Critical Infrastructure Resilience Strategy: Design, Operations and Maintenance Guide

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Guide summary

This guide is part of the NSW Critical Infrastructure Resilience (CIR) Strategy suite of supporting tools and focuses on resilient design, operations and maintenance. It partners with the NSW CIR Strategy Planning Guide to cover the largest components of asset management.

This brief summary of the elements and concepts in this guide gives busy practitioners an overview, with relevant document sections giving more detail, and further reading options at the end of each section providing depth on the concepts and practices, and examples of implementation.

The goal of infrastructure resilience is less disruption and faster return to service. This includes the provision of partial service for periods of time, sometimes called graceful degradation. More detail on the topic of infrastructure resilience can be found in the CIR Strategy Infrastructure Resilience Guide on the NSW opengov website.

One of the key aspects of resilience is that it focuses on minimising the consequences of infrastructure service failure, rather than the probability of infrastructure service failure. This helps to address risk in an uncertain future with uncertain, difficult-to-quantify risks.

As outlined in the CIR Strategy, to improve the resilience of NSW infrastructure service, we must partner, prepare and provide. This guide focuses on how to follow those priorities in relation to the design, operations and maintenance of infrastructure.

Partner

- Plan, design, operate and maintain infrastructure with all stakeholders, including emergency management agencies, and other infrastructure providers.
- Champion a risk management approach to providing infrastructure service within your own organisation, with other infrastructure providers, and with other stakeholders such as emergency services and emergency management committees.
- Focus on the infrastructure service rather than the infrastructure assets. This allows designers and operators to consider all stakeholder perspectives, including technical, environmental and social.

Prepare

- Move from standards-based to performance-based design with resilience embedded.
- Integrate resilience and security as early in the project as possible.
- Move from an asset based to a system based designed approach. This should include the systems owned by other infrastructure providers as well.
- Apply resilience engineering principles to the design of complicated infrastructure networks and systems.
- Understand the criticality and interconnections of the infrastructure you design, operate or maintain (see the CIR Criticality Guide or the Interconnectedness Guide for more detail).
- Exercise for infrastructure emergencies and understand how infrastructure is likely to fail.
- Move to predictive rather than reactive maintenance strategies. New technologies can assist.

Provide

- Operationalise resilience into all phases of asset management and business as usual. (This has been done successfully with safety in infrastructure).
- Designing for safe failure of infrastructure to avoid or minimise loss of life and protect the property of the asset owner and the community.
- Separate the infrastructure from the hazards as much as possible.
- Integrate organisational resilience principles into infrastructure operation and maintenance (see the CIR Strategy Organisational Resilience guide for more detail).
- If infrastructure must be reconstructed, build back better. This means stronger, faster and more inclusively with the community.
- Promote a culture of safety – this is a pre-requisite in infrastructure for increased resilience.

Items in this summary have been broken up into Partner, Prepare, Provide to align with the CIR Strategy priorities. For the ease of navigation, detailed sections of this guide have been broken up into large asset management phases, including design, operations and maintenance. Although resilience engineering covers all asset management phases, a detailed section on it can be found under the design heading.

By integrating resilience early during the planning and design of infrastructure, understanding and managing the risks to infrastructure, assessing criticality as a way to prioritise effort, modelling and understanding the way our different infrastructure connects and interconnects to other systems, and embedding resilience in our business as usual, we can use infrastructure to create safer, more secure and more disaster resilient communities.

Introduction to the Critical Infrastructure Resilience Strategy

NSW benefits from critical infrastructure (CI) that provides secure and reliable essential services, such as food, water, energy, transport, telecommunications and health care. The CI of NSW is exposed to an increasing number of threats, hazards, shocks and stresses.[1],[2] Disruptions to critical infrastructure can result in loss of life, negative economic impact and harm to communities, including psychological distress.[3] More frequent natural disasters of greater magnitude[4], and a heightened risk profile in relation to criminal threats including cyber-attack[5],[6] mean NSW's infrastructure and organisations must be more resilient than ever. The CIR Strategy[7], released on 13 September 2018, encourages leaders in business and government to support communities by improving CIR across NSW.

The CIR Strategy promotes CI that can:

- withstand shock events to continue operating; or
- be returned to service as soon as possible after any disruption; and
- respond to long-term stresses.

A focus on physical infrastructure alone will not achieve this. This strategy has three outcomes:

- Improved **infrastructure resilience** which is focussed on the resilience planned for, designed and built into assets, network and systems (resistance, reliability, redundancy, enhancing response and recovery).
- Improved **organisational resilience** which refers to the resilience of the organisations, personnel and processes supporting the infrastructure to supply the service (organisational resilience, enterprise risk management, business impact analysis, preparedness, response, continuity and recovery).
- Improved **community resilience** which focuses on the role the community plays in building and maintaining its own resilience while contributing to CIR. Building resilience within the community requires an integrated approach involving both government and business (information and warnings, managing service disruptions, community partnerships).

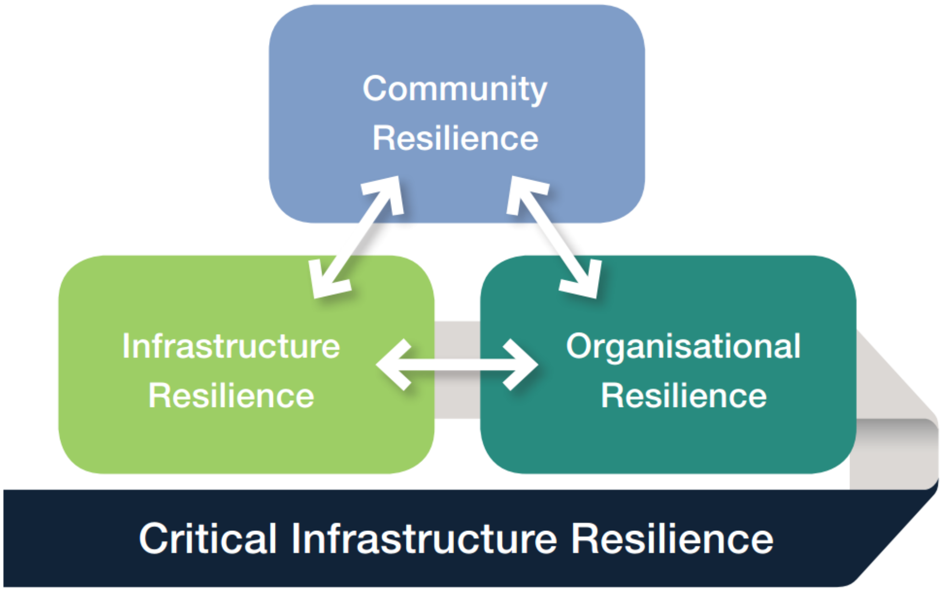


Figure 1: CIR is enhanced through infrastructure, organisational and community resilience

To achieve these outcomes, priority is given to:

- **Partnering** for shared responsibility around critical infrastructure resilience;
- **Preparing** for all hazards, not just the ones we can foresee; and
- **Providing** continued service from critical infrastructure with minimal disruption.

The benefits of the strategy are identified as:

Strategy Benefits	
Critical Infrastructure Providers (Regardless of ownership)	• Reduced business disruption • Enhanced reputations and business confidence • Reduced total cost of asset ownership and increased return on investment • Better understanding of infrastructure interconnectedness, allowing vulnerabilities to be addressed across multiple CI provider organisations • Stronger cultures to meet business challenges (not just emergency events)
For Communities	• Reduced service disruption to the people and businesses of NSW • More effective emergency management arrangements • More resilient communities, reducing the social costs of disasters
NSW GOVERNMENT **For Government**	• Enhanced capability and co-ordination of response and recovery agencies • Reduced response, reconstruction, and recovery costs arising from emergency events
For all of us	• Stronger partnerships between business, government and the community • Enhanced resilience against hazards and threats • Insurance premiums that incorporate the benefits of resilience-building activity • Improved adaptation to long-term stresses such as climate change and population growth

Other guides provide information around infrastructure resilience, using criticality to prioritise resilience improvements to infrastructure, and understanding the interconnectedness of infrastructure, as well as guides focused on specific types of infrastructure.

This guide focuses on infrastructure resilience through the asset lifecycle. A separate guide provides information on infrastructure planning and this guide focuses on integrating resilience into the design, operate and maintain phases of the infrastructure lifecycle.

Infrastructure resilience and the infrastructure lifecycle

Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events.[8]

This guide suggests some of the ways that infrastructure can be planned, designed, operated and maintained in more resilient ways to reduce service disruption and/or decrease restoration time after disruption.

