Towards the Futureproofing of UK Infrastructure

Tariq Masood*, PhD

[1]Distributed Information and Automation Laboratory (DIAL), Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS

[2]Centre for Smart Infrastructure & Construction (CSIC), Department of Engineering, University of Cambridge, Trumpington Street, Cambridge

Duncan McFarlane, PhD

[1]Distributed Information and Automation Laboratory (DIAL), Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS

[2]Centre for Smart Infrastructure & Construction (CSIC), Department of Engineering, University of Cambridge, Trumpington Street, Cambridge

Ajith Kumar Parlikad, PhD

[1]Distributed Information and Automation Laboratory (DIAL), Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS

[2]Centre for Smart Infrastructure & Construction (CSIC), Department of Engineering, University of Cambridge, Trumpington Street, Cambridge

John Dora, BSc (Hons) [CEng FICE FRMetS]

[3]John Dora Consulting Limited, Charlbury, Oxfordshire OX7 3RW

Andrew Ellis

[4]Heathrow, London

Jennifer Schooling, PhD

[2]Centre for Smart Infrastructure & Construction (CSIC), Department of Engineering, University of Cambridge, Trumpington Street, Cambridge

* Email address of corresponding author: tm487@cam.ac.uk

Abstract

Ensuring long-term performance from key infrastructure is essential to enable it to serve society and to maintain a sustainable economy. The futureproofing of key infrastructure involves addressing two broad issues:

(i) Resilience to unexpected or uncontrollable events e.g. extreme weather events; and

(ii) Adaptability to required changes in structure and / or operations of the infrastructure in the future.

Increasingly, in their respective roles, infrastructure owners, designers, builders, governments and operators are being required to consider possible future challenges as part of the life cycle planning for assets and systems that make up key infrastructure.

In this paper, we report on a preliminary study aimed at exploring the following questions related to infrastructure and infrastructure systems:

- What does 'futureproofing' of infrastructural assets mean?
- Why and when to futureproof critical infrastructure?
- How can infrastructure assets and systems be prepared for uncertain future events?
- How can futureproofing considerations be incorporated into infrastructure asset management practices?

In order to seek answers to the above questions, we conducted two industrial workshops bringing together leading practitioners in the UK infrastructure and construction sectors, along with government policy makers. This paper captures lessons learnt from the workshops, and proposes a simple framework for linking futureproofing into broader asset management considerations. Case studies of Dawlish Railway and Heathrow Airport are also presented.

Keywords

Infrastructure futureproofing, Infrastructure planning; whole life management, Risk, Resilience, Change Management, Adaptability, Replaceability, Reusability, System stability.

1. Introduction

The aim of this paper is to explore the 'what, why and how' of infrastructure futureproofing – ensuring that a nation's infrastructure is fit for the future in addition to satisfying current needs. Infrastructure assets have long service lifetimes, and are therefore subject to a range of 'disruptions' over time such as extreme weather events, changes of use, and ageing. Identification of such disruptions and developing a strategy for mitigating the risks of such disruptions through effective asset management processes is essential for long-term sustainability of infrastructure systems. Although there is widespread agreement amongst practitioners about the need to address this, there is a lack of a structured, common approach for considering the changing future needs of infrastructure as part of their asset management plans. In order to help industry move towards this goal, this paper proposes a framework for infrastructure futureproofing, which includes a set of criteria that can be used for assessing the level of futureproofing in existing infrastructure systems. The framework was developed through a number of case studies and by conducting two industrial workshops bringing together leading practitioners in the UK infrastructure and construction sectors, along with government policy makers.

To begin, this paper presents an overview of infrastructure futureproofing and the need to consider the futureproofing of infrastructure assets. Following this, the paper covers general issues and views on how to futureproof infrastructure; some futureproofing strategies currently in use in the infrastructure sector, and their implications. A framework is proposed for assessing the futureproofing requirements of infrastructure, including a set of criteria for futureproofing assessment. The framework is supported by examples from two case studies. Key barriers to infrastructure futureproofing are presented. Finally, the ISO 55001 Asset Management standard is examined to highlight the interplay between futureproofing and infrastructure asset management, and the value of futureproofing over the life cycle of an asset is discussed. In addressing these key questions, the paper aims to clarify the role of futureproofing in the management of key infrastructure.

