) and risk?

2.6 Is there a way to know the most vulnerable structures? (e.g. to prioritise investment)?

2.7 How do we measure optimal resilience and the effectiveness of risk reduction?

Hypothesis 3: We don't know about the risks (black swans), including future changes.

Questions to demonstrate hypothesis 3:

3.1 Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?

3.2 Can the likelihood and impact of risks be accurately measured given interdependent infrastructures?

3.3 Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?

3.4 Are a sufficiently wide range of responses available when there is limited information?

Hypothesis 4: We don't identify the "right" interventions because:

Hypothesis 4.1: Resilience is undervalued in many investment decisions.
4.1 Questions to demonstrate hypothesis 4.1:

4.1.1   Why is resilience is undervalued?

4.1.2   How is resilience valued?

4.1.3   Is resilience undervalued due to a regulatory or policy gap?

4.1.4   Are we not accounting for interdependencies and/or cascading failures?

4.1.5   Are we undervaluing benefits?

4.1.6   Are valuing benefits conflated with the value of the services themselves?

4.1.7   Can the value of benefits be couched in terms of acceptable (scale, scope, length) outages?

4.1.8   Does efficiency (system cost optimisation) necessarily lead to a system less resilient to extremes?

4.1.9   Can / how should we value adaptive capacity and optionality?

4.1.10   Have we prioritised the right properties of resilient infrastructure (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?

Hypothesis 4.2: Lack/wrong incentives.
4.2 Questions to demonstrate hypothesis 4.2:

4.2.1   Are there barriers to strategic, cross-sectoral assessment and planning?

4.2.2   Are decisions based on public perception, and is this leading to different risk acceptance (eg car vs air safety; natural vs man-made hazards) and often focusing on the short term?

4.2.3   Political dimension?

4.2.4   How can NIC manage conflicting stakeholder incentives so that resilience is assured?

Hypothesis 4.3: Capability.
4.3 Questions to demonstrate hypothesis 4.3:

4.3.1   Is it always clear what the "right" interventions are?

4.3.2   If the "right" interventions are identified, is there the capability and capacity to implement them?

4.3.3   Do we need new capabilities (e.g. not just coping capability, adaptive capability, but others such as agile capability)?

4.3.4   Do we know all the skills we need to have adequate resilience capabilities?

4.3.5   Can we learn from or collaborate with organisations that have experience and history in managing emergency situations?

Hypothesis 5: There is a lack coordination.

Questions to demonstrate hypothesis 5:

5.1 Is lack of knowledge and communication about resilience of infrastructure hindering effective planning and response?

5.2 Is lack of coordination and trust between government and private sector providers hindering effective planning and response?

5.3 Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?

5.4 Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?

Hypothesis 6: Stakeholders are not satisfied with the current level of infrastructure resilience.

Questions to demonstrate hypothesis 6:

6.1 Is the public receiving enough assurance or support to cope with disruptions?

6.2 Is the public encouraged (or not discouraged) to have unrealistic expectations?

6.3 Are emergency responders satisfied with the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?

6.4 Are businesses satisfied with (or disproportionally impacted by) the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?

6.5 What is the basic level of service that safeguards that stakeholders take for granted?

6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets stakeholders' needs?

6.7 Is human thinking and action considered sufficiently in resilience assessment?

Hypothesis 7: Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability). There might be cases in which the resilience investments are disproportionately high compared with the probability of the events.

Questions to demonstrate hypothesis 7:

7.1 Are investments intended to improve resilience unused?

7.2 Can infrastructure operators rely on past experience of disruption events to assess occurrence probability?

Hypothesis 8: The relative resilience of different parts of the system is different (is it a bad thing?)

Questions to demonstrate hypothesis 8:

8.1 If different resilience frameworks are used by different parts of the system, then can the whole system's resilience be known?

8.2 Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?

Appendix D – Key Points from the Free-listing Exercise

This appendix provides 5 tables to give an overview of the key points from each of the five questions addressed in the feedback from the Free-listing exercise.

Table 5. Free-listing Key Points Overview: Q1 - Why should infrastructure services be resilient?

To meet societal needs	• Whether it runs or not affects people's lives (quality of life) • They are critical to social and economic operational success • Infrastructure services have to be resilient to support societal needs • To ensure continued delivery of services on which the UK public rely • Essential to how our lives run • Because infrastructure underpins society
Cost of failure is high	• Because failure costs are extremely high
Minimize impact on other sectors	• To minimise impact to other sectors and dependencies
Public safety	• Better accountability of private infrastructure operators for resilience plans
Security of supply	• Maintain services through adversity • Part of a social contract. People expect it to run • Resilient infrastructures provide security of supply and maintain global competitiveness • To ensure continued delivery of services on which the UK public rely • Better accountability of private infrastructure operators for resilience plans
Global competitiveness	• Vital to the UK economy • Resilience ensures better running overall not just during extremes • Resilient infrastructures provide security of supply and maintain global competitiveness • Infrastructures provide socio-economic benefits • They are critical to social and economic operational success
For society to trust service provision	• Better accountability of private infrastructure operators for resilience plans
Protect vulnerable groups	•

Table 6. Free-listing Key Points Overview: Q2 - How resilient is/are the service/s relevant to your work?

Recovery from a break	• By what measure? • Variable from recovery within days down to ~ hours
Availability	• Fairly resilient I think • Services are generally very resilient but disruption is public and impactful
Scale dependent	
Service level dependent	• (transport) resilience of services delivered by large transport orgs are on a journey to being resilient
Depends on where/person in the network/criticality	• My work depends on all infrastructures of which the networked systems used daily are not very resilient!
Depends on other services	• My work depends on all infrastructures of which the networked systems used daily are not very resilient!
Depends on perception	• (public perception?) • Reputation •
Nationally falls down infrequently	• Fairly resilient I think • Services are generally very resilient but disruption is public and impactful
Depends on redundancy, e.g. transport is very resilient	• Roads, aviation, maritime – high resilient • Rail – moderately resilient • Transport adequately resilient due to redundancy of networks • Water/waste water: reasonably resilient to known hazards • Telecoms on all the time • Resilience as transport key to many sectors
	• Ensuring resilience allows the economy to run • Quality of attraction for future investment

Table 7. Free-listing Key Points Overview: Q3 - Does it matter to what they are resilient?

Danger – resilience to known risks is risk management	• Depends on likelihood of event and impact of event • May be important in different possible futures
Whether resilience matters in time as resilience is not static	• Resilience is not static – it changes over time (and space)
Extreme events matter to recover	• YES extreme events • It matters for some systems but for the critical systems it should not be context specific
Depends on overloading re design capacity; spatial aspect – don't over design everywhere	• Yes – overloading of capacity
Timing of resilience investment/ adaptation timescale	• Future proofing vs current needs, e.g. for transport, how will connect autonomous vehicles change the way people travel?
Response depends on risk of hazard frequency and impact	• Different hazards require different measures, i.e. digital vs climate
Depends on availability and location of expertise; depends on stakeholder	
It shouldn't matter	• No, conceptually it should be an all-hazards approach • In its finest definition services should be resilient to the "no matter what" • It should NOT matter what the hazard is
In practice need to know to what you are resilient to and in what conditions	• Yes • It does matter – different responses/hardening are needed for different risks • Yes, for planning/testing purposes – a range of scenarios including severe but plausible stress conditions • Yes, infrastructure is a system of systems and each component has to have resilience properties as does the joined up system of systems

In system of systems which is very complex, cannot know all vulnerabilities, e.g. NASA (counter Apollo 13)	• Not really • Yes and no • Focus on specific vulnerabilities reduces resilience
Know frequent ones because they re-occur	• Long-term deterioration • We have good risk assessment procedures but a lack of depth of understanding (transport sector)
Know from stories	• The key vulnerability to networked systems come from natural hazards that cause physical failures and disruption of services • Social upheaval is a key vulnerability that can disrupt the infrastructure services relevant to my work •
Which are key depends on who want to know	• Funding for climate change/adaptive measures
Can't know because of interdependencies	• Most key vulnerabilities are known, some not, some unknowable • Impossible to know them all • End-to-end system architecture across sectors • Data/information sharing across sectors
Failures from interdependencies (cascading)	• Generally but single points of failure (especially in support systems) sometimes found as why fail • (transport) interdependencies not well understood, focus on short term threats
Ability to react is as important as knowing key vulnerabilities	• No, and maybe never will as the system of system evolves: so maybe 'knowing' is not the right term: 'ability' to … • Assume systems and processes will fail and work on that basis
Can't prepare for unknowns	• We know of vulnerabilities but difficult to see ontological uncertainties • Extreme (weather) events • For some resilience questions there are 'unknowns' • The future is uncertain