Ultimately, the way that the partners in infrastructure resilience (infrastructure providers, governments and the community) commit to the ideas behind resilience, and organise their resources to produce increase resilience, will determine overall increases in critical infrastructure resilience.[Error! Bookmark not defined.] Promoting resilience as business as usual will result in the best resilience improvements for the people and businesses of NSW.

The methods for improving infrastructure resilience in the table below were identified within the CIR Strategy. The strategy also highlights the importance of improving organisational resilience and community resilience to create overall improvements to critical infrastructure resilience. Guides focussed on these aspects of infrastructure resilience are available on the opengov website.

Although these methods are categorised within simplified phases of the asset management lifecycle, many of them also apply across multiple phases (e.g. using resilient engineering approaches during asset refurbishment or maintenance).

Together with the CIR Strategy Infrastructure Planning Guide, the largest phases of the asset management lifecycle are covered to provide information and ideas on how best to improve critical infrastructure resilience across NSW.

Table 1: Improving infrastructure resilienceError! Bookmark not defined.

Improving Infrastructure Resilience	
Infrastructure Planning	• Integrated planning and investment • Good data enabling good decision making • Locating infrastructure in less risk-prone locations • Risk avoidance in the planning stage • Hazard mitigation
Infrastructure Design	• Resilience by design • Security by design
Infrastructure Operations and Maintenance	• Maintenance resilience – Maintenance planning – Remote sensors • Operations resilience – Faster service restoration • Reconstruction resilience – Infrastructure betterment in restoration or reconstruction

Asset management

Infrastructure asset management is complex. Books, training courses, and university degrees have been built around asset management. For the purposes of this guide, the Asset Management Council's definition of asset management as "The life cycle management of physical assets to achieve the stated outputs of the enterprise"[9] is used.

The complex interaction between asset performance to an agreed level of risk and the cost to provide the service are covered in the ISO 55000 series on Asset Management. Considering resilience in asset management requires a more sophisticated understanding of risk beyond the enterprise and appropriate levels of service for the community. With the right tools and understandings, this can provide a greater achievement of an enterprise's objectives, including the objectives communities expect of infrastructure service.

The balance of risk, performance (including reliability, availability, maintainability and supportability), and cost expressed as part of AMBoK can be supplemented with an understanding of resilient design (including resilience engineering), operations and maintenance to produce good outcomes for NSW infrastructure operators, and the communities and organisations that rely upon them. For more information on asset management, please refer to Infrastructure NSW's page on asset management, with the NSW Government expected to soon release an updated version of their Asset Management Policies through Treasury, including principles relating to the balance of risk, performance and cost and a whole-of-life-cycle approach..

This guide uses a simplified asset lifecycle to describe good resilience practice for infrastructure throughout simplified stages with practical steps on how to integrate infrastructure resilience into infrastructure projects and operations.

The CIR Strategy highlights that carefully considered resilience enhancements in planning and design have long-lasting impacts during the full lifecycle of the assets and result in:

- Decreased Interruptions
- Reduced Recovery Time
- More Rapid Restoration or Reconstruction

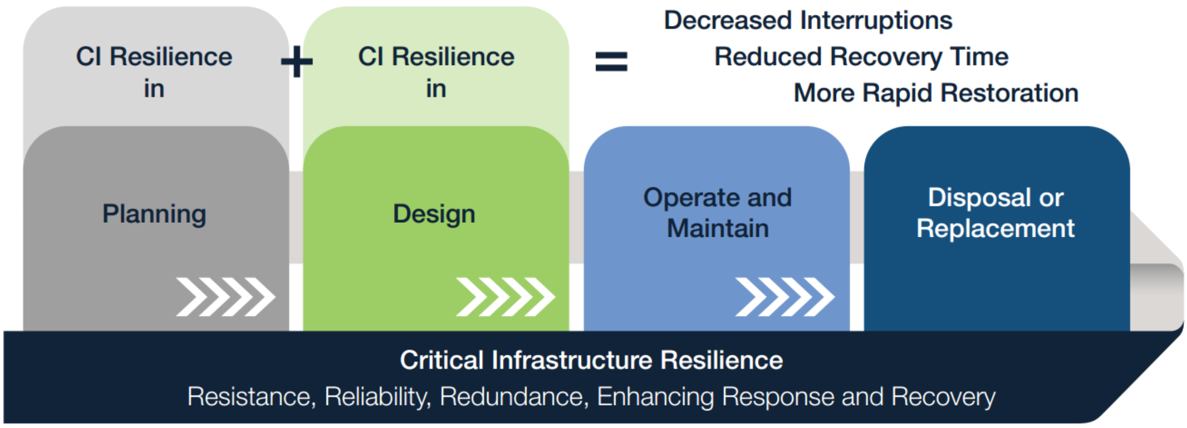


Figure 2: Embedding resilience in planning and design pays back during operation and maintenance

Resilience requires infrastructure professionals to take wider responsibility for factors not always considered within current design practice and at a much earlier stage in addressing infrastructure needs.[10]

Although planning and design provide excellent benefit for resilience investment, resilience enhancement is available throughout the entire life of the asset, including during operations and maintenance.

The earlier that resilience enhancements are included in infrastructure planning, design and operations, the more likely they are to reduce the total cost of ownership of the asset across its designed life, and sometimes beyond.

Over the lifetime of a building, for example a hospital or a school, the additional up-front project costs to embed resilience are unlikely to be more than 3% of the total costs, but the operating costs will often constitute 85% of the total. On the same scale, the design costs are likely to be 0.3-0.5% of the whole life cycle costs, and yet it is through the design process that the largest impact can be made on operating costs[11], even without quantifying the costs or benefits of social and environmental factors.

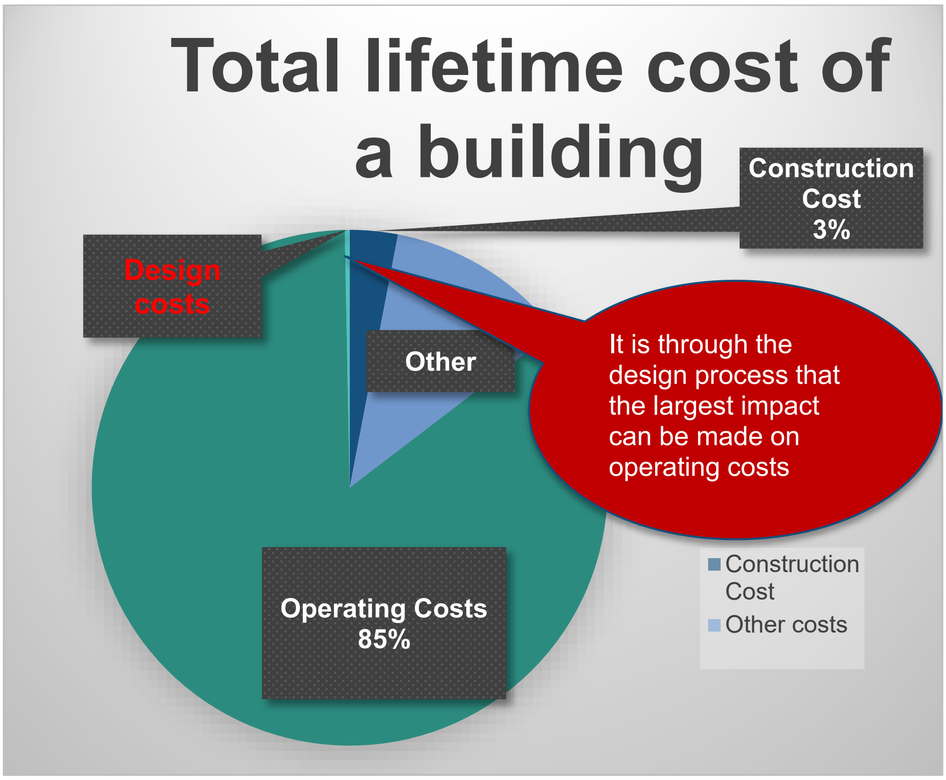


Figure 3: The value of resilient design [11]

Adding a small amount of extra time and effort into planning and design can have significant economic and reliability benefits across the lifetime of an asset. As illustrated in the figure above, this could have significant economic benefits. While the lifetime costs against different infrastructure vary by percentage (e.g. operating costs of roads are estimated at closer to 50%[12]) all infrastructure types can benefit from operating cost reduction through resilience increases during planning and design.