2. What is infrastructure futureproofing?

Futureproofing is the process of anticipating future events, changes, needs or uses in order to prepare appropriately, minimise impact and capitalise on opportunities (Atkins, UCL and DFID 2012). Other related terms used in the context of futureproofing are *obsolescence management* (Romero Rojo et al 2008; Romero Rojo 2011), *reconfigurability* (Koren et al 2013) and *digital preservation* (CCSDS 2012; Barbau et al 2014)). Shetty (2014) defined futureproofing in an asset management context as "the process of anticipating the distant future and taking actions to minimise risks and maximise opportunities for value realisation from assets". The term 'futureproofing' has also been used for long-term business continuity (ISO 22301 2012) and long-term information continuity (Masood et al 2013).

We define infrastructure futureproofing as *"the process of making provision for future developments, needs or events that impact on particular infrastructure through its current planning, design, construction, operation and maintenance processes"*. Essentially, infrastructure futureproofing involves the consideration of future disruptions in the asset management systems of the organisations responsible for infrastructure management.

There are generally two major dimensions of infrastructure futureproofing: (1) infrastructural resilience - resilience to unexpected / uncontrollable events and circumstances; and (2) change management capability - capability to adapt or respond to changing needs, uses or capacities.

Infrastructural Resilience: In simple terms, this property refers to the ability of the infrastructure to maintain/resume normal operations during/ after an adverse event. This might include ability to withstand climate change variations, flooding events or even terrorist actions. This addresses sustainable asset longevity and asset management for future revenue, i.e. developing resilience to emerging risks and liabilities as well as resilience against disruptions.

Adaptability and Change Management Capability: Flexibility to adapt to an unexpected and uncertain future means changing the way we build by allowing for future growth and capacity requirements (considering dimensions of capacity, suitability, usability and desirability that contributes towards achieving futureproofing). This also means building or managing a business to avoid / reduce impact of future change events, and taking account of future drivers (climate, carbon, resources, and population) in decision making in advance. Examples of futureproofing in this context include a capacity upgrade of an underground train station, easier reuse of substructure elements and buried structures, and allowing infrastructure life to be extended through capacity changes such as adding extra lanes to a bridge or building more floors on an existing building.

These definitions of infrastructure futureproofing are applicable to a wide scope of infrastructure including transport, energy, water and communication. However, because of the nature of the organisations engaged in this study, this paper is more focussed on transport infrastructure [rail, road and highway networks including structures e.g. bridges and tunnels; mass transit systems; railways; airports, etc].

3. Why consider futureproofing of infrastructure?

It is a significant commitment to consider futureproofing and take appropriate actions which increase the level of futureproofing of key infrastructure. Three key issues that motivate the need to futureproof infrastructure are:

(i) Ageing infrastructure and long operational lifetimes
(ii) Extreme weather events
(iii) Capacity enhancements and changing uses of key infrastructure.

Other reasons for futureproofing include risk reduction, and reduced effort in redesign, redevelopment, reconstruction or demolition with diminishing Govt. budgets, reduced life cycle costs, changes in legislation e.g. on carbon footprints and recognising opportunities for future exploitation. Wider social, economic and environmental benefits of futureproofing are also important for infrastructure with high vulnerability and lower capacity to respond to risks (Atkins, UCL and DFID 2012). These issues capture some of the evolving debates around the need for anticipating and managing future scenarios for critical infrastructure carefully and thoroughly. In resolving these key issues, it also needs to make economic sense to do so by measuring and quantifying value of potential disruption to a company's operation. We will now explore each of three key issues in detail.

3.1 Ageing infrastructure and long operational lifetimes

Infrastructure assets generally have long operational lifetimes. For instance, much of the UK's existing infrastructure was originally built in the 19th century, e.g. London's sewerage system and the Royal Albert Bridge over the River Tamar (DEFRA 2011). The national infrastructure has been recently assessed (ICE 2014) and was mostly found to be 'in need of attention' or 'at risk', with the exception of strategic transport (e.g. rail) and water infrastructure, which were considered to be 'adequate for now'. No major infrastructure category was graded as 'fit for the future'.

HM Treasury has recently identified planned investment needs in excess of £375 billion to replace ageing assets and those assets that don't comply with EU regulations, to help meet policy commitments e.g. climate change targets, support economic growth and to meet the future needs of a growing population (House of Commons 2014; Waller 2014). In order to achieve the investment goals, national infrastructure plan was first published in 2010 and is regularly updated every year since then (HM Treasury 2014; Waller 2014; HM Treasury 2013; HM Treasury 2010).