Media doesn't report on maintenance – it's not a blue ribbon event	• Difficult to make a case for something that has not already failed • Because resilience properties are not well expressed or articulated. • Resilience does not add to usual assessment criteria; if value was used it is easier
It's not difficult if the regulator says you to have to do it; CEOs have primary responsibility for resilience	• Who benefits? Who pays?
If the public has this as an objective it would change private action	• Customer either don't value or value lower price more than higher availability • From a regulators perspective this is relying on luck. We have to challenge that choice in the context of our public objectives
Some industries have it – aviation, nuclear	• Resilience assessment often single sector
The challenge is usually making the cost vs benefit statement	• How do you attribute savings to a disaster that didn't happen? • It's possible for an organisation to choose not to invest in resilience because risks may not crystallise
Cost to add or retrofit resilience is higher than building it in	• Interventions not very innovative
If you take a holistic view of value to elaborate arguments	• Value of resilience not well understood/articulated
Don't have all the data/evidence we need	• Rare events – difficult to quantify impact • Resilience is difficult to measure due to lack of appropriate data and model
What other benefits accrue from resilience? (Maintenance can reduce overall cost of infrastructure)	• Resilience benefit is difficult to quantify
Net Present Value creates a short term focus but infrastructure is long-lived (Privatisation leads to cost reduction)	• Because of economic metrics assuming BAU (business as usual) • Full value of resilience does not fit to economic model • It's easier to make a business case for immediate needs than it is to highlight potential loss and disruption over time
Need to build resilience into design and maintenance strategies, not separate it out;	• Cost of adding resilience to existing networks is high and new builds on the old
Cost reduction after design affects next round of investment	• Because of high cost of increasing resilience unless more sophisticated basis for decision making

Appendix E – Expert Review of Hypotheses and Questions

This Appendix presents feedback on each of the eight hypotheses considered in the Expert workshop breakout sessions.

Table 10. Notes from Discussion and Critical Appraisal of **Hypothesis 1** (discussion by Breakout 3)

Original Hypothesis and Questions Points raised by the group are marked with superscripts ([a-c]) and associated highlights. These points are elaborated in the next row of this table. H1: More[a] resilient infrastructure systems[c] would make a greater contribution[a] to the Commission's objectives of supporting economic growth[b], increased[a] competitiveness and quality of life now and in the future. • **How does infrastructure resilience** (or the lack of) relates to competitiveness, economic growth and quality of life? (Logic chain) • What are the current and future **impacts** of infrastructure resilience (or the lack of) on economic growth? competitiveness? quality of life? (E.g. flooding) • What **trade-offs** are acceptable when operators must stop critical infrastructure services to prevent cascading effects? • Do emergency plans assess **BIA (Business Impact Analysis) and SIA (Social Impact Analysis)** sufficiently well to prioritise competitiveness, quality of life and economic growth?
Points Raised by Group [A] More than what? – What is the baseline? – should there be an integrated baseline assessment? - what should the methodology be? – what indicators would be needed? – how do these relate to the three NIC strategic objectives? [B] this objective when worded in full emphasizes sustainable and across all regions of the UK, neither should be lost when simplifying the wording of the objective [C] It was strongly recommended that the focus be on the SERVICES or outcomes that the system enables, and not the system itself. SERVICE more readily enables a focus on the purpose of the infrastructure and the interdependent system as a whole involved with the provision of the service than the word system, which can too easily be reduced to referring to a specific sector or specific asset.
Cross Referencing with Free-listing exercise Three post-it notes were added to the chart based on responses to Free-listing question 1 (see Table 2) [*question 1 Why do you want your service to be resilient?*]. These notes were: - To keep communities connected - Economic sustainability - Quality of life in developed + developing services/countries
Comments from Critical Appraisal Exercise None captured
Proposed rewording for Hypothesis More resilient infrastructure <u>services</u> would better <u>enable</u> increased economic growth, competitiveness and quality of life now and in the future
Proposed rewording for Questions The group focused exclusively on the hypothesis in the time allowed

Original Hypothesis and Questions

Points raised by the group are marked with superscripts ([a-h]) and associated highlights. These points are elaborated in the next row of this table.

H2: Resilience of infrastructure systems is not dynamically optimal[a] for both regulated and publicly[b] owned sectors.

- 2.1 Are investments in infrastructure resilience below/above the optimum level[c]? (e.g. drought and flooding)
- 2.3 **Are we not investing in the right things[d]?**
- 2.4 **Are investments targeted at the right part[d] of the national infrastructure to prevent sustained and targeted attacks?**
- 2.5 **To optimise, what trade-off[e] is needed between performance, cost (of investment in resilience) and risk?**
- 2.6 Is there a way to know the most vulnerable structures? (e.g. to prioritise investment[f])?
- 2.7 How do we **measure optimal resilience[g]** and the effectiveness of risk reduction[h]?

Points Raised by Group

[A] Hypothesis 2: **Interpret what optimal means**? Updating the optimal every time? For now, or next year? Never Optimal! Does optimal include cost? **Cost and value optimal**? Value of what? How do you value resilience?

[b] Hypothesis 2: What is the reason to put the words **"Regulated and publicly"**? What do you mean by them? What about **private investment**? Private sectors need to be there as well.

All sectors are mixture of privately owned businesses and publicly own businesses and publicly owned government department.

[c] Q 2.1: We do not have a good understanding of cost and resilience right now we can **quantify how much we do spend, but how much the value is**? There are deep questions without answer about **Social value? Environmental value?**

You can find Cost to different sector but not in complete whole! We cannot really know that.

What is the Benefits? People measure benefits in terms of Direct damages to something but the wider system losses generally are not quantified.

Not worth discouraging the commission from the aim of optimal. With a right level of research, we could manage start quantifying values. **Intervention:** We need **to have measures called Resilience capital** that reflect all of these. it is doable require lot of work just need good investment. [d] Q 2-3: That MP who has the political power to force resilience spending through one means or another will be pushing for that to be increased. That is kind of our feedback and evaluation system. **Those who shout louder are those who get the most resilience!** which is not necessarily an optimal way of doing things for society. In public sector you have **the risk of very small effectual section having the larger say.**

[e] Q2-5: Resilience is always a trade off! **you cannot afford complete and perfect resilience** (truism). you can always have less than complete. You always **trading off how much do you spend against what is going to be wrong.**

[f] Q2-6: **It is Different from being commercial rather than being completely regulated or government funded**! The calculation about resilience would be how much compensation do you

pay to how many customers if sth fails? The cost of paying compensation will be compared to the cost of resilience.

[g] **Q 2-7: Optimal to what?** Optimal for certain sections is different! If things are Imperfect! Perfection is impossible! In the human system people can make mistake!

Can we define optimal? does Optimal matter?

[h] **Q2-7: Plan Adaptation**! We have very Reasonably CPA team for predictions.

They have **various level of predictions for different scenarios**. you can choose to invest according to one or another scenario to adapt to risk! which scenario you choose? It should be based on the estimation of which kind of those can be happen?

Intervention: We might build a well-defined level of cost for each scenarios! each scenarios can be costed! **Investment decision is political and difficult to quantify**! justify each different decision based on specified cost.

Cross Referencing with Free-listing exercise

Post-it notes were added to the chart based on responses to Free-listing questions 1, 3 and 5 (see Table 2). These notes were: [*question 1 Why do you want your service to be resilient? Question3 Does it matter to what? Question5 Why is the business case for resilience difficult to make?*].

-   Q1: Societal and environmental value
-   Q1: Trade-off between resilience value and cost of failure
-   Q3: Adaptation Plan for different scenarios
-   Q3: Depends on Stakeholders: public or private sector
-   Q3: Responses depends on risk
-   Q3: Need to plan what you are resilient to
-   Q5: Cost of resilience is higher
-   Q5: Private companies have different perspective than public sector

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Comments from Critical Appraisal None recorded

Proposed rewording for Hypothesis

Resilience of infrastructure systems is not appropriately valued for both publicly regulated and privately owned sectors.

There is a lack of appropriate investment on infrastructure resilience within both publicly regulated and privately owned sectors.

Proposed rewording for Questions

-   New Questions: Is The cost of the resilience lower than the cost of disaster a good way to define value ?!
-   Question: do we need to consider How much the value (Including social and environmental values) is rather than how much we do spend?
-   Question: what is the value of avoiding the lost or cost of disaster?
-   Question: What is the Benefits? How to quantify the wider system losses generally rather than just measure the cost of direct damages?

Table 12. Notes from Discussion and Critical Appraisal of **Hypothesis 3** (discussion by Breakout 1)

Original Hypothesis, Questions and Answers

Answers to these questions are shown in blue. Points raised by the group are marked with superscripts ([A-E]). These points are elaborated in the next row of this table.