Planning

A detailed Infrastructure Planning guide has been developed as part of the [CIR Strategy] and is available on the [open gov website].

The CIR Strategy Planning Guide was designed with urban planners in mind, but the resource will be useful to anyone involved in infrastructure planning and design.

Key planning measures discussed in the guide include:

- Integrating Resilience Early
    - Looking for hazard mitigation strategies at the earliest possible stage
- Collaborative Planning
    - Community
    - Other Infrastructure Providers
    - Government
- Planning Based on Good Data
    - Hazard Maps
    - Risk Management (Past Hazards)
    - Climate Change and Extreme Weather Prediction Models (Future Hazards)
    - Security Assessments (Past & Future Threats)
- Lessons/Information Management: Planning Based on Lessons Learned
    - Assessing the success of previous projects with mitigation measures included
    - Review of past crises and near accidents

If infrastructure providers choose resilience-led design, greater investment is needed earlier so that alternative infrastructure service solutions can be considered, and so that all relevant stakeholders can be engaged.[13]

Asset life

More and more frequently infrastructure assets are being kept in service beyond their designed life. Although infrastructure renewal beyond designed life is becoming more prevalent, it is also sometimes more viable with advances in technology.

Condition-based assessment (over age-based assessment) may allow the extension of an asset's useful life, but a risk-based approach must be taken, and the increasing likelihood of natural hazards and human-centred threats should be considered carefully if this approach is to be taken.

Realistic, run-to-fail strategies may be appropriate for less critical assets, but infrastructure service providers need to be diligent in assessing all options when adopting these sorts of strategies, as interdependencies with other more critical infrastructure could lead to negative outcomes for communities. A wholistic view of the service that assets provide can assist with perspective around end-of-life (EOL) decisions for specific assets.

If replacement is selected as the appropriate strategy for a set of infrastructure, the planning processes highlighted in the CIR Strategy Infrastructure Planning Guide provide useful ways to embed resilience into new infrastructure from the earliest stage of the asset lifecycle.

Climate change

A changing climate affects the predicted life of an asset, the materials that comprise the asset, and the future conditions the asset must operate in.

One aspect of resilience is to consider not just the conditions an infrastructure asset, system or network must operate in today, but the likely conditions in the future. Doing this during planning and design can significantly reduce the total cost of ownership of the asset over the life of the asset.

Higher temperatures, higher or lower rainfall, sea level rise and increasing salinity, and increases in extreme weather such as bushfires, flooding, storms and wind events are likely to put infrastructure assets, networks and systems under increased strain in the future.

The effects of extreme weather are often the most obvious and dramatic. Infrastructure assets (including up to 30,000km of road and 1500km of rail) are likely to be more at risk of impact from storm surge inundation should sea level rise increase in line with projections.[14]

The impact from extreme events can be obvious, but climate change can also impact asset maintenance in terms of ongoing changes in the use of infrastructure. Transport, water and energy networks are sensitive to climatic conditions and climate change is likely to lead to increased asset maintenance costs, decreased capacity or reliability, and shorter useful asset lives, while potentially increasing the need for the infrastructure systems themselves (e.g. increased cooling demands based on higher temperatures).[15]

One way that most infrastructure providers have adopted to assist with a warmer future climate is to raise design temperatures for assets that include metal such as electricity transmission lines and railroad tracks. Another is to integrate flood planning into green spaces – effectively making room for drainage in city parks and outdoor areas to save costlier assets such as buildings and infrastructure from flooding.

The AdaptNSW website has tools to help understand and adapt to the future climate of NSW. Additional guidance is provided through bodies such as the Institute of Public Works Engineering Australia via tools and publications such as Practice Note 12.1:2018, Climate Change Impacts on the Useful Life of Infrastructure.

Planners, designers and operators can use these tools and guidance to better enable them to provide resilient infrastructure services into a future with a changing climate.

Infrastructure investment impacts on design and operations

Investors who fund infrastructure projects are increasingly focussed on sustainability and resilience, due to the long-term nature of the return on their investment[16]. By building resilience into infrastructure planning, design, operations and maintenance, infrastructure owners and operators can address the concerns of investors who increasingly want wider incomes from their infrastructure investment – not just an economic return, but an increased focus on environmental and social returns as well, which in turn can increase economic return over the life of infrastructure assets.

Further reading

National Institute of Building Sciences. 2018. *Building Resilience*. Excerpted from the 12th Edition of Architectural Graphic Standards. Available at www.wbdg.org/resources/building-resiliency

OECD (2018), "Climate-resilient infrastructure", OECD Environment Policy Papers, No. 14, OECD Publishing, Paris, doi.org/10.1787/4fdf9eaf-en .

Kete, Nancy. 2016. *Building Resilience in Critical Infrastructure* Lloyd's Research Foundation: Joint Programme on Resilience Engineering. Available at: www.youtube.com/watch?v=ZW7OsZL7Zt0

Investor Group on Climate Change. 2018. Investing in Resilience: Tools and Frameworks for Managing Physical Climate Risk. igcc.org.au/wp-content/uploads/2018/07/IGCC-Investing-in-Resilience-report_FINAL.pdf

Resilient design

Resilient design is going beyond standard design to consider the hazards and threats that an infrastructure asset, system or network is likely to be exposed to during its design life, and more and more frequently even beyond its designed life.

Although in NSW and Australia many codes and standards exist around how to design and build infrastructure, relying purely on these can expose infrastructure to significant risk. Even though design standards may ensure the physical integrity of an asset under a given set of circumstances, only rarely do they consider the integrity of the service that is being provided by the infrastructure. [17]

This is not to say that codes and standards cannot be effective. There are many examples where infrastructure is now better prepared for natural hazards such as earthquakes as a result of updated building codes, and Australia's performance-based codes allow resilience solutions to be embedded in projects at the discretion of the project owner. However, standards and codes are often general and do not always take into account specific risks that might apply to infrastructure based on its location, risk profile or the hazards and threats infrastructure is likely to face across its lifetime.

Standards and codes are also usually based on past experience, and we know that future operating conditions for infrastructure are likely to be very different from operating conditions today. The obvious change is to the climate and the frequency and severity of natural hazards, but significant challenges also exist around population growth, urban density, aging supporting infrastructure and malicious threats including cyberattack. Standards based on history can't cover every possible future event, and resilient design is a method of considering future events and ensuring infrastructure systems can withstand and adapt to an uncertain future.

Where risks are not easily embedded in a standard a different approach is needed that considers risks earlier, before a specific engineering solution is chosen. These types of risks require investigation to determine how they affect the infrastructure solution.[18] This approach requires infrastructure to be considered within a wider context which includes how the infrastructure service is going to be delivered not for the life of the asset, but during the worst conditions the asset is likely to face during its useful life.

By assessing place-based and other risks, designing for known hazards and threats, and integrating broader resilience concepts to mitigate against unknown threats and hazards, infrastructure planners and designers can plan for a less-than-certain future.

Resilient design is more about a strategic approach rather than a specific design tool. Resilience and security in design can be coupled more effectively with risk management, which is necessary to address an uncertain future with uncertain threats and hazards. [19]

An infrastructure asset or network can sometimes reduce resilience and contribute to vulnerability, such as paved surfaces re-directing flood water to unintended locations, electricity lines as sources of bushfires, or it can be used as an attack vector for a malicious attacker. Resilient design should consider the risk that infrastructure assets create and attempt to treat those risks in the most appropriate way.

Depending on how critical an asset is to the provision of an infrastructure service, resilient design may need to consider defence in depth, meaning that multiple methods of building resilience may be required to address potential vulnerabilities.[20]

Especially where planned infrastructure is likely to provide service to another set of critical infrastructure, the interconnections must be considered during the design, and an appropriate level of redundancy be provided based on customer, organisation and community requirements.

Some of the ways in which resilience can be increased via good design include:

- Separating the infrastructure from the risk or hazard.
- Designing the infrastructure to resist likely hazards.
- Considering protection works which may be physically separate assets that protect the infrastructure itself (such as sea walls, security screening, or wind breaks).
- Design the infrastructure to degrade gracefully.
- Designing the infrastructure for safe failure.