3.2 Extreme weather events

Climate and weather are changing globally. UK has recently faced a range of extreme weather events e.g. flooding, wind and snow storms and drought. Such natural hazards account for 10-35% of all delays or service interruptions to electricity, road and rail infrastructure (IPCC 2001; IPCC 2014; Committee on Climate Change 2014; DfT 2014a).

During 2009-2014, severe flooding in the UK caused a number of road bridges to collapse as well as disrupting the airports, road, and rail infrastructure (DfT 2014a; HM Government 2011). Well over a thousand major roads and another over a thousand railway assets are located in areas of significant chance of flood risk (Environment Agency 2009) (see Figure 1).

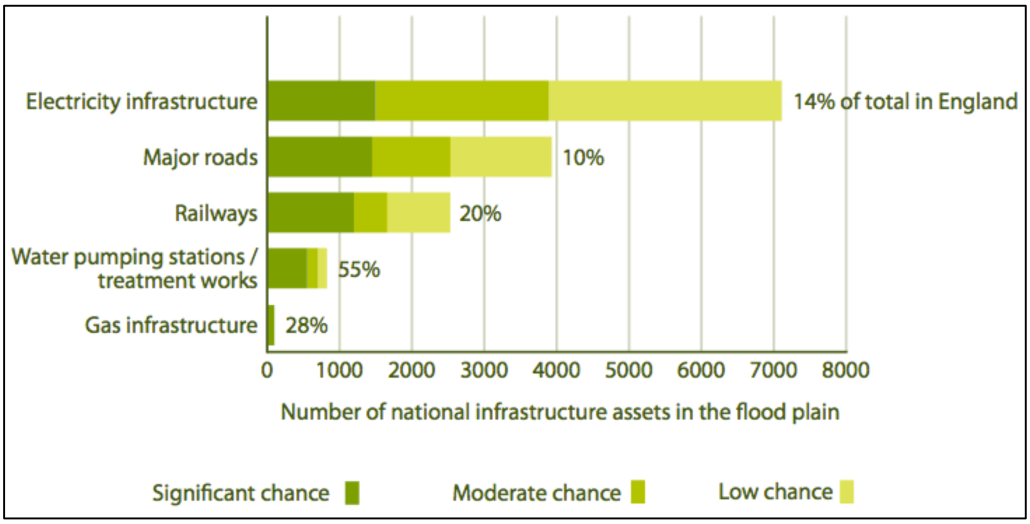

Figure 1: National transport and utilities infrastructure assets in flood risk areas (Environment Agency 2009)

The Intergovernmental Panel on Climate Change (IPCC) has predicted increasingly dramatic weather changes in the future, which highlights the need for infrastructure to be designed and maintained keeping future climate variations in mind (IPCC 2001; IPCC 2014).

These challenges are also increasingly being recognised by transport providers. Network Rail and the rail industry are keen to learn how climate change will affect their ability to achieve and deliver a safe railway, a highly reliable railway, increased capacity and value for money (Network Rail 2010; DfT 2014a). Network Rail's Tomorrow's Railway and Climate Change Adaptation (TRaCCA) programme has identified *heating and floods related impacts on safety, performance and likely negative impact from climate change* (Network Rail 2010; RSSB 2011; Dora 2014; Avery 2014).

Similarly, London's transport network has a number of areas that have the potential to be affected by weather related events e.g. flooding, overheating, low temperatures and snow (TfL 2015a). Transport for London (TfL) conducted Business Climate Change Risk Assessment exercise in 2011 (TfL 2015a) and the results suggest that there are many weather-related risks that fall under medium to very high impact but very low likelihood. Crossrail has also identified key *climate change impacts* as increased flooding (fluvial, tidal and pluvial or surface water), high temperatures (extreme weather events) and increased water scarcity (TfL 2015a; Paris 2011).

3.3 Capacity enhancements and changing uses of key infrastructure

Anticipated or unanticipated user driven changes to the loading of infrastructure and infrastructure systems are also expected to occur over long infrastructure life cycles, necessitating significant modifications to assets. The consequences of such disruptions and changing requirements are significant over long infrastructure life cycles.