H3: We[A] don't know[B] about the risks[C] (black swans), including future changes[D].

- Q1 Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?
- Q2 Can the likelihood and impact of risks be accurately measured given interdependent infrastructures?
- Q3 Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?
- Q4 Are a sufficiently wide range of responses available when there is limited information?

3.1 Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?

- We should be doing this but are not. NIC must major on resilience
- Resilience must be furthest up political tree, need NIC/NIP to act as strategic gate keeper
- From a sectoral perspective, will have impact. Initiatives on (digital) transformation are a problem for funding cycles, e.g. lack of on knowledge on how CAV (connected autonomous vehicles) will pan out
- Not using resilience at the highest level
- Doesn't say which dimension of resilience – needs to be specific.
- There is uncertainty about future risks and opportunities which may impact infrastructure resilience

3.2 Can the likelihood and impact of risks be accurately measured given interdependent [7] infrastructures?

- No.
- Knowing (measuring) and achieving resilience have a large disconnect.
- Models are built top down and don't accommodate for example train driver behaviour
- Sector interdependency analysis is missing
- Need to re-assess touch points
- Uncertainties
- There are conflicting structures in place to describe failures
- Can assumptions be made on standards?
- Could allow for major failure
- Future changes may compromise infrastructure resilience

3.3 Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?

- No
- Changes may improve resilience but smart motorways don't
- Information low helps the public become more accepting
- How to communicate risks is not clear

3.4 Are a sufficiently wide range of responses available when there is limited information?

- This refers to elasticity across modes of transport
- How much support is there within a sector and also across sector boundaries
- 'Weather resilience' response, such as drones and use of artificial intelligence (AI) on response delay

- What are the incentives for one provider to another, e.g. contamination of water supply in a town (Christchurch) – how do people get potable water?

Points Raised by Group

These points are from both the cross referencing with the Free-listing exercise and the critical appraisal exercise

- Infrastructure resilience is the ability of transport, energy, telecommunications and water and waste systems to collectively provide services even when chronic stresses or acute shocks occur
- Risks are hazards to which a system is vulnerable

[A] Who are 'we'?
[B] The statement 'don't know' is binary – can we do something about it?
[C] Risks needs to be wider – include opportunities
[D] Need to unpick – how is the future knowable? Scenario approaches; climate technology
[E] Importance of understanding interdependencies – dynamic changes over time

Proposed rewording for Questions

- The consequences of known changes, such as those in the National Infrastructure Plans, and partially known changes, such as Connected Autonomous Vehicles, are not reviewed for their effects on infrastructure resilience
- Interdependencies in infrastructure change dynamically over time and are not well understood, so the likelihood and severity of risks upon infrastructure resilience cannot be easily determined.
- The consequences of controllable changes and continuous improvement are not assessed for resilience before being adopted
- Are a sufficiently wide range of responses available to deliver infrastructure resilience when there is limited information?

Original Hypothesis, Questions and Answers

Answers to these questions are shown in blue. Points raised by the group are marked with superscripts ([a-h]) and associated highlights. These points are elaborated in the next row of this table.

H4.1: We don't identify the "right" interventions because Resilience is undervalued in many investment decisions[A, B, C]

Q1: Why is resilience is undervalued?[D]

- It's not quantifiable
- Total value cannot be measured as it includes indirects, social, economic, etc.
- Its value is not fully understood
- We can't get to the level of details that people use infrastructure services

Q2: How is resilience valued[E]?

- There is no metric
- Resilience is not just business continuity
- It depends on public perception of it
- Politics changes public perception
- Could learn from countries on how they cope and where they target to improve resilience
- How can we value the resilience of mature infrastructures when they are changed? e.g. smart motorways
- There is a reputational impact on operators
- There is a consequence for willingness to pay

Q3 [F] Is resilience undervalued due to a regulatory or policy gap?

- Industrial disputes compromise resilience
- The separation of the functions of infrastructure means it is not perceived as an integrated whole

Q4: Are we not[G] accounting for interdependencies and/or cascading failures?

- Our knowledge of cascading failures is inadequate
- Work on EARTHEX expands on interdependent infrastructures

Q5 [H]Are we undervaluing benefits?[I]

- How can we value benefits?
- Not all benefits are monetary

Q6: [J]Are valuing benefits [K]conflated with the value of the services themselves?

- The benefits of resilient infrastructure are not explicitly communicated

Q7: Can the value of benefits be couched [L] in terms of acceptable (scale, scope, length) outages?[M]

- Acceptable outages need describing
- Design to 'kill' vs comm'n?
- Pre-warning of outages by providing customer information

Q8: Does efficiency [N](system cost optimisation) necessarily lead to a system less resilient to extremes?[O]

- Yes. Redundancy and efficiency are two ends
- When is system optimised? After build?
- What new project is designed with resilience in mind?
- Some good international examples: Dubai, Singapore, Beijing

Q9: [P]Can / how should we value adaptive capacity and optionality?
• Yes we should • We don't know how
Q10: Have we prioritised the right properties[Q] of resilient infrastructure (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?
• Keep safety separate • Consider graceful failure • Consider elasticity • Wood – graceful extensibility
Points Raised by Group These points are from both the cross referencing with the Free-listing exercise and the critical appraisal exercise - [A] Questions should be open-ended – no yes/no framing - [B] Is the right question (how can) resilience be included in investment decisions? - [C] Interventions pre or post disaster? 4.1 and 4.3 seem different - [D] is it … if so why? - [F] 1.1.2 and 1.1.3 is there a bias leading to think that resilience is undervalued because of regulatory or policy gap? - [E] quantified? - [G] Delete 'not' - [H] Consolidate 1.1.1 and 1.1.5 - [I] Reword - How are we valuing benefits? - [J] Difficult to understand point - [K] Reword – Is the value of benefits - [L] Unclear – needs to be open ended - [M] Reword – can acceptable outages be defined in terms of value of benefits? - [N] How are resilience and efficiency related? - Capacity – is it resilient? How does redundancy fit? - [P] Too detailed – could it be merged with 1.1.10 - [Q] Should resilience be articulated in terms of its different properties?

Table 14. Notes from Discussion and Critical Appraisal of **Hypothesis 4.2** (discussion by Breakout 1)

Original Hypothesis, Questions and Answers

Answers to these questions are shown in blue. Points raised by the group are marked with superscripts ([a-h]) and associated highlights. These points are elaborated in the next row of this table.

Hypothesis 4.2: We don't identify the "right" interventions because of lack/wrong incentives [A B C]

Q1: Are there barriers to strategic, cross-sectoral assessment and planning?

- Private sector
- Government silos

Q2: Are decisions based on public perception, and is this leading to different risk acceptance [D](eg car vs air safety; natural vs man-made hazards) and often focusing on the short term?

- Yes

Q3 Political dimension?

- What is the will/stated position of the people?

Q4 How can NIC manage conflicting stakeholder incentives so that resilience is assured?[E]

- By communicating/talking
- Thought leadership
- NIC as 'go to' place
- Embed at NIC
- Conflicting objectives across the system
- Who pays and who benefits balance

Points Raised by Group

These points are from both the cross referencing with the Free-listing exercise and the critical appraisal exercise

[A] Biased framing – what are the barriers to incentivizing resilience?
[B] Incentives depend on the economic case for paying for resilience. Who pays?
[C] Consolidate – no point in undertaking resilience independently of public perception and political dimension
[D] Feels superior – may imply public perception is not valid
[E] What are the conflicting objectives the NIC need to manage

Table 15. Notes from Discussion and Critical Appraisal of **Hypothesis 4.3** (discussion by Breakout 1)

Original Hypothesis, Questions and Answers

Answers to these questions are shown in blue. Points raised by the group are marked with superscripts ([a-h]) and associated highlights. These points are elaborated in the next row of this table.

H4.3 We don't identify the "right" interventions because of capability[A][B]

Q1: Is it always clear what the "right" interventions[C] are?

- No, especially if cross functional prioritisation is needed
- Investment decisions at sub-system level may be inconsistent with system level optimisation
- Time inconsistency

Q2: If the "right" interventions are identified, is there the capability and capacity to implement them?

- Yes capabilities
- Not capacity

Q3: Do we need new capabilities[D] (e.g. not just coping capability, adaptive capability, but others such as agile capability)?

- What skills are there
- Needs to be considered at scoping and not post hoc
- Each retrofit is a new project which should consider resilience skills
- Do we need to introduce/foster/require that decision makers/operators/ xxx have different capabilities beyond coping and adaptive capacity?

Q4: Do we know all the skills we need to have adequate resilience capabilities?