Resilience engineering

Resilience Engineering[21] is a growing discipline to increase safety, security and resilience around critical infrastructure assets, networks and systems. The aims of resilience engineering are to:

- Preserve critical functionality
- Ensure graceful degradation of service (instead of abrupt total system loss)
- Enable fast recovery after disruption

Resilience Engineering tries to achieve these aims by:

- Defining scientific-engineering methods to achieve the aims
- Extending classical risk management approaches to suit resilience engineering
- Building in reliability and maintainability of systems
- Integrating security, safety and cybersecurity into engineering approaches
- Focusing on social and organisational outcomes during engineering

When applying resilience engineering to infrastructure networks or systems it can be defined as:

> *the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions. The essential characteristic of a resilient system is the ability to adjust its functioning so that it can succeed in different – and difficult – situations.*[22]

A key aspect of resilience engineering is that its aim is not only to prevent things going wrong, but also to ensure that things go right. The more likely it is that something goes right, even under the most difficult conditions, the less likely it is that something goes wrong.[22]

For designers, operators, and maintenance providers, it includes a shift from an asset-based approach to a systems-based approach which looks at the interactions between the technical, social, economic and organisational components of infrastructure systems over time.[23] It complements the concept of looking at infrastructure as a way to provide a service, with the service provision as the focus rather than the physical infrastructure asset.

Engineering has traditionally addressed risk based on known threats with given loads and boundary conditions. Historically, systems have been designed to recover from adverse conditions and adapt based on experience. But increasingly, resilience goals can be missed with this approach, because disruptive events are happening at unexpected times and in unanticipated ways, and the increasing complicatedness (on top of natural complexity) and interconnectedness of infrastructure systems mean the potential for cascading failures in most systems is growing.[24] Engineered systems and nature are strongly interconnected and resilience engineering tries to account for these interdependencies.[25]

Adopting a resilience engineering approach can help systems anticipate, respond, adapt to, and learn from both expected and unexpected disturbances. It is important to note that the best mechanism for an infrastructure service system to do this may not be a technical one.

There are four main aspects of resilient systems in resilience engineering. Systems that can address these aspects, whether through technical, organisational or social processes or procedures, go a long way to being resilient:

- Knowing what to do and how to respond to disturbance disruptions;
- Knowing what to look for what may become a threat or an opportunity to the system service;
- Knowing what to expect, how to identify changes, disruptions or pressures and their consequences; and
- Know what has already happened and learning the right lessons from the experience, which includes both successes and failures.[22]

Not every infrastructure service within NSW is going to fulfil these aspects of resilient systems perfectly, but they can provide a useful objective when considering how to build resilient infrastructure services in a more complex and complicated world.

Security by design

Security, including physical security, system security, and cybersecurity, should be integrated into planning and design of infrastructure in the same way that the CIR Strategy advocates resilience is. Some infrastructure assets are covered by the Commonwealth's Security of Critical Infrastructure Act 2018 which details the requirements for those assets. Some infrastructure providers work closely with the NSW Police Force as part of the NSW Protecting Critical Infrastructure from Terrorism Program.

For most infrastructure, the owner and/or operator is responsible for security. Embedding security principles into the design of the infrastructure from the outset yields better results for all types of security of critical infrastructure assets, networks and systems and creates a stronger balance between security and functionality.

A strong security management approach will include design around physical, system, cyber and personnel security and will integrate security in a holistic approach (e.g. Crime Prevention Through Environmental Design CPTED)

Further information on security management can be found in the CIR Strategy Organisation Resilience guide. Further ways to promote resilient design, including resilience engineering and security by design are explored below and are categorised with the CIR Strategy guiding principles of Partner, Prepare and Provide.

Partnering for resilient design

Resilient design, including resilience engineering, is as much a political, economic and social issues, as it is an engineering one.[26] To enable resilient design, all partners in planning, designing, operating and maintaining infrastructure need to learn about resilience and be involved.

By partnering early in design innovative solutions to complex problems can be identified. These can include traditional grey infrastructure (built environment) but also increasingly green infrastructure (natural) and blue infrastructure (water-based) options. This infrastructure combination can be defined as “the creative combination of natural and artificial (blue and green as well as grey) structures intended to achieve specific resilience goals (e.g., flood management, public health, etc.)”[27]. More on green infrastructure is included in the CIR Strategy Planning Guide. Integrating elements of natural and human-made infrastructure for service provision requires more partners in planning and design – collaborating with other infrastructure providers and professions, as well as the community, but can produce solutions that are less costly to maintain and provide greater resilience.

Partnering early and consulting widely with all stakeholders can help meet additional needs. As an example, when planning flood mitigation infrastructure (withstand) it may be worth considering transport and evacuation routes should the infrastructure fail (enhancing response and recovery).

Preparing for resilient design

Preparing for design usually happens in the infrastructure planning stage. A key aspect of preparing for resilient design is not only to consider other infrastructures but to consider the entire lifespan of the infrastructure being designed. By designing with maintenance and operations in mind, the total cost of the infrastructure over its entire life can be reduced. Particularly in harsh climatic conditions, designing for low maintenance can be useful and reduce costs significantly. Examples of designing for lower maintenance can be material choices or construction types that are easy to maintain.

A related aspect is also to design with recovery in mind. This can be done by designing using standardised parts and materials available locally, which can enhance the speed of repair, recovery or reconstruction to enable infrastructure service to be returned as quickly as possible. Examples of this include designing control interfaces for speed of operation rather than design convenience.

Resilience is especially important for those systems and assets which are critical to a community in a post-disruption or disaster environment. Any infrastructure that supports key facilities such as hospitals must be operated with its importance in mind. For more information on prioritising infrastructure based on its criticality, see the CIR Strategy Criticality Guide, and for information on ways that infrastructure systems are interconnected, see the CIR Strategy Interconnectedness Guide.

Providing resilient design

The long-lived nature of infrastructure assets means that design decisions can lock-in vulnerability if they fail to consider likely impacts across asset life. The reverse is true, and resilience built into infrastructure assets, networks and systems can help provide a more resilient future for many years to come.

Resilient design has traditionally been viewed as assets and structures that can withstand extreme events but increasing natural hazards and malicious threats show a need for infrastructure as a system to be more resilient.

Designing across all related dimensions to lower probabilities of failure, reduce negative consequences when failure occurs (graceful degradation in service), and enable faster recovery from failure can all be integrated into resilient design. [28]

Analysing and learning from previous failures can help designers understand how infrastructure systems fail when subjected to extreme conditions. Alternative engineering solutions identified can include different materials, technologies and strategies, and some of these may be able to be retrofitted to existing infrastructure. [28]

Modular designs to infrastructure networks and systems may increase reliability, the ability to operate in different types of conditions, including abnormal operating states (such as when a larger infrastructure network is unavailable).

Soft fail options, including graceful degradation of systems, may allow designers and engineers to select the way in which the system will fail, possibly maintaining some of the more critical services while less critical, non-essential services fail first.

Further reading

Further reading includes items that explain the principles of resilient design further and examples of resilient design from around the world.

Jackson, Scott. 2016. *Principles for Resilient Design - A Guide for Understanding and Implementation* in IRGC (2016), Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016. www.irgc.org/riskgovernance/resilience

Gallego-Lopez, C.; Essex, J. (with input from DFID) *Designing for infrastructure resilience*. Evidence on Demand, UK (2016) 22p www.gov.uk/dfid-research-outputs/introducing-infrastructure-resilience.

American Society of Civil Engineers. 2017. *Sustainability and Resilience in Our Engineered World*. www.youtube.com/watch?v=nenUNJso59Y

Woods, D. D. (2018). *Resilience is a verb*. In Trump, B. D., Florin, M.-V., & Linkov, I.(Eds.). IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems. Lausanne, CH: EPFL International Risk Governance Center. beta.irgc.org/wp-content/uploads/2018/12/Woods-for-IRGC-Resilience-Guide-Vol-2-2018.pdf

Physical Security Management Guidelines: Security Zones and Risk Mitigation Control Measures – matryxconsulting.com.au/wp-content/uploads/2015/06/Australian-Government-physical-security-management-guidelines-Security-zones-and-risk-mitigation-measures.pdf

National Guidelines for Protecting Critical Infrastructure from Terrorism – www.nationalsecurity.gov.au/Media-and-publications/Publications/Documents/national-guidelines-protection-critical-infrastructure-from-terrorism.pdf

Multihazard Mitigation Council (2018). Natural Hazard Mitigation Saves: Utilities and Transportation Infrastructure. Principal Investigator Porter, K.; co-Principal Investigators Scawthorn, C.; Huyck, C.; Investigators: Eguchi, R., Hu, Z.; Schneider, P., Director, MMC. National Institute of Building Sciences, Washington. www.nibs.org/page/mitigationsaves

Resilient operations

Incorporating resilience strategies into the planning and design of new critical infrastructure will serve NSW well in the future, but a large proportion of NSW infrastructure has already been built.Error! Bookmark not defined.