For instance, problems at Heathrow due to winter snowstorms during winter 2010/11 were compounded by the lack of spare or contingency capacity at the airport as it already operated to its maximum every day (UK Parliament 2011). At present, Heathrow is planning to expand its capacity by reconfiguring its terminals. A number of capacity upgrade projects are being undertaken for underground stations in London e.g. Bond Street, Tottenham Court Road, and Bank/Monument underground stations (worth hundreds of millions of pounds) (TfL 2015b). London's rail capacity is also being enhanced by building Crossrail (Europe's largest infrastructure project worth £14.8 billion) (Crossrail 2015).

Land use changes and user driven future changes to infrastructure and infrastructure systems also need to be considered. Examples include Canary Wharf redevelopment, changing modes of use of buildings e.g. warehouse to residential conversion or change of a residential block into an office building or vice versa. The consequences of such disruptions and changes over long infrastructure life cycles are potentially significant. However, there has been very little systematic understanding of the benefits and costs of providing flexibility at design stage to incorporate future growth and change (Fawcett 2011).

When developing strategies for futureproofing infrastructure assets against the aforementioned disruptions, organisations need to also consider the socio-economic and behavioural impact of those actions, and their wider implications. For instance, would constructing another lane of M25 just increase the demand, and result in the need for further lanes? Such behaviours are a result of complex interrelationships between organisational strategies, government policies, and various other factors, making them hard to predict. However, identifying the possible scenarios and including them in the assessment process would be beneficial.

4. Barriers to infrastructure futureproofing

Figure 2 identifies a number of the key barriers to infrastructure futureproofing with key elements noted in each of the categories (Masood et al 2014). In the figure the barriers have been categorised into key areas. Clearly if the economic value of futureproofing was clearer, other barriers would be reduced.

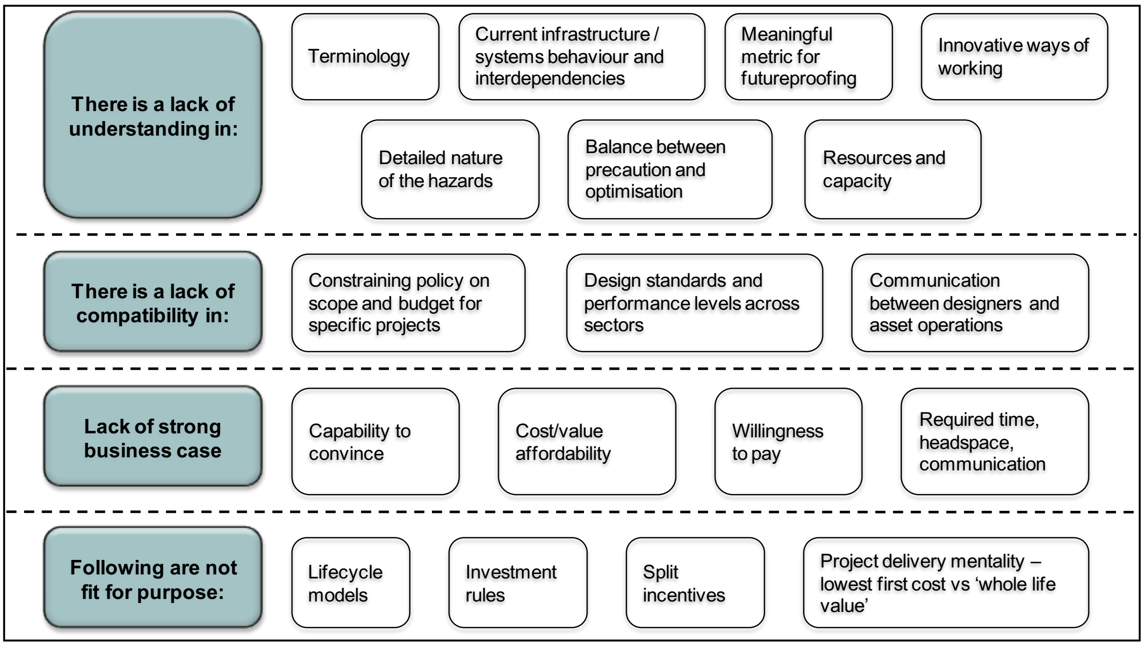

Figure 2: Key barriers to infrastructure futureproofing (Masood et al 2014)

The identified barriers to futureproofing highlight the need to take action in this regard. The key actions will be based around enhancing understanding of the concepts e.g. establishing a common terminology and meaningful metrics for futureproofing. Another action will be to enhance communication and introduce effective feedback loops between different stakeholders, for example feeding back knowledge from operators / maintainers to designers to inform futureproof design decisions. Stronger business cases for infrastructure futureproofing are also required. Steps need to be taken to align investment rules with whole life thinking as well as raising awareness levels across industry on futureproofing issues. These actions need to be taken with a shared responsibility amongst Government, Industry and other stakeholders.