- Hard shoulder on motorways - Soft/hard engineering – transform maintainability
- Raised levels protect flooding - "accidental sustainability"

Q5: Can we learn from or collaborate with organisations that have experience and history in managing emergency situations?

- Skills for good engineering should not be a separate module in a degree course
- Needed in professional practice, e.g. ICE
- Need social engagement
- Need systems thinking, 'cultural' and 'change management' to make people change
- Could learn from emergency but not from risk management, on how to cope
- Distributed systems
- Other countries emergency response, e.g. Japan, NZ especially in situations where unknown emergencies arise, e.g. unknown fault line
- UK flooding – from Netherlands
- 'fear' of not repeating 1953 floods

Points Raised by Group

These points are from both the cross referencing with the Free-listing exercise and the critical appraisal exercise

[A] grammar
[B] Is this about resources or resourcefulness?
[C] What does it mean? This is superior/leading
[D] Suggest it is worded into one open ended question – what is the hypothesis here?

Original Hypothesis and Questions

Points raised by the group are marked with superscripts ([a-e]) and associated highlights. These points are elaborated in the next row of this table.

H5: There is a lack coordination[a].

5.1 Is lack of knowledge [b] and communication about resilience of infrastructure hindering effective planning and response?

5.2 Is lack of coordination and trust between government and private sector[c] providers hindering effective planning and response?

5.3 Are there barriers [d] to information sharing among stakeholders in the public and private sectors which reduce resilience?

5.4 Are roles and responsibilities clearly defined[e] across national infrastructure for capability vs desired resilient properties?

Points Raised by Group

[a] H1: There is not any area where there is perfect coordination. So what is the motivation to having this drone on as a special hypothesis?

It sounds like a government problem. Within the government there are various elements of coordination for resilience but when it gets down a few levels more there really is not as much coordination that should be.

[b] 5.1 Lack of knowledge about the interdependencies at lower layers cause the whole system failure. **It has not been planned at organisational level how to face those cascading** failures.

Interdependencies and cascading are good questions to ask. We do not know How much risk is within interdependencies. There is not good **coordination in adaptation for** climate resilience. There is lot of **central work** that does not actually feed out to the rest of government and the rest of society.

[c] 5.2 Coordination not just between government and private sector as well as coordination within government is an issue.

Everybody is interested in how they are effected by everything else nobody ask how we are going to affect other systems as it goes back to the organisations reliability issues.

[d] 5.3 There is lack of correct cross sectors understanding.

NIC tries to do sth for coordination is a good thing but it should not be in a too high level.

NIC recommend we need more coordination! It is not in a sufficient practical level!

Understanding your criticalities is the reason for coordination.

There is a bit of work going on with national service security centre, a knowledge base programme, trying to gather the information about critical infrastructure in every level all sectors including government infrastructure and put it in one data base which is highly secured and

classified, **are they critical and supported by regulators? understanding the whole picture** is probably where UK has a real gap.

Intervention: The benefits is in identifying **the key points** identifying the **key weakness** and how we potentially **fix them**.

It is not enough to just know about interdependencies at one layer up or down but it is required to **start digging down a little bit more further**.

CTS is doing a good job but The problem is **the structure they are working within in.**

[e] 5.4 Lack of coordination has to mater! has to be important! that national infrastructure say sth about coordination.

Understanding those interconnections is nobodies job at the moment so it is NIC's job to do it!

But in the other hand there is also technical CTS's Job. Civil contingencies secretary in main cabinet office. They have the primary job of coordinating civil contingencies and responses within government.

Cross Referencing with Free-listing exercise

Six post-it notes were added to the chart based on responses to Free-listing question 2 and 4 (see Table 2). These notes were:

- Q2: Scale dependent
- Q2: Depends of perceptions
- Q4: Which are key depending on who wants to know
- Q4: Failure from interdependencies (cascading)
- Q4: Ability to react is important to knowing key vulnerabilities
- Q4: Cannot prepare for unknown

Comments from Critical Appraisal

The hypothesis is too obvious and needs to be richer.

The right coordination should be considered within one organization and within government as well rather than just between government and private sector.

Proposed rewording for Hypothesis

None but not happy with it!

Proposed rewording for Questions

- Is lack of coordination and trust within government or between government and private sector providers hindering effective planning and response?

New Questions:

- Is lack of knowledge and communication about different components interdependencies hindering effective planning and response?
- Is the existing and future knowledge (existing database of infrastructure interdependencies) supported by regulators?
- How much risk is within interdependencies?
- How to define an effective coordination within different layers of organisations?
- What will be the mechanism to feed out the central work to government and wider society?

Original Hypothesis and Questions

Points raised by the group are marked with superscripts ([a-g]) and associated highlights. These points are elaborated in the next row of this table.

H6: Stakeholders[c] are not satisfied with the current level of infrastructure[a] resilience[b].
- Is the **public[d] receiving enough assurance** or support to cope with disruptions?
- Is the public[d] encouraged (or not discouraged) to have **unrealistic expectations**?
- Are **emergency responders[d] satisfied** with the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience[e] (as opposed to asking increased infrastructure resilience)?
- Are **businesses[d] satisfied** with (or disproportionally impacted by) the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?
- What is the **basic level of service that safeguards what stakeholders** are taking for granted or their life?
- Do we have **agreeable principles, standards, and designs** for infrastructure resilience that meets stakeholders' needs?
- Would a wider consideration of **human thinking and action** in resilience assessment change decisions/outcomes?

Points Raised by Group

[A] as with Hypothesis 1 it was suggested the hypothesis explicitly refer to SERVICE. The reasons given were the same. SERVICE more readily enables a focus on the purpose of the infrastructure and the interdependent system as a whole involved with the provision of the service than the word system, which can too easily be reduced to referring to a specific sector or specific asset.

[B] It was suggested that this should be RELIABILITY or DISRUPTION rather than RESILIENCE. Resilience as a multi-faceted concept is too broad for a single hypothesis, and that other alternative wordings be considered. It was also suggested that the emphasis given in any answer (i.e. resilience, disruption or reliability) will depend upon who is asked.

[C] Stakeholders was considered not specific enough because no consensus will exist across all stakeholder groups. Stakeholders should be defined, with the caveat that any list will not be exhaustive.

[D] Closely connected to C. Does public, emergency responder and business adequately capture the full range of stakeholders? Other stakeholders for inclusion include:

- Operators
- Owners (both the provider of the service and the owner(s) of the system(s) providing that service)

[E] For purposes of Expectation Management

[F] Cognitive bias [from the critical appraisal] the hypothesis makes the assumption that the current situation is not satisfactory. The hypothesis is leading, but not sure how best to change this.

[G] Ambiguity [from the critical appraisal] it is assumed that everybody uses the word Resilience in the same way

Cross Referencing with Free-listing exercise

None

Comments from Critical Appraisal

Integrated as Superscripts [F and G] above
Proposed rewording for Hypothesis
- Stakeholders are not satisfied with the current level of disruption to infrastructure services
Proposed rewording for Questions
The group focused exclusively on the hypothesis in the time allowed

Original Hypothesis and Questions

Points raised by the group are marked with superscripts (ᵃ⁻ᵍ) and associated highlights. These points are elaborated in the next row of this table.

H7[b c d e]: ~~Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability). There might be cases in which the resilience investments are disproportionately high compared with the probability of the events.~~

- Are investments intended to improve resilience **unused**?
- Can infrastructure operators **rely on past experience** of disruption events to assess occurrence probability?[a]

Points Raised by Group

[a] The group emphatically answered No to this question

[b] The group didn't understand the wording of the hypothesis and crossed the whole thing out

[c] After further reflection and discussion of the intended meaning of the hypothesis, two alternative wordings were attempted (see below)

[d] Risk is one type of Incertitude. Risk management cannot be applied to all incertitude types. Often in interdependent systems it is not possible to either i) confidently attach probabilities to the impacts of disruptive events (incertitude type: uncertainty) or ii) understand how the impacts of disruption will will be cascade across the system, meaning the full range of outcomes or impacts from a disruptive event can't be known (incertitude type: ambiguity) or iii) both I and ii (incertitude type: ignorance)

[e] The hypothesis could be merged with effectiveness of interventions hypothesis

[f] **Cognitive bias** [from the critical appraisal] the hypothesis assumes probabilities will be clear, and can be known and used in a meaningful way. This suggests a bias toward application of risk management techniques even if system complexity make alaetory uncertainty (variation we do not know enough about to apply probability to) and epistemic uncertainty (gaps in knowledge of system characteristics and performance) systemic realities

[g] **Ambiguity** [from the critical appraisal] the hypothesis wording is fundamentally ambiguous and the group struggled to understand it and the crossed it out

[h] **Inclusion (avoiding marginalization)** [from the critical appraisal] two points were raised. The first related to communications and the whether the hypothesis marginalizes those who do not understand probabilities and risk. The second related to who makes the judgement that a resilience investment is disproportionately high compared with the probability of the event, stakeholders with high likelihood of experiencing disruption but little power to influence decisions, must be included in such decisions.