There is much that can be done to increase the resilience of existing infrastructure through the operations (and maintenance) phase of the asset lifecycle. In many cases, increasing infrastructure resilience via optimised operations can decrease whole-of-life maintenance costs and potentially extend the life of infrastructure assets.[29]

As an example of resilient options, some infrastructure providers are pursuing the goal of adaptive self-healing networks, where control systems can take action to limit disturbances due to changing conditions from spreading into system-wide collapse. These controls may even bring an infrastructure network back to full service, potentially without human intervention. In some infrastructure types such as communications, self-healing networks are already prevalent. Where they already exist, work is often ongoing to improve the capabilities of self-healing networks.

This section on operations is broken up into the three guiding principles of the CIR Strategy of Partner, Prepare and Provide.

Organisational resilience

Many of the options discussed below for promoting resilient operations rely on an infrastructure provider's internal processes and organisation.

The CIR Strategy Organisational Resilience Guide discusses ways to increase the organisational resilience of infrastructure provider. Topics discussed include

- Risk Management
- Capability Improvement
- Exercising and Lessons Management
- Security Management
- Insurance Management
- Emergency Management
- Business Continuity Management

All of these organisational resilience disciplines can assist with resilient operation of infrastructure for infrastructure provider organisations.

Partnering for resilient operations

Just as no large set of infrastructure can operate independently from every other set of infrastructure, no infrastructure organisation should operate independently from other infrastructure providers. Priority 1: Partner within the CIR Strategy highlights the interconnected nature of our infrastructure and the organisations that support it.

Partnering for resilient operations can occur at many levels, including within an organisation, between organisations, and with the community.

Within an organisation

It's not just external organisations that infrastructure professionals need to partner with to ensure resilient infrastructure operations.

Operations staff within infrastructure organisation are well-placed to understand the requirements of the organisation and the community in relation to infrastructure service and must partner with capital works and project teams on new infrastructure, and maintenance teams on existing infrastructure, to help create a more resilient organisation, and therefore a more resilient infrastructure service.

Attaching operations staff to projects for new infrastructure will reduce the total cost of ownership of infrastructure assets over the lifetime of the asset, as operations staff frequently have insights into the best way to produce infrastructure that can be operated effectively (especially in a crisis) and maintained more easily.

In some cases owners performance requirements can assist in this space to ensure resilient outcomes from new infrastructure, but much like standards and codes, unusual operating environments or conditions are likely to require risk assessment and more consideration from operations staff on how best to address known risks and prepare for the potential unknown risks across the life of the asset.

Other infrastructure organisations

The NSW government seeks to promote greater collaboration between agencies and sectors on asset management and asset operations in NSW.[7,30]

Within the NSW Critical Infrastructure Resilience Strategy, both sector based, and cross-sector groups are encouraged to meet and share methods on infrastructure resilience, not just in operation but across all activities.

Other forums also exist, such as the Asset Management Community of Practice through Engineers Australia, the Institute of Public Works Engineering Australasia and sector-specific groups such as the NSW Water Directorate.

At the National level, the Department of Home Affairs also provides the Trusted Information Sharing Network for Critical Infrastructure Resilience and the relevant industry sector groups within the TISN.

If relevant groups are not providing suitable forums for infrastructure resilience knowledge sharing and collaboration, infrastructure organisations are encouraged to establish their own relevant groups. For more information please contact Resilience NSW.

Understanding infrastructure interconnectedness

A better understanding of interconnections between different types of infrastructures during the operation phase will also allow providers to lean on each other for more rapid service restoration and use interconnections as strengths rather than becoming interdependencies and cascading failures. Comprehensive information on connectedness, interconnectedness, dependencies and interdependencies can be found in the CIR Strategy Interconnectedness Guide.

Various tools and techniques are available for understanding infrastructure interconnections and these are also discussed in the CIR Strategy Interconnectedness Guide.

Inter-agency coordination

Much like in design where risk must be assessed, when developing strategies for resilient operations, it is important to consider not just normal operating conditions, but also crisis operating conditions.

By establishing relationships with emergency services and first responders, infrastructure organisations can more effectively operate in crisis, which makes it easier and more likely to provide a resilient infrastructure service.

Joint planning and exercising with emergency services can assist greatly in performance of critical infrastructure systems under duress.

Some Local and Regional Emergency Management Committees (LEMC and REMC) are comfortable to invite infrastructure providers to local planning and committee meetings, given how vital infrastructure can be to community emergency response and recovery. For LEMCs contact your local council (Local Emergency Management Officer - LEMO), and for regional committees contact your local Regional Emergency Management Officer (REMO) from NSW Police.

Community partnerships

Understanding the needs of the community can make the provision of infrastructure service more effective, especially in times of duress or emergency.

Partnerships with the community via pervasive technology can also help identify where an infrastructure network is not operating correctly or needs maintenance, as illustrated in the case study on crowdsourcing asset maintenance status.

Preparing for resilient operations

Preparing for resilient operations mean preparing for normal operation, the expected shocks and stresses that history has taught us are likely, but also the unexpected shocks that come with a more complex and complicated world in which the infrastructure delivers its service.

Much like resilient design, resilient operations requires a broadening of focus from a simple concern with immediate operations to a set of concerns covering the organisation, technology, upstream and downstream influences through the supply chain[25], and the community's expectations around infrastructure service.

Below are some of the ways that resilience can be built – which is key to being ready for when the unexpected disruption events impact on infrastructure service.

Understanding infrastructure criticality

Understanding a complex set of infrastructure as much as possible is not a trivial task. Deciding what's most important to keep operating, what is likely to fail, how your infrastructure is likely to fail and what effects that might have on a network or system, is complicated, but will aid decision-making when a crisis eventuates.

Resilience is especially important for those systems and assets which are critical to a community in a post-disruption or disaster environment. Any infrastructure that supports key facilities such as hospitals must be operated with its importance in mind. For more information on prioritising infrastructure based on its criticality, see the CIR Strategy Criticality Guide, and for information on ways that infrastructure systems are interconnected, see the CIR Strategy Interconnectedness Guide.

Data

Good asset data helps prevent failure, increase utilisation, and improve operation. Good asset data aids in the understanding of your infrastructure, and coupled with criticality and interconnectedness information, other sets of infrastructure as well.

Good data aids in the balance between cost, risk and asset performance, and can aid in avoiding unscheduled outages. Additional new data sources for predictive maintenance such as low-cost sensors are discussed in resilient maintenance.

Other data besides asset data can assist with resilient operations. Transport providers in Stockholm collect vehicle location data and use it to advise drivers on optimal travel routes, helping to optimise the operation of the transport network[30].

Modelling potential hazards and exercises

Although there are significant benefits to infrastructure providers of embedding resilience in their infrastructure and operations, it is clear that those benefits extend to the customers and community they provide infrastructure service to. The OECD modelled a major flood in Paris and found that although the infrastructure sector suffered between 30 and 50% of the direct losses in flood damages, the disruption to just electricity supply and transport infrastructure caused a flow-on effect of between 35% and 85% of business losses.[31] The importance of infrastructure to the community, and therefore the speed and efficacy of any disaster recovery, should not be underestimated. Ensuring that infrastructure is climate resilient will help to reduce direct losses to infrastructure providers, but also reduce the indirect costs of disruption to whole communities.

When modelling potential hazards, it is often useful to look at big disruptions – large emergency events that are unlikely. Testing plans and scenarios against large disruptions often helps with smaller disruption events, but only exercising or testing against small events is unlikely to help infrastructure organisations and the staff that must respond in large events that often overwhelm local capability to cope.

Training hard can often decrease the shock that comes with a large natural hazard or human-made threat and allow a swifter and more effective response.

Emergency planning and management

For critical infrastructure providers the operations phase also means integrating infrastructure into emergency and security planning. More guidance on this is included in the CIR Strategy Organisational Resilience Guide.

Simulating failure

Simulations can aid understanding how infrastructure systems are likely to fail. By understanding what other systems and infrastructures the failure of a system may impact, partnerships can be created to decide how to address these failure scenarios.

Understanding failure modes can assist with strategies to avoid failure, but also to respond to and manage a failure when it occurs, or take pre-emptive failure which might include increasing redundancy, to ensure failed assets do not impact on infrastructure service provision.

Enhancing response and recovery

By utilising data, failure simulations, and good understanding of infrastructure and other connected infrastructures, response and recovery to emergency situation can be enhanced.