5. How to futureproof infrastructure?

The growing set of drivers for a more formal and considered approach to managing the future of critical infrastructure, naturally leads to the question of how infrastructure can be futureproofed. To a certain extent, companies already do futureproof, using a number of strategies for assessing and managing non-civil assets and systems across life cycle stages. These strategies are summarised in Figure 3 which represents the outputs from an industrial futureproofing workshop, literature and a series of interviews with practitioners (see acknowledgements for the list of companies involved). The figure classifies futureproofing strategies according to whether they are design-related or management-related (x-axis), and whether they are focussed on individual assets or at the system level (y-axis). For example, obsolescence forecasting is used in the aerospace and defence sectors at the design stage as well as through-life for dealing with long life products and services (Romero Rojo 2011).

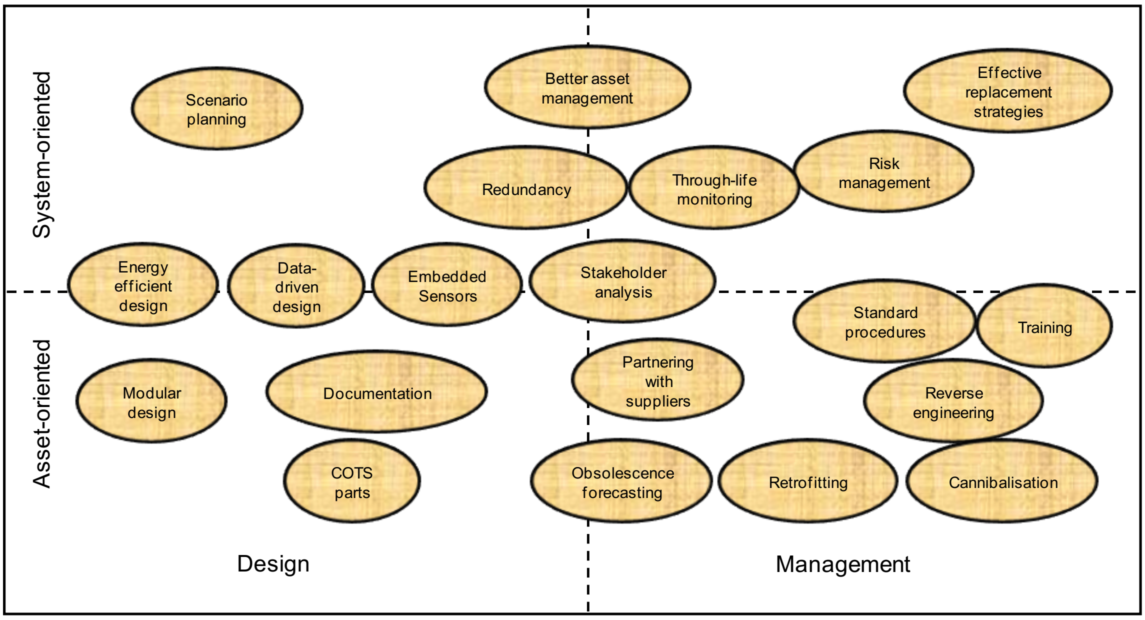

Figure 3: Futureproofing strategies for industrial assets and systems

Futureproofing-related strategies relevant for civil infrastructure assets and systems partially overlap with those used for non-civil assets and systems. For example, Heathrow considers future issues while conducting its overall master planning exercises in following areas: runway capacity, stand capacity, terminal capacity, surface access and infrastructure like heating, cooling, power, aircraft fuel systems, drainage, communications and IT, and baggage (Ellis 2014). Some organisations carry out long term scenario planning and robust decision-making techniques while also considering strategic growth and resilience of the network capacity, security and climate change views e.g. Atkins' futureproofing cities project (Atkins, UCL and DFID 2012).

Other futureproofing strategies used for infrastructure assets and systems include: improving decision support tools, developing strong governance processes, working with and influencing asset owners and policy makers on ensuring efficient planning and design of interconnected infrastructure assets, preparing climate change adaptation plans via conducting feasibility studies and investing in sustainability and energy monitoring capability enhancement.