[I] **Challengeable/unevidenced claims** [from the critical appraisal] A semantic point was raised here. By definition challengeable, and not supported by complete evidence. An effective Hypotheses should be worded so that it can be falsified by logical evidence or statistical analysis

[J] **Is anything Missing**? [from the critical appraisal] clarity and purpose. The group thought they understood the hypotheses purpose, but were not certain. It was felt it need revisiting

Cross Referencing with Free-listing exercise *(as written on post-it notes)*
- Historical investments in resilience have not provided value for money?
- Historically investment in resilience has been value-engineered out

Comments from Critical Appraisal Integrated as Superscripts ᴳ ᴴ ᴵ ᴶ above

Proposed rewording for Hypothesis

- Resilient Investments should be driven by tolerance to the impacts of disruption (rather than probability) to services OR
- We do not maximize the value from resilience investments

Proposed rewording for Questions None proposed

Table 19. Notes from Discussion and Critical Appraisal of **Hypothesis 8** (discussion by Breakout 2)

Original Hypothesis and Questions

Points raised by the group are marked with superscripts ([a-c]) and associated highlights. These points are elaborated in the next row of this table.

H8: **The relative resilience of different parts of the system is different**[a] (is it a bad thing[b]?)

- 8.1[c] If different resilience frameworks are used by different parts of the system, then can the whole system's resilience be known?
- 8.2[d] Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?

Points Raised by Group

[a] Yes, obviously. Why we try to get through this because it is a truism. Different parts are different. What is the point in beneath?

The problem we have is in component level, if you look at transport system, rail is very clearly less resilient than road!

Intervention: Design for resilience, the component that will be design for a 1in200 years flood is more expensive and harder to replace compare to the component that will be design for a 1in50 years flood. So the first one should have a higher resilience accommodated within its design.

[b] It is **an inevitable thing**. In a system level? Politically? Hard to say!

The system resilience depends on the weakest link when weakest link failed in a network system the whole system might shut down.

It seems **very obvious**. Have an **equivalent level of resilience** to the system is important.

[c] Is this question actually right? Are different components of a system actually using different frameworks? The framework would be the same.

Trial and error, but it is not the best way to do that.

You upgrade the part of the system that causes you the most problem. This is what is currently have been done.

[d] It still be different. If you boost the weakest point up and move to the nest weakest there still will be differences, you always having different things having different resilience.

It worth to having highly efficient and less resilient systems just for the efficiency value as long as you are not completely critically relaying on the overall way of getting sth done.

Having one highly efficient line and one less efficient but highly resilient, is probably distinct solution! If you can afford it. If you cannot what do you choose? And that is an interesting question!

Cross Referencing with Free-listing exercise

Comments from Critical Appraisal None captured

Proposed rewording for Hypothesis

- Different parts of the system do not have equivalent level of resilience. It is an inevitable thing. OR
- The relative resilience of different parts of the system is different. It is an inevitable thing.

Proposed rewording for Questions

New Questions:

- Is an **equivalent level of resilience** to the system important?
- How you can make it, giving equivalent level of resilience to different part of the system?
- Can you afford having different systems with different efficiency and resilience? (having one highly efficient and less resilient element or having a less efficient and high resilient element)

Appendix F – Hypotheses and Questions reworded Post Expert Input

Current Hypothesis and questions	Rewarded and new Hypothesis and questions
Hypothesis	
Hypothesis 1: More resilient infrastructure systems would make a greater contribution to the Commission's objectives of supporting economic growth, increasing competitiveness and quality of life, now and in the future.	H1: More resilient infrastructure services would better enable increased economic growth, competitiveness and quality of life now and in the future
Questions	
1.1 How does infrastructure resilience (or the lack of) relates to competitiveness, economic growth and quality of life? (Logic chain)	1.1a Do highly resilient economic infrastructure services impact the feasibility of realising:
	NIC strategic objectives (competitiveness)?
	NIC strategic objectives? (economic growth)
	NIC strategic objectives? (quality of life?)
	1.1b Does low resilience economic infrastructure services impact the feasibility of realising:
	NIC strategic objectives? (competitiveness)
	NIC strategic objectives? (economic growth)
	NIC strategic objectives? (quality of life)
1.2 What are the current and future impacts of infrastructure resilience (or the lack of) on economic growth?	1.2a How resilient are current infrastructure services?
1.3 What are the current and future impacts of infrastructure resilience (or the lack of) on competitiveness?	What impact does the current level of infrastructure service resilience (Q) have on NIC strategic objectives? (competitiveness)?
1.4 What are the current and future impacts of infrastructure resilience (or the lack of) on quality of life? (E.g. flooding example)	What impact does the current level of infrastructure service resilience (Q) have on NIC strategic objectives? (economic growth)?
	What impact does the current level of infrastructure service resilience (Q) have on on NIC strategic objectives? (quality of life)?
	1.3 If infrastructure service resilience remains at current levels, what impact will this have for future:
	NIC strategic objectives? (competitiveness)

Current Hypothesis and questions	Rewarded and new Hypothesis and questions
	NIC strategic objectives? (economic growth)
	NIC strategic objectives? (quality of life)
	1.4 If infrastructure service resilience declines in the future, what impact will this have for future:
	NIC strategic objectives? (competitiveness)
	NIC strategic objectives? (economic growth)
	NIC strategic objectives? (quality of life)
	1.5 If infrastructure services were to become more resilient, what impact will this have for future:
	NIC strategic objectives? (competitiveness)
	NIC strategic objectives? (economic growth)
	NIC strategic objectives? (quality of life)
1.5 What trade-offs are acceptable when operators must stop critical infrastructure services to prevent cascading effects?	1.5 What short-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?
	1.5 What long-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?
1.6 Do emergency plans assess BIA (Business Impact Analysis) and SIA (Social Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?	1.6 Do emergency plans assess BIA (Business Impact Analysis) and SIA (Social Impact Analysis) and Environmental Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?
	1.6 Do emergency plans assess SIA (Social Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?
	1.6 Do emergency plans assess Environmental Impact Analysis) sufficiently well to prioritise competitiveness, quality of life and economic growth?
1.7 Do we use appropriate ways of analysing national infrastructures? (e.g. complexity based methods)	1.7 What approaches do you recommend to improve understanding and analysis of infrastructure service performance?
	1.7 What approaches do you recommend to improve understanding and analysis of infrastructure service resilience?

Current Hypothesis and questions	Rewarded and new Hypothesis and questions
Hypothesis	
H2: Resilience of infrastructure systems is not dynamically optimal for both regulated and publicly owned sectors.	H2: There is a lack of appropriate resilience investment within both publicly regulated and privately owned sectors.
Questions	
2.1 and 2.2 Are investments in infrastructure resilience below/above the optimum level? (e.g. drought and flooding)	
2.3 Are we not investing in the right things?	
2.4 Are investments targeted at the right part of the national infrastructure to prevent sustained and targeted attacks?	2.1 Are investments targeted at the right parts of national infrastructure?
2.5 To optimise, what trade-off is needed between performance, cost (of investment in resilience) and risk?	2.2 Can risk be used to target resilience investment?
2.6 Is there a way to know the most vulnerable structures? (e.g. to prioritise investment)?	2.3 Does performance efficiency need to be traded-off with resilience investment?
2.7 How do we measure optimal resilience and the effectiveness of risk reduction?	2.4 How can the effectiveness of resilience investment be measured?
	2.5 When the expected cost of disaster (including compensation) is higher than the cost of resilience then can this indicate a case for investment
	2.6 Should the cost of resilience include social, economic and environmental costs
	2.7 Will indirect costs of disaster be included in cost of disaster?
	2.8 What is the effect of effect on infrastructure resilience when sub-systems have different levels of efficiency and resilience?
Hypothesis	
Hypothesis 3: We don't know about the risks (black swans), including future changes.	H3.1: There is uncertainty about future risks and opportunities which may impact infrastructure resilience
	H3.2: Future changes may compromise infrastructure resilience
Questions	
3.1 Are National Infrastructure Plans (and effects) considered sufficiently in resilience assessment?	3.1.1 Are the consequences of known changes, such as those in the National Infrastructure Plans, and partially known changes, such as Connected Autonomous Vehicles, reviewed for their effects on infrastructure resilience?