Predicting failures can allow intervention prior to failure, or pre-positioning of repair crews, equipment and spares in the event of pre-warning to large natural hazard events.

Having well understood and effective processes for response and recovery allows infrastructure workers to more effectively respond to emergency events and minimise infrastructure service disruption. Process-based resilience emphasizes the capability of people to adapt infrastructure to manage surprise[25] and allows decision-makers to take a more wholistic view of infrastructure service provision.

Predicting potential shortfalls in the ability to manage an emergency event can activate mutual assistance agreements with other providers, which can include staff, parts or resources and even finances (or simply an agreement to meet costs).

Providing resilient operations

Emergency response

Well prepared organisations can mobilise pre-staged staff, equipment and spare parts ahead of predicted hazards such as cyclones or predicated floods. Organisations who have good understanding of asset criticality and interdependencies can equip their repair crews with information based on service restoration priorities.[32] This often relies on the partnering between organisation outlined above, with relationships both inside the organisation and between organisations being critical to the success of the emergency response.

Learning from previous hazards and events

Smaller or averted crises, near-misses, minor events and even disruptions successfully mitigated through normal operation can be used to learn from and increase the adaptive capacity of the systems to provide infrastructure service.[33] Data can be gathered on the solutions or strengths that allowed the system to avert a possible event, or the weaknesses that led to the occurrence of the event. This data can be used to make the system more resilient as opportunities arise and can be used to create simulations or exercises to test the system against realistic scenarios or extrapolated for large-scale exercises.

Safety in operations.

Risk management is more effective if it is underpinned through a culture of safety that includes training and education and community and business awareness.[34] Safety should not be isolated from core (business) process, nor vice versa. Safety is the prerequisite for productivity, and productivity is the prerequisite for safety. Safety must therefore be achieved by improving the core processes rather than by constraining them.[22]

In the same way that safety is embedded across most, if not all, infrastructure organisations in Australia, resilience and sustainability – that is, operating with an eye to the future, should also be embedded within the culture of infrastructure service organisations to better serve their communities, and also their shareholders.[16]

Resilient reconstruction: build back better

Infrastructure reconstruction costs can form a significant portion of disaster reconstruction costs after extreme weather. It is estimated that $17bn is likely to be spent on the direct replacement of infrastructure due to disaster damage up to 2050 in Australia alone.[35]

Building back better – integrating resilience into the reconstruction of infrastructure – has all of the benefits of resilient planning and design of normal projects over the life of the asset. In addition, it helps support communities to regain their livelihoods. Reconstructing assets better able to withstand natural hazards (resilience), reconstructing faster (being prepared for disasters), and building back more inclusively (partnering with other stakeholders) infrastructure owners and communities can realise major benefits, estimated to save about 31% of current losses due to natural hazards.[36] There is also the benefit of a newer asset capable of reducing total cost of ownership and maintenance costs.

Building back better doesn't have to be just about the physical infrastructure. If a process or supporting system fails, and infrastructure outage duration is longer than it needs to be, improving a business process, organisational structure or operating procedure is also building back better.

Further reading

Further reading includes items that explain the principles of resilient operations further and examples of resilient operations from around the world.

Operations and Maintenance in the Whole Building Design Guide. 2018. National Institute of Building Sciences. www.wbdg.org/facilities-operations-maintenance.

Hollnagel, Erik. (2010). *Resilience Engineering and Integrated Operations in the Petroleum Industry*. 2010. www.researchgate.net/publication/282325239_Resilience_Engineering_and_Integrated_Operations_in_the_Petroleum_Industry/download

Lloyd's. 2017. *Future Cities: Building Infrastructure Resilience*. Emerging Risk Report 2017, Society and Security. hwww.lloyds.com/news-and-risk-insight/risk-reports/library/society-and-security/arup

Resilient maintenance

Infrastructure cannot be resilient if it is poorly maintained. Increasing climate and disaster risk increases the resources, expertise and skills needed to maintain infrastructure. Maintenance also preserves the economic value of infrastructure investment, extending the life of infrastructure into the future.[37]

The relationship between operations and maintenance is heavily intertwined. What provides benefit in operations as outlined in the Resilient Operations section, generally holds true for resilient maintenance as well.

This section on maintenance is broken up into the three guiding principles of the CIR Strategy of Partner, Prepare and Provide.

Partnering for resilient maintenance

Partnering for resilient maintenance can provide benefits for all stakeholders. Vegetation maintenance (the clearing of trees and vegetation around infrastructure, especially overhead power lines) is often cited as key for emergency management around electricity infrastructure. Taking a resilience approach would step beyond the reaction of vegetation maintenance to create planned vegetation corridors with low-growing trees that don't introduce hazards to overhead power lines. This could save millions of dollars in vegetation management costs over the lifetime of an asset.[38] Partnering with other CI providers on maintenance programs can also create economies of scale, such as the case study in the appendix of Essential Energy's *Plan Before you Plant* guide, which informs the public and other infrastructure providers such as councils on how to best manage vegetation around electricity infrastructure. Not only does this reduce Essential Energy's vegetation maintenance costs, it saves councils time and cost by ensuring they plant the best green infrastructure in the best locations to benefit both their community and the infrastructure they rely upon.

Enhancing partnerships with subcontractors is key to improved resilience as the photo below illustrates.

Figure 4: Sub-optimal vegetation maintenance reduces infrastructure resilience

This vegetation clearing around the electricity line may actually meet the specified clearance distance, but completely misses the point. In high winds branches are more likely to drop on to the conductors and cause outages that affect service provision to the community.

If the maintenance subcontractor can understand the bigger picture of why they are trimming the trees, perhaps through a performance contract or similar[25], they can become active partners in ensuring infrastructure resilience for the community and reduce maintenance costs.

Preparing for resilient maintenance

Most infrastructure organisations are likely to use a computer-aided asset management systems to schedule maintenance, but new advancements in asset and works management systems can often use geographical tagging and logic to optimate maintenance schedules and reduce lost time accessing infrastructure assets.

Computer-aided maintenance and asset management systems can sometimes be linked to low-cost sensors to increase this efficiency and tailor maintenance schedules as required. These may also be tied to systems management where maintenance can be scheduled for periods of low asset utilisation to have least (or no) impact on infrastructure service.[39]

Using all available avenues for optimising maintenance programs and funding, increases the resilience of infrastructure to shocks and stresses.

Predictive maintenance

New technologies, including low costs remote sensors, provide greater data on the condition and performance of critical infrastructure and can be used by providers for predictive maintenance and improving the benefits of planned maintenance.[40]

Reactive maintenance is often more costly and must be done in shorter timeframes than predictive maintenance.

Sticking to rigid maintenance schedules may leave assets exposed for long periods of time or over-maintained, where additional costs do increase overall asset or system resilience, reliability or performance.

An example of low-cost sensors for predictive maintenance is included in the case studies at the Appendix to this document.

Providing resilient maintenance

Not completing resilient and timely maintenance on infrastructure systems, networks and assets can result in reductions in reliability and significantly more emergency work. Emergency work is sometimes poorly scoped and completed under extreme deadlines, which leads to increases in the total cost of ownership of the asset, and sub-optimal distribution of maintenance funding.[41]

Monitoring and inspection

Real-time or near-real-time monitoring with low-cost sensors can provide useful information about asset performance which can be used for more effective maintenance and faster emergency response.[25] It can also highlight early deterioration[23] and enable maintenance or replacement prior to any service interruption, or at least a scheduled rather than unplanned outage. It can also reduce physical inspection requirements.

Technology can also assist when inspections are needed. Drones (or unmanned aerial vehicles UAVs) can inspect assets without any need for the operator to leave the ground, particularly useful for tall or hard to access infrastructure assets.

Performing maintenance

The benefits of effective maintenance scheduling flow through to maintenance crews as well, as they will see that their time is more valued, and they are performing better with less backlogs.

Equipping crews with additional items beyond their normal maintenance task can yield significant benefits. For example, equipping maintenance crews with non-destructive testing tools can allow them to identify and potentially remedy issues before they cause an outage to the infrastructure service.[25]

Further reading

Further reading includes items that analyse the state of infrastructure maintenance in Australia, explain the principles of resilient maintenance further and examples of resilient maintenance practice from around the world.

Infrastructure Australia. 2015. *Infrastructure Maintenance*. Available at www.infrastructureaustralia.gov.au/sites/default/files/2019-07/GHD-Infrastructure-Maintenance.pdf

Operations and Maintenance in the Whole Building Design Guide. 2018. National Institute of Building Sciences. www.wbdg.org/facilities-operations-maintenance.