However, it emerges from discussions with related organisations that there is a lack of a structured, common approach for considering the changing future needs of infrastructure as part of its asset management plans. Current approaches miss the opportunity to consider and assess infrastructure futureproofing at a system level (McBain 2014; Dora 2014). Moreover, unexpected asset failures may also be partly due to a lack of systematic consideration of future infrastructure scenarios during earlier life cycle stages e.g. planning and design.

6. A structured framework for considering infrastructure futureproofing

In this section we propose a systematic approach to infrastructure futureproofing. It is proposed that as a minimum the following should be considered while considering futureproofing of infrastructure (see Figure 4):

1. Conduct requirements analysis
2. Analyse current infrastructure management practice
3. Identify and analyse futureproofing considerations
4. Identify and analyse key issues related to a futureproofing strategy
5. Develop a model for futureproofing-considered infrastructure management

These elements represent a potential pathway to establishing future consideration as part of an overall infrastructure asset management plan.

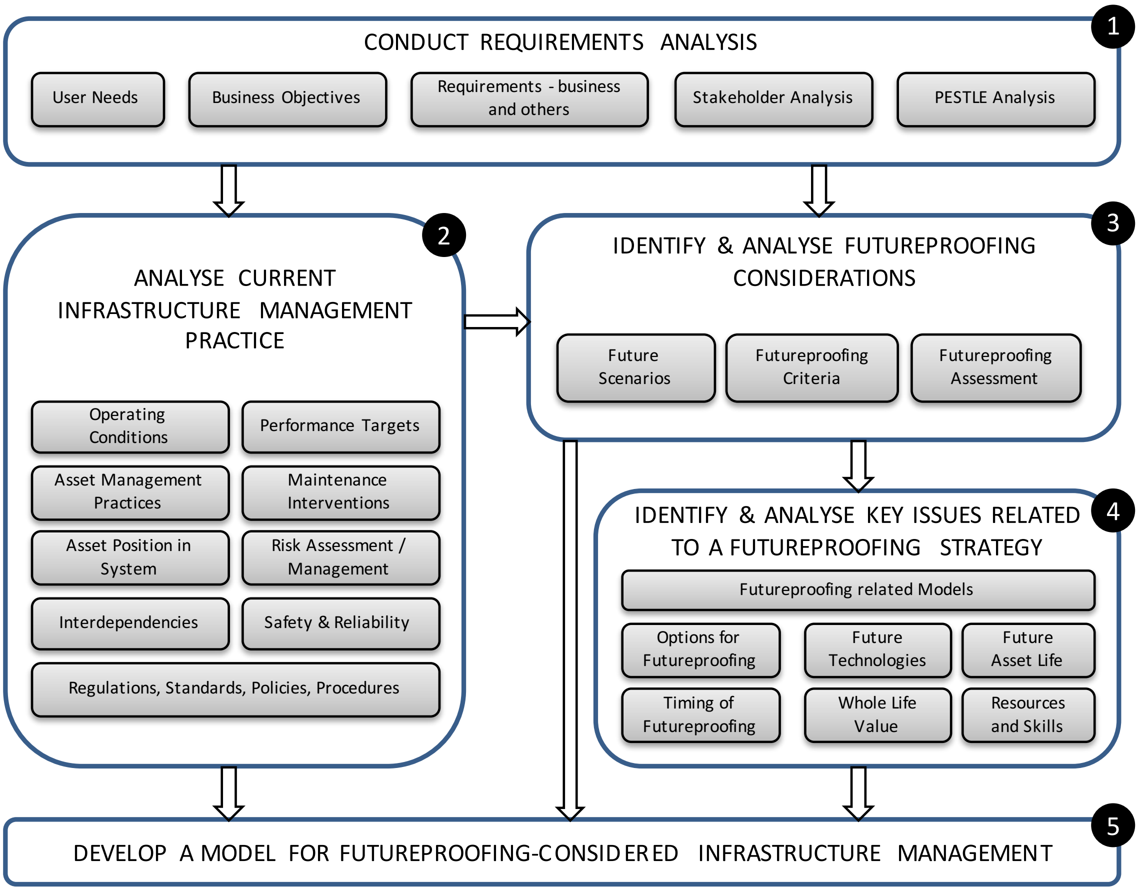

Figure 4: A framework for futureproofing of infrastructure portfolio

For each of the elements of the framework proposed in Figure 4, we will now identify key issues and conclude by identifying key steps remaining to consolidate these requirements into a useable framework.