Current Hypothesis and questions	Reworded and new Hypothesis and questions
3.2 Can the likelihood and impact of risks be accurately measured given interdependent infrastructures?	3.2.1 Interdependencies in infrastructure change dynamically over time and are not well understood, so can the likelihood and severity of risks upon infrastructure resilience be determined?
3.3 Are the consequences of endogenous or continuous improvement changes in organisations, technology and methods (e.g. smart systems) assessed for resilience before being adopted?	3.2.2 Are the consequences of controllable changes and continuous improvement be assessed for resilience before being adopted?
3.4 Are a sufficiently wide range of responses available when there is limited information?	3.1.2 Are a sufficiently wide range of responses available to deliver infrastructure resilience when there is limited information?
Hypothesis	
Hypothesis 4.1 We don't identify the "right" interventions because resilience is undervalued in many investment decisions.	Hypothesis 4.1 We don't identify the "right" interventions because resilience is undervalued in many investment decisions.
Questions	
4.1.1 Why is resilience is undervalued?	4.1.1 Why is resilience is undervalued?
4.1.2 How is resilience valued?	4.1.2 How are the benefits of resilience quantified?
4.1.3 Is resilience undervalued due to a regulatory or policy gap?	(part of 4.1.1)
4.1.4 Are we not accounting for interdependencies and/or cascading failures?	4.1.3 Are we accounting for interdependencies and/or cascading failures?
4.1.5 Are we undervaluing benefits?	(now part of 4.1.2)
4.1.6 Are valuing benefits conflated with the value of the services themselves?	4.1.4 Can we value the benefits of resilience independently of the value of the services provided?
4.1.7 Can the value of benefits be couched in terms of acceptable (scale, scope, length) outages?	4.1.5 Can acceptable outages indicate the value of the benefits of resilience?
4.1.8 Does efficiency (system cost optimisation) necessarily lead to a system less resilient to extremes?	4.1.6 How are efficiency and resilience related?
	4.1.7 Does an efficient system reduce capacity for resilience?
4.1.9 Can / how should we value adaptive capacity and optionality?	(now part of 4.1.8)
4.1.10 Have we prioritised the right properties of resilient infrastructure (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?	4.1.8 Should infrastructure resilience be prioritised according to creating capacity to deliver its different properties (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?

Current Hypothesis and questions	Rewarded and new Hypothesis and questions
Hypothesis	
Hypothesis 4.2 We don't identify the "right" interventions because of lack/wrong incentives.	H4.2 Incentives for resilience investment are inadequate
Questions	
4.2.1 Are there barriers to strategic, cross-sectoral assessment and planning?	4.2.1 Are there barriers to strategic, cross-sectoral assessment and planning?
4.2.2 Are decisions based on public perception, and is this leading to different risk acceptance (e.g. car vs air safety; natural vs man-made hazards) and often focusing on the short term?	4.2.2 Do public perceptions influence decisions only for the short term?
4.2.3 Political dimension?	4.2.3 What is the position of the people on infrastructure resilience?
4.2.4 How can NIC manage conflicting stakeholder incentives so that resilience is assured?	4.2.4 What conflicting objectives do NIC need to manage to ensure infrastructure resilience?
Hypothesis	
Hypothesis 4.3 We don't identify the "right" interventions because of capability.	H4.3 The resources don't exist to identify interventions to improve infrastructure resilience
Questions	
4.3.1 Is it always clear what the "right" interventions are?	4.3.1 Do approaches exist to identify interventions that improve infrastructure resilience?
4.3.2 If the "right" interventions are identified, is there the capability and capacity to implement them?	4.3.2 Does capacity exist to implement interventions to improve infrastructure resilience?
4.3.3 Do we need new capabilities (e.g. not just coping capability, adaptive capability, but others such as agile capability)?	4.3.3 Are new capabilities are needed for infrastructure resilience?
4.3.4 Do we know all the skills we need to have adequate resilience capabilities?	4.3.4 Do we know the strategies that create infrastructure resilience?
4.3.5 Can we learn from or collaborate with organisations that have experience and history in	4.3.5 Can infrastructure training embrace resilience?
Hypothesis	
H5: There is a lack coordination.	H5: There is a lack coordination in resilient investment
Questions	
5.1 Is lack of knowledge and communication about resilience of infrastructure hindering effective planning and response?	5.1 Is lack of knowledge and communication about resilience of infrastructure hindering effective planning and response?

Current Hypothesis and questions	Reworded and new Hypothesis and questions
5.2 Is lack of coordination and trust between government and private sector providers hindering effective planning and response?	5.2 Is lack of coordination and trust within government or between government and private sector providers hindering effective planning and response?
5.3 Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?	5.3 Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?
5.4 Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?	5.4 Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?
	5.5 What lack of knowledge and communication about interdependencies hindering effective planning and response?
	5.6 Are existing sources of knowledge on infrastructure interdependencies used by regulators for decision making?
	5.7 What is the risk of failure of each interdependency?
	5.8 What mechanisms will help to coordinate resilient investment in infrastructure?
	5.9 What mechanism is needed to share findings with other government departments and wider society?
Hypothesis	
Hypothesis 6: Stakeholders are not satisfied with the current level of infrastructure resilience.	Infrastructure customers (the public, businesses and emergency responders) are not satisfied with current levels of disruption to infrastructure services
Questions	
6.1 Is the public receiving enough assurance or support to cope with disruptions?	Do the public receive sufficient support to cope with the impacts of disruptions to infrastructure services?
6.2 Is the public encouraged (or not discouraged) to have unrealistic expectations?	Are public expectations of infrastructure service levels realistic?
	Are public expectations of support to cope with infrastructure service disruptions realistic?
6.3 Are emergency responders satisfied with the resilience of the infrastructure they rely on, and, if so, what is the case for increasing their own resilience (as opposed to asking increased infrastructure resilience)?	6.3 Are emergency responders satisfied with the current resilience of the infrastructure services they rely on?
	What is the case for emergency responders increasing the resilience of their own operations?

Current Hypothesis and questions	Reworded and new Hypothesis and questions
	What is the case for improving the resilience of economic infrastructure services to support emergency responders?
6.4 Are businesses satisfied with (or disproportionally impacted by) the resilience of	6.3 Are businesses satisfied with the current resilience of the infrastructure services they rely on?
	Are businesses disproportionally impacted by disruptions to the infrastructure services on which they rely?
	What is the case for businesses to increase the resilience of their own operations?
	What is the case for improving the resilience of economic infrastructure services to support businesses?
6.5 What is the basic level of service that safeguards that stakeholders take for granted?	Do infrastructure users take a minimum level of infrastructure service provision for granted?
	What is the minimum level of infrastructure service provision without which infrastructure users cannot sustain their own operations
6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets stakeholders' needs?	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the public needs?
	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the business needs?
	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets emergency responders needs?
New hypothesis?	
6.7 Is human thinking and action considered sufficiently in resilience assessment?	6.7 Is human thinking and action considered sufficiently in resilience assessment?
Hypothesis	
Hypothesis 7: Disproportionate impacts of events that might occur or have occurred (compared to their occurrence probability). There might be cases in which the resilience investments are disproportionately high compared with the probability of the events.	Investments in the resilience of infrastructure services should be driven by tolerance to the impacts of disruption to these services. Not the probability of service disruption.
	We do not maximize the value of investments in the resilience of infrastructure services
Questions	
7.1 Are investments intended to improve resilience unused?	How can investments in infrastructure services resilience be most effectively targeted to deliver the greatest level of benefit to the system of interest?