Lloyd's. 2017. *Future Cities: Building Infrastructure Resilience*. Emerging Risk Report 2017, Society and Security. www.lloyds.com/news-and-risk-insight/risk-reports/library/society-and-security/arup

Appendix A: Case studies

Case study: Partnering for design - Essential Energy's vegetation maintenance education

It's not just the infrastructure that an organisation designs itself that impacts on critical infrastructure assets and systems.

This is especially true when natural hazards impact on a community, when climatic events can bring multiple types of infrastructure into contact with each other in ways they weren't designed for.

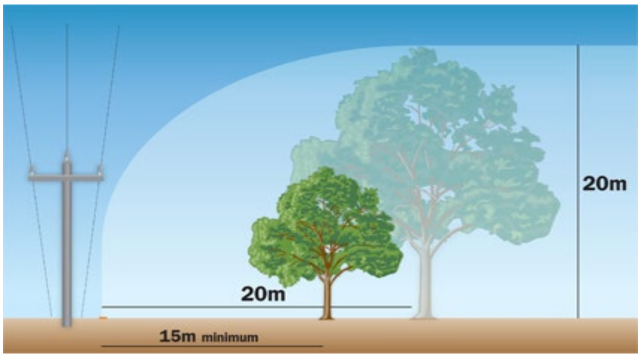
Short-sighted decisions relating to green infrastructure can be costly, as has been the case in recent years with the susceptibility of African Mahogany trees in Northern Australia to be impacted by cyclones and exacerbate damage to people, other infrastructure and private property. [1]

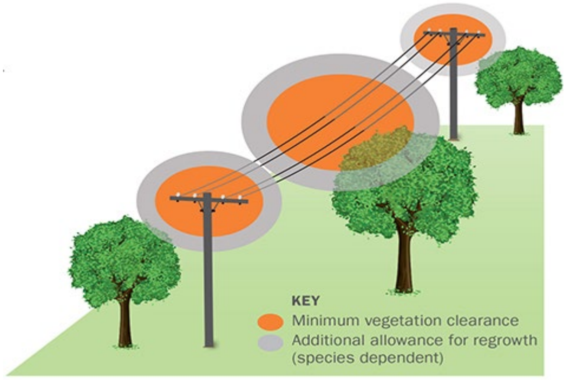
Collaborations between infrastructure providers, councils and the community, can ensure that green infrastructure does not adversely affect built infrastructure and vice-versa.

These sorts of relationships can be extended through partnerships not just in design, but in emergency planning, preparedness, response and recovery, to allow infrastructure providers to share resources and provide more cohesive responses.

Click here for more information on Essential Energy's Plan Before You Plant Guide.

Click here for more information on wind-resistant green infrastructure from Greening Australia.





[1] ABC News. *One year on from Cyclone Marcus, a Darwin tree-planting scheme promises not to repeat past mistakes.*

Case study: resilient operations - planning for emergency response with Transport for NSW

Rail is a significant transport link for many people within the greater Sydney area and may provide a supplementary means of evacuation should major roads be closed during a flood event.

The effects of flood on rail assets can include:

- Flooding of stations, rail lines and control systems
- De-energisation of overhead electricity lines (supply or traction)
- Increased boarding times and service delays
- Land slippage or rail line washaway

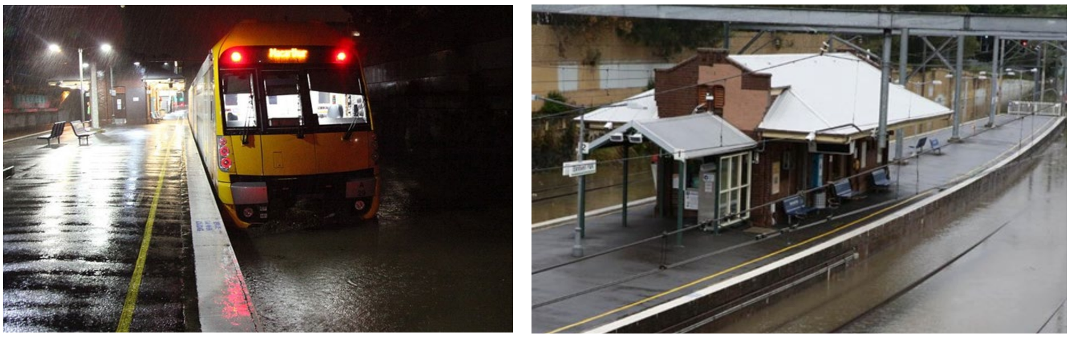


Figure 5: Flood effects on rail assets

Transport for NSW uses tabletop exercises and weather modelling at key locations to predict impact on their assets from extreme weather. This gives a good understanding of not only the impact to rail assets and services, but also the capability of the network to provide evacuation routes to displaced persons during an emergency event.

Figure 6: Using weather models to predict flood impact on rail assets

The models also allows predictions around graceful degradation of services, i.e. where an infrastructure service doesn't just simply stop working but can operate at a reduced level even though it has been impacted by a natural hazard event.

Transport for NSW can estimate the ability to evacuate passengers by rail based on several contingencies, including operating without signals, operating without electricity, and operating without both with diesel trains.

This ability to predict a level of operation even in the worst of circumstances allows better interagency planning for extreme events and contributes to a safer, more secure NSW.

Case study – Community as a partner in infrastructure maintenance

Mobile applications for reporting infrastructure damage

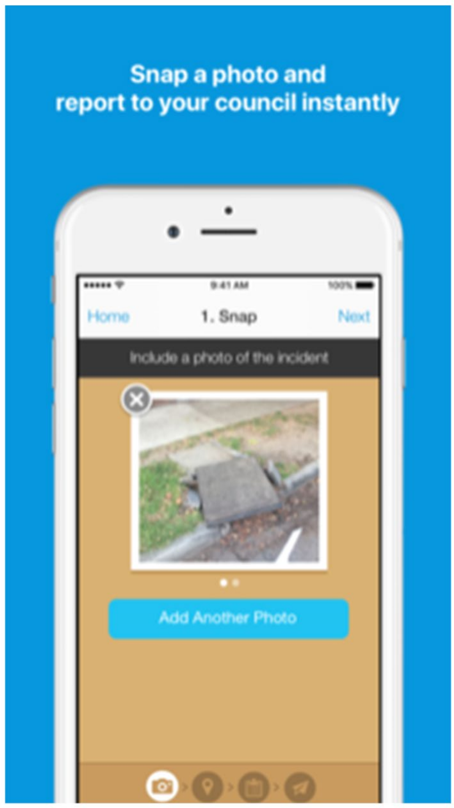
A number of NSW critical infrastructure providers are promoting the use of smartphone technology in order to enhance their response to critical and routine infrastructure issues.

Some organisations are using software they have developed in house, whilst others are promoting the use of publicly available apps to residents so they can easily and instantly capture, report and provide feedback to their local Council and other infrastructure providers on common issues such as water leaks, pot holes, fallen trees, cracked pavements, broken playground equipment, graffiti, illegal dumping and a range of other issues that need attention.

Some platforms are increasingly sophisticated and allow transfer of images and use the smart phone's GPS location. These platforms provide an example of how smart phone technology can be used to crowdsource information from the community in order to enhance response to critical and routine infrastructure issues.

Further information is available from:

- [Bega Valley Shire Council]
- [Campbelltown City Council]
- [Sutherland Shire Council]
- [Essential Energy]



Appendix B: Abbreviations and glossary

Abbreviation	Meaning
All Hazards	An approach to manage the uncertain nature of emergency risk by building resilience to all or multiple hazards
CI	Critical Infrastructure
CIP	Critical Infrastructure Protection (protection against terrorism specifically)
CIR	Critical Infrastructure Resilience (protection against all hazards)
Dependency	When a critical infrastructure relies on another critical infrastructure, good or service for continued service provision
Disaster	When a hazard or threat intersects with a vulnerability, and the ability of local resources or business as usual to cope is overwhelmed
EMDRR	NSW Emergency Management and Disaster Resilience Review
Hazard	A threat, usually natural, that unintentionally disrupts critical infrastructure service provision
Infrastructure Provider	An organisation responsible for providing an infrastructure service at a state, regional or local level, whether publicly or privately owned
Interdependency	When multiple critical infrastructures rely on each other for continued service provision
Mitigation	Measures taken in advance to reduce the likelihood or consequence of a hazard or threat.
sSector	An industry or service group identified within the CIR Strategy
SEMC	State Emergency Management Committee
SCADA	Supervisory Control and Data Acquisition (SCADA) systems are used for remote monitoring and control in the delivery of critical services such as electricity, gas, water, waste and transportation.
SLERA	NSW State Level Emergency Risk Assessment
Threat	A hazard, usually man-made, that deliberately disrupts critical infrastructure service provision
TISN	Trusted Information Sharing Network (information sharing network co-ordinated by Commonwealth Home Affairs Department)
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards. (Source: NDRRF Glossary)

Appendix C: References

[1] Resilience NSW, 2017, *NSW State Level Emergency Risk Assessment*. Available at https://www.opengov.nsw.gov.au/publications/19463.
[2] 100 Resilient Cities. *What is Urban Resilience?* Available at www.100resilientcities.org/resources/.
[3] Australian Business Roundtable for Disaster Resilience & Safer Communities, 2016, *The Economic Cost of the Social Impact of Natural Disasters.* Available at australianbusinessroundtable.com.au/our-papers/social-costs-report.
[4] State of New South Wales through Office of Environment and Heritage, 2016, *About Climate Change in NSW.* Available at climatechange.environment.nsw.gov.au/About-climate-change-in-sssss.
[5] State of New South Wales through NSW Police Force, *Secure NSW: The Current Security Environment.* Available at www.secure.nsw.gov.au/the-current-security-environment/.
[6] Commonwealth of Australia, 2017, *Australian Cyber Security Centre 2017 Threat Report.*
[7] Resilience NSW, 2018, *Critical Infrastructure Resilience Strategy*. Available at https://www.opengov.nsw.gov.au/publications/19460.
[8] U.S Department of Homeland Security, National Infrastructure Advisory Council, 2009, *Critical Infrastructure Resilience Final Report and Recommendations*.
[9] Asset Management Council Ltd., 2014, Framework for Asset Management: Asset Management Body of Knowledge (AMBoK). (Engineers Australia Technical Society).
[10] Gallego-Lopez, C.; Essex, J (with input from DFID), *Designing for infrastructure resilience. Evidence on Demand, UK*, 2016, 22p www.gov.uk/dfid-research-outputs/introducing-infrastructure-resilience .
[11] Commission for Architecture and the Built Environment (CABE) UK
[12] Infrastructure Partnerships Australia, 2011, *Road Maintenance: Options for Reform*. www.infrastructure.org.au/Content/RoadMaintenanceOptionsforReform.aspx
[13] Gallego-Lopez, C.; Essex, J. (with input from DFID) *Designing for infrastructure resilience. Evidence on Demand, UK,* 2016, 22p www.gov.uk/dfid-research-outputs/introducing-infrastructure-resilience
[14] Infrastructure Australia, 2015, *Infrastructure Maintenance.* Available at infrastructureaustralia.gov.au/policy-publications/publications/files/GHD-Infrastructure-Maintenance.pdf
[15] OECD, 2018, *Climate-resilient infrastructure,* OECD Environment Policy Papers, No. 14, OECD Publishing, Paris, doi.org/10.1787/4fdf9eaf-en.
[16] Investor Group on Climate Change, 2018, *Investing in Resilience: Tools and Frameworks for Managing Physical Climate Risk*. igcc.org.au/wp-content/uploads/2018/07/IGCC-Investing-in-Resilience-report_FINAL.pdf
[17] Guthrie, P.; Konaris, T, 2012, *Infrastructure and Resilience*. Government Office of Science, Foresight project 'Reducing Risks of Future Disasters: Priorities for Decision Makers'. UK, 2012.
[18] Gallego-Lopez, C.; Essex, J. (with input from DFID) *Designing for infrastructure resilience. Evidence on Demand, UK,* 2016, 22p www.gov.uk/dfid-research-outputs/introducing-infrastructure-resilience .
[19] Sansavini, Giovanni, 2016, *Engineering Resilience in Critical Infrastructures* in IRGC. Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016
[20] Jackson, Scott, 2016, *Principles for Resilient Design - A Guide for Understanding and Implementation* in IRGC (2016), Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016. www.irgc.org/riskgovernance/resilience
[21] Häring, I. Scharte, B. Stolz, A. Leismann, T. Hiermaier, S, 2016, *Resilience Engineering and Quantification for Sustainable Systems Development and Assessment: Socio-technical Systems and Critical Infrastructure*. IRGC (2016). Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016
[22] Hollnagel, Erik. (2010). Resilience Engineering and Integrated Operations in the Petroleum Industry. www.researchgate.net/publication/282325239_Resilience_Engineering_and_Integrated_Operations_in_the_Petroleum_Industry.
[23] El Nakat, Ziad Salim, 2015, *Disaster risk management in the transport sector: A review of concepts and international case studies*. Washington, D.C. : World Bank Group. documents.worldbank.org/curated/en/524081468188378328/Disaster-risk-management-in-the-transport-sector-a-review-of-concepts-and-international-case-studies.
[24] Hiermaier, S.; Hasenstein, S.; and Faist, K., 2017, *Resilience Engineering: How to Handle the Unexpected*. 7th REA Symposium 26-29th June 2017.
[25] Hall, P.; Carter, C.; Bill, E.; O'Connor, M.; Simpson, M., 2017, *Resilience Return on Investment (RROI) via The Resilience Shift*. 30/06/2017.
[26] Kupers, R. and Foden, M., 2017, *Learning for Resilience and Complex Systems Thinking*. Agenda Setting Scoping Studies Summary Report via The Resilience Shift. 15/06/2017.
[27] Staddon, C.; De Vito, L.; Zuniga-Teran, A.; Schoeman, Y.; Hart, A.; and Booth G., 2017, *Contributions of Green Infrastructure to Enhancing Urban Resilience* in Agenda Setting Scoping Studies Summary Report for The Resilience Shift. 30/06/2017.

[28] Gallego-Lopez, C.; Essex, J. (with input from DFID), 2016, *Designing for infrastructure resilience. Evidence on Demand*, UK.
[29] Infrastructure Australia, 2015, *Infrastructure Maintenance*. Available at infrastructureaustralia.gov.au/policy-publications/publications/files/GHD-Infrastructure-Maintenance.pdf.
[30] Infrastructure NSW, 2018, *Building Momentum: State Infrastructure Strategy 2018-2038*. insw-sis.visualise.today/documents/INSW_2018SIS_BuildingMomentum.pdf.
[31] OECD, 2018, *Climate-resilient infrastructure*, OECD Environment Policy Papers, No. 14, OECD Publishing, Paris, doi.org/10.1787/4fdf9eaf-en.
[32] Snell, M.; Eisenberg, D.; Seager, T.; Spierre-Clark, S.; Young, Joon Oh; Thomas, J.; and McBurnett, L., 2016, *A Multidimensional Review of Resilience: Resources, Processes, and Outcomes.* IRGC (2016). Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016.
[33] Gößling-Reisemann, Stefan, 2016, *Resilience – Preparing Energy Systems for the Unexpected*. IRGC. Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. v29-07-2016.
[34] Lloyd's, 2017, *Future Cities: Building Infrastructure Resilience. Emerging Risk Report 2017*, Society and Security. www.lloyds.com/news-and-risk-insight/risk-reports/library/society-and-security/arup.
[35] Australian Business Roundtable for Disaster Resilience and Safer Communities, 2016, *Building Resilient Infrastructure.* Available at australianbusinessroundtable.com.au/our-research/resilient-infrastructure-report.
[36] The World Bank and The International Bank for Reconstruction and Development, 2018, Stephane Hallegatte, Jun Rentschler, Brian Walsh. *Building Back Better: Achieving Resilience through stronger, faster, and more include post-disaster reconstruction*.
[37] Gallego-Lopez, C.; Essex, J. (with input from DFID), 2016, *Understanding Risk and Resilient Infrastructure Investment. Evidence on Demand, UK*.
[38] Queensland Government, 2011, *Planning for stronger, more resilient electrical infrastructure.*
[39] OECD (2018), "Climate-resilient infrastructure", OECD Environment Policy Papers, No. 14, OECD Publishing, Paris, doi.org/10.1787/4fdf9eaf-en .
[40] Commonwealth Scientific and Industrial Research Organisation, 2017, *Monitoring the health of structures*. Available: www.data61.csiro.au/en/Our-Work/Future-Cities/Planning-sustainable-infrastructure/Structural-health-monitoring.
[41] Marathe, N.; Kempe, K.; Schaeper, N., 2018, *Effective Renewals Planning Process With Robust Investment Planning For Treatment Operating Assets In Sydney Wate*r. Ozwater 2018, 8 May 2018.