Current Hypothesis and questions	Reworded and new Hypothesis and questions
	What types of interventions are needed? Is their evidence regarding which interventions are most effective in what contexts?
7.2 Can infrastructure operators rely on past experience of disruption events to assess occurrence probability?	Do Infrastructure operators know enough about the dynamics of the interdependent system in which they operate to address all challenges using risk management tools?
Hypothesis	
H8: The relative resilience of different parts of the system is different (is it a bad thing?)	H8: Sub-systems system have different levels of resilience.
Questions	
8.1 If different resilience frameworks are used by different parts of the system, then can the whole system's resilience be known?	8.1 Do sub-systems assess resilience using different frameworks?
8.2 Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?	8.2 Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?
	8.3 Is there a way to reconcile measures of resilience from different subsystems

Appendix G – Questions by Categorisation

Meeting NIC Strategic objectives	Value, benefits and perception	Planning and preparedness (for disruption and recovery)
Do highly resilient economic infrastructure services impact the feasibility of realising:	4.1.1 Is the total value enabled by economic infrastructure services under-estimated?	1.6 How could resilience and emergency planning accommodate BIA (Business Impact Analysis)?
NIC strategic objective (i): sustainable economic growth?	4.1.1 Is the total value of ensuring infrastructure services are resilient under-estimated?	1.6 How could resilience and emergency planning accommodate SIA (Social Impact Analysis)?
NIC strategic objective (ii): improved competitiveness?	4.1.4 What is the total value of avoiding disruption to infrastructure services?	1.6 How could resilience and emergency planning accommodate EIA (Environmental Impact Analysis)?
NIC strategic objective (iii): improved quality of life?	4.1.5 What level of acceptable outages are tolerable?	3.2.1 Is risk management sufficient in open, dynamic infrastructure systems?
Does low resilience economic infrastructure services impact the feasibility of realising:	4.1.2 How can the benefits of resilient infrastructure services be most effectively quantified?	3.1.2 Are a sufficiently wide range of responses available to deliver infrastructure resilience when there is limited information?
NIC strategic objective (i): sustainable economic growth?	4.2.2 What impact does public perceptions have on infrastructure decision making?	5.1 Is lack of communication about resilience of infrastructure hindering effective planning and response?
NIC strategic objective (ii): improved competitiveness?	4.2.3 What is the position of the people on infrastructure service resilience?	5.2 Is lack of coordination and trust within government hindering effective planning and response?
NIC strategic objective (iii): improved quality of life?	Are public expectations of infrastructure service levels realistic?	5.2 Is lack of coordination and trust between government and private sector providers hindering effective planning and response?
What impact does the current level of infrastructure service resilience have on the feasibility of realising:	4.2.4 What conflicting objectives do NIC need to manage to ensure resilient infrastructure services?	5.5 What lack of communication about interdependencies hindering effective planning and response?
NIC strategic objective (i): sustainable economic growth?	Do infrastructure users (the public, businesses, emergency responders) take a minimum level of infrastructure service provision for granted?	Do the public receive sufficient support to cope with the impacts of disruptions to infrastructure services?
NIC strategic objective (ii): improved competitiveness?	6.3 Are emergency responders satisfied with the current	What is the case for emergency responders increasing the

resilience of the infrastructure services they rely on?

resilience of their own operations?

NIC strategic objective (iii): improved quality of life?

6.3 Are businesses satisfied with the current resilience of the infrastructure services they rely on?

What is the case for improving the resilience of economic infrastructure services to support emergency responders?

If infrastructure service resilience remains at current levels, what impact will this have for the future feasibility of realising:

NIC strategic objective (i): sustainable economic growth?

NIC strategic objective (ii): improved competitiveness?

NIC strategic objective (iii): improved quality of life?

If infrastructure service resilience declines from current levels, what impact will this have for the feasibility of realising future:

NIC strategic objective (i): sustainable economic growth?

NIC strategic objective (ii): improved competitiveness?

NIC strategic objective (iii): improved quality of life?

If infrastructure service were to become more resilient, what impact will this have for the future realisation of:

NIC strategic objective (i): sustainable economic growth?

NIC strategic objective (ii): improved competitiveness?

NIC strategic objective (iii): improved quality of life?

What short-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?

What long-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?

Are businesses disproportionally impacted by disruptions to the infrastructure services on which they rely?

What is the value proposition for businesses to invest in resilience?

Assessment/knowledge/measures for performance/ efficiency and resilience	Skills and capabilities for implementing resilience	Strategies and interventions
4.3.1 Do approaches exist to identify interventions that improve <u>infrastructure service resilience</u>?	4.3.2 Does capacity exist to implement interventions to improve infrastructure resilience?	Do we understand the root causes of low resilience in infrastructure services?
1.7 What approaches do you recommend to improve understanding and analysis of <u>infrastructure service performance</u>?	Are new capabilities are needed for improving infrastructure service resilience?	4.3.4 Do we know the strategies that create infrastructure resilience?
1.7 What approaches do you recommend to improve understanding and analysis of infrastructure service resilience?	Is there a common understanding of resilience amongst infrastructure practitioners?	Do we know the standard practises that reduce the resilience of infrastructure services?
4.1.6 How are efficiency and resilience related?	Is resilience a central component of training future infrastructure practitioners?	5.3 Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?
4.1.7 Does an efficient system reduce capacity for resilience?	5.4 Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?	How can we avoid interdependencies becoming critical pathways for infrastructure service disruption of failure?
Is there a trade-off between managing for infrastructure services for resilience and managing for efficiency?	5.6 How can the NIC help regulators make better use of existing sources of knowledge on infrastructure interdependencies?	5.8 What mechanisms are needed to better coordinate investment in resilient infrastructure services?
4.1.8 Should infrastructure resilience be prioritised according to creating capacity to deliver its different properties (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?	5.6 How can the NIC help decision maker make better use of existing sources of knowledge on infrastructure interdependencies?	5.8 What mechanisms are needed to incentivise increased levels of investment in resilient infrastructure services?
How can investments in infrastructure services resilience be most effectively targeted to deliver the greatest level of benefit to the system of interest?		5.8 What mechanisms are needed to supported collaborative portfolios of investment in resilient infrastructure services?
2.1 Are investments targeted at the right parts of national infrastructure?		5.9 What mechanism is needed to share findings with other government departments and wider society?

2.2 Can risk be used to target resilience investment?

2.4 How can the effectiveness of resilience investment be measured?

2.5 When the expected cost of disaster (including compensation) is higher than the cost of resilience, can it indicate a case for investment?

2.6 Should the cost of resilience include social, economic and environmental costs?

2.7 Will indirect costs of disaster be included in cost of disaster?

3.1.1 Are the consequences of known changes, such as those in the National Infrastructure Plans, and partially known changes, such as Connected Autonomous Vehicles, reviewed for their effects on infrastructure resilience?

What approaches do we need to account for resilience in dynamic, changing, interdependent infrastructure systems?

What approaches do we need to account for performance in dynamic, changing, interdependent infrastructure systems?

4.1.3 Are we accounting for interdependencies and/or cascading failures?

4.2.1 Are there barriers to strategic, cross-sectoral assessment and planning?

5.1 Is lack of knowledge about resilience of infrastructure hindering effective planning and response?

What is the case for businesses to increase the resilience of their own operations?

What is the case for improving the resilience of economic infrastructure services to support businesses?

6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the public needs?

6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the business needs?

6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets emergency responder needs?

What types of interventions are needed? Is there evidence regarding which interventions are most effective in what contexts?

5.5 What lack of knowledge about interdependencies hindering effective planning and response?
Do Infrastructure operators know enough about the dynamics of the interdependent system in which they operate to address all challenges using risk management tools?
What is the minimum level of infrastructure service provision without which infrastructure users cannot sustain their own operations?
6.7 Is human thinking and action considered sufficiently in resilience assessment?

2.8 What does it mean for infrastructure resilience when sub-systems have different levels of efficiency and resilience?

8.1 Do sub-systems assess resilience using different frameworks?

8.2 Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?

8.3 Is there a way to reconcile measures of resilience from different sub-systems?

Appendix H – Additional points from Gap Analysis

The wider benefits of resilience, and the opportunity cost of inaction, are often excluded from cost benefit analysis (CBA)

We do not compare the cost of actions that increase resilience against accurate counterfactuals

The opportunity cost of not acting now is not zero

Wider Frameworks to translate sector based analysis into whole system insight and action are needed/currently absent

Resilience is constrained by barriers to strategic cross sectoral resilience assessment and planning

Resilience analysis too frequently focuses on the initial causes of disruption (e.g. exogenous hazards, single points of failure) rather than understanding the system characteristics that make a system susceptible to the occurrence of interdependence related disruptions (cascade, escalating, common cause failures) following an initial disruption

Whole system resilience needs more than an optimisation of the resilience of each individual sector

Resilience can be destroyed as well as created, therefore we need to think about drivers of low resilience, barriers to improving resilience as well as 'solutions' to create resilience

Getting the right balance between too little and too much investment in resilience is a significant challenge

Identifying the right actions for investment and avoiding the wrong actions is vital

Identifying the right scale to target actions and avoiding action at the wrong scales is likewise vital

Identifying systemic leverage points, both where to intervene and with what actions is vital.

Barriers to resilience include lack of co-ordination, lack of knowledge, poor communication about the value of resilience, local optimisation by individual sectors

Appendix I – NIC post-review iteration of the Hypotheses

H7.1 Investing on improving infrastructure resilience is more cost- effective if decisions are made by looking at system level, by improving multiple aspects of resilience (i.e. robustness, resourcefulness, ability to recover rapidly, and ability to adapt pro-actively to emergent challenges) and by considering vulnerabilities.

H1: More resilient infrastructure services would better enable increased economic growth, competitiveness and quality of life now and in the future

H3.1: The uncertainty about future risks and opportunities which may impact infrastructure resilience means that we can only achieve resilience using a range of responses.

H3.2: Future changes may compromise infrastructure resilience

H6 Infrastructure customers (public, businesses and emergency responders) are not satisfied with current levels of disruption to infrastructure services

H2: There is a lack of appropriate investment on the resilience of infrastructure services.

H4.1 We don't identify the "right" interventions because resilience is undervalued in many investment decisions.

H4.2 We don't identify the "right" interventions because incentives for resilience investment are inadequate

H4.3 The resources don't exist to identify interventions to improve infrastructure resilience

H5: There is a lack coordination in resilient investment [alternative: there is a perceived lack of coordination in resilient investment, but it isn't real]

Appendix J – Final Hypotheses and Questions, including re-categorization, gap analysis and NIC final iteration

Hypothesis	Linked Questions/Assertions
H1: More resilient infrastructure services would better enable increased economic growth, competitiveness and quality of life now and in the future	If infrastructure service resilience remains at current levels, what impact will this have for the future feasibility of realising:
	NIC strategic objective (i): sustainable economic growth?
	NIC strategic objective (ii): improved competitiveness?
	NIC strategic objective (iii): improved quality of life?
	If infrastructure service resilience declines from current levels, what impact will this have for the feasibility of realising future:
	NIC strategic objective (i): sustainable economic growth?
	NIC strategic objective (ii): improved competitiveness?
	NIC strategic objective (iii): improved quality of life?
	If infrastructure service were to become more resilient, what impact will this have for the future realisation of:
	NIC strategic objective (i): sustainable economic growth?
	NIC strategic objective (ii): improved competitiveness?
	NIC strategic objective (iii): improved quality of life?
	What short-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?
	What long-term trade-offs, between NIC strategic objectives and the resilience of infrastructure services, are acceptable?
H2: There is a lack of appropriate resilience investment in infrastructure service resilience	4.1.6 How are efficiency and resilience related?
	2.1 Are investments targeted at the right parts of national infrastructure?
	How resilient are current infrastructure services?
H3.1: The uncertainty about future risks and opportunities which may impact infrastructure resilience means that we can only	3.1.2 What is the best approach to deliver infrastructure resilience when there is limited information?

achieve resilience using a range of interventions.	
H3.2: Future changes may compromise infrastructure resilience	3.1.1 Are the consequences of known changes, such as those in the National Infrastructure Plans, and partially known changes, such as Connected Autonomous Vehicles, reviewed for their effects on infrastructure resilience?
Hypothesis 4.1 We don't identify the "right" interventions because resilience is undervalued in many investment decisions.	4.1.1 Is the total value enabled by economic infrastructure services under-estimated?
	4.1.4 What is the total value of avoiding disruption to infrastructure services?
	Are the wider benefits of resilience, and the opportunity cost of inaction, excluded from cost benefit analysis (CBA)?
	Are we comparing the cost of actions that increase resilience against accurate counterfactuals ?
	What is the value proposition for businesses to invest in resilience?
	2.6 Should the cost of resilience include social, economic and environmental costs?
	2.7 Will indirect costs of disaster be included in cost of disaster?
	4.1.2 How can the benefits of resilient infrastructure services be most effectively quantified?
H4.2: We don't identify the "right" interventions because incentives for resilience are inadequate	5.8 What mechanisms are needed to incentivise increased levels of investment in resilient infrastructure services?
	What is the case for emergency responders increasing the resilience of their own operations?
	4.1.3 Are we accounting for interdependencies and/or cascading failures?
	What is the case for improving the resilience of economic infrastructure services to support emergency responders?
	4.2.1 Are there barriers to strategic, cross-sectoral assessment and planning?
	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the public needs?
Hypothesis 4.3 The resources don't exist to identify interventions to improve infrastructure service resilience	1.6 How could resilience and emergency planning accommodate BIA (Business Impact Analysis)?
	1.6 How could resilience and emergency planning accommodate SIA (Social Impact Analysis)?
	1.6 How could resilience and emergency planning accommodate EIA (Environmental Impact Analysis)?
	4.3.1 Do approaches exist to identify interventions that improve <u>infrastructure service resilience</u>?

	4.3.2 Does capacity exist to implement interventions to improve infrastructure resilience?
	Is there a common understanding of resilience amongst infrastructure practitioners?
	Is resilience a central component of training future infrastructure practitioners?
	Do we understand the root causes of low resilience in infrastructure services?
	Do we know the standard practises that reduce the resilience of infrastructure services?
	Do wider Frameworks to translate sector based analysis into whole system insight and action exist?
H5: There is a lack coordination of interventions to improve the resilience of infrastructure services	5.8 What mechanisms are needed to better coordinate investment in resilient infrastructure services?
	Is resilience constrained by barriers to strategic cross sectoral resilience assessment and planning?
	Are new capabilities are needed for improving infrastructure service resilience?
	5.8 What mechanisms are needed to supported collaborative portfolios of investment in resilient infrastructure services?
	5.4 Are roles and responsibilities clearly defined across national infrastructure for capability vs desired resilient properties?
	5.1 Is lack of communication about <u>resilience</u> of infrastructure hindering effective planning and response?
	5.2 Is lack of coordination and trust within government hindering effective planning and response?
	5.2 Is lack of coordination and trust between government and private sector providers hindering effective planning and response?
	5.5 What lack of communication about <u>interdependencies</u> hindering effective planning and response?
	5.3 Are there barriers to information sharing among stakeholders in the public and private sectors which reduce resilience?
	5.9 What mechanism is needed to share findings with other government departments and wider society?
	Do Infrastructure operators know enough about the dynamics of the interdependent system in which they operate to address all challenges using risk management tools?
H6: Current levels of disruption to infrastructure services do not meet the need and expectations of infrastructure customers	4.2.2 What impact does public perceptions have on infrastructure decision making?

(public, businesses and emergency responders)	
	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets the business needs?
	6.6 Do we have agreeable principles, standards, and designs for infrastructure resilience that meets emergency responder needs?
	4.2.3 What is the position of the people on infrastructure service resilience?
	4.2.4 What conflicting objectives do NIC need to manage to ensure resilient infrastructure services?
	Do infrastructure users (the public, businesses, emergency responders) take a minimum level of infrastructure service provision for granted?
	6.3 Are emergency responders satisfied with the current resilience of the infrastructure services they rely on?
	6.3 Are businesses satisfied with the current resilience of the infrastructure services they rely on?
	Are businesses disproportionally impacted by disruptions to the infrastructure services on which they rely?
	What is the case for businesses to increase the resilience of their own operations?
	What is the case for improving the resilience of economic infrastructure services to support businesses?
	What is the minimum level of infrastructure service provision without which infrastructure users cannot sustain their own operations?
	4.1.5 What level of acceptable outages are tolerable?
H7: Investing on improving infrastructure resilience is more cost effective if decisions are made by looking at system level, by improving multiple aspects of resilience (e.g. robustness, resourcefulness, ability to recover rapidly, and ability to adapt pro-actively to emergent challenges) and by considering vulnerabilities	How can investments in infrastructure services resilience be most effectively targeted to deliver the greatest level of benefit to the system of interest?
	4.1.7 Does an efficient system reduce capacity for resilience?
	4.1.8 Should infrastructure resilience be prioritised according to creating capacity to deliver its different properties (e.g. Stability, Robustness, Availability, Expandability, Safety, Flexibility and Reliability)?
	2.8 What does it mean for infrastructure resilience when sub-systems have different levels of efficiency and resilience?
	8.1 Do sub-systems assess resilience using different frameworks?

	8.2 Can the resilience of critical components of infrastructure be weighted accordingly in resilience assessment?
	8.3 Is there a way to reconcile measures of resilience from different sub-systems?
	Does/should resilience analysis focuses on the initial causes of disruption (e.g. exogenous hazards, single points of failure) rather than understanding the system characteristics that make a system susceptible to the occurrence of interdependence related disruptions (cascade, escalating, common cause failures) following an initial disruption?
	How can systemic leverage points, both where to intervene and with what actions be identified?
	What is the right scale for targeting actions?
	How can investments in infrastructure services resilience be most effectively targeted to deliver the greatest level of benefit to the system of interest?
	2.2 Can risk be used to target resilience investment?
	2.5 When the expected cost of disaster (including compensation) is higher than the cost of resilience, can it indicate a case for investment?
	What approaches do we need to account for resilience in dynamic, changing, interdependent infrastructure systems?
	What approaches do we need to account for performance in dynamic, changing, interdependent infrastructure systems?
	How can we avoid interdependencies becoming critical pathways for infrastructure service disruption of failure?