To illustrate the approach being proposed, two case studies will be used to exemplify the framework where appropriate: *Dawlish Railway* and *Heathrow Airport*. These cases have been selected because of the very different future challenges they face. In the case of Dawlish railway, the key issue is the need for resilience in the face of environmental events, while Heathrow's challenges are more concerned with the rapidly changing needs of its customers and the growth of the industry generally.

Network Rail's four mile long Dawlish sea wall is actually a series of wall sections of different construction forms, running from Teignmouth through Dawlish to Langstone Rock at the western tip of Dawlish Warren. Along this stretch parts of the walls are separated by tunnels. The walls have been maintained on a basically reactive basis for at least the past 30 years with the only recent investment in the early 2000s being around £10M spent on forming a concrete toe along the base of the wall, which has served to increase the wall's resistance to undermining. It has suffered from major failures in the past but none as serious as around 80 metres breach on the 4th February 2014 due to wind and sea's high tide washing away ballast and the foundations on which the track is built (DfT 2014a).

Taking about eight weeks to repair and accompanied by numerous other failures, damage to the station at Dawlish and serious geotechnical failure of the cliffs above the line near Teignmouth, and the storms over the winter of 2013/14 have brought into question the future of the sea wall and the resilience of this portion of the Great Western Main Line that serves much of Devon and is the only line connecting Cornwall with the rest of the country. These require spending roundly £600K pa maintaining Network rail-owned sea and estuary walls between Exeter, Newton Abbot, and Exmouth (Network Rail 2014a).

The *Heathrow Airport* case study provides insights into future proofing at the Heathrow airport which needs to consider a wide range of variables that will, or might change in the future. Political, economic, environmental, technological factors all need to be factored into decisions about how to futureproof the on-going development of the airport.

6.1 Conduct requirements analysis

Initially, a detailed (future) requirements analysis is needed. During this stage, user needs and requirements (business and external) must be identified by conducting PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis and stakeholder analysis (e.g. UK Government, Regulators, Public, Investors, Media and Legal bodies).

The requirement to provide a service connecting Exeter with stations between Exeter and Newton Abbot is enshrined in the First Great Western franchise and Network Rail's operating licence set out by the Office of Rail Regulation and the Department for Transport via the

Railways Act provisions (Network Rail 2009). These provisions are reviewed and confirmed within the five-year regulatory cycle (DfT 2014b).

RSSB (2008) showed how climate-change induced sea level rise and increased storminess will impact the *Dawlish Railway*. Dawson (2012) reinforced this by examining disruptions, damages, repairs and wider economic consequences for the south west.

The development of utilities infrastructure at the *Heathrow Airport* requires thinking about the long term plan and growth of the airport and futureproof to ensure the infrastructure will meet those requirements. An example of this is the management of the airport's high voltage electrical network where there is a long term plan to create a network that offers both improved resilience and increased capacity. This is then being built incrementally as the need for additional electrical demand arises or when there is a need to undertake work on the network in a particular area. Without a future proofing plan the network would be developed in a way that would be unsustainable, with individual projects simply installing infrastructure to meet their needs to reduce cost but not in a way that enables ongoing improvement.

6.2 Analyse current infrastructure management practice

In order to understand futureproofing problem of an infrastructure, it is important to analyse the current infrastructure management practice (in other words the ability of an infrastructure to respond to the present day let alone future requirements) e.g. the current operating conditions, current performance targets, current asset management practice, asset position in system, interdependencies, regulations, standards, policies and procedures, safety and reliability, risk assessment, and maintenance interventions.

If a particular infrastructure community has issued a sector-specific or a group-of-infrastructure level guidance, those would be useful at this stage. For example, Cabinet Office (2013a) provides a summary of the 2013 sector resilience plans for nine national infrastructure sectors: Communications, Emergency Services, Energy, Finance, Food, Government, Health, Transport, and Water.

Network Rail traditionally maintains its sea defences in Devon on a rolling programme of masonry repointing and a 'find and fix' policy where minor defects are repaired before they become hazardous. Whilst the sea wall complex in itself affords protection to the *Dawlish Railway*, prevents erosion of the soft sandstone cliffs and protects *Dawlish* town from the full force of the sea, it is not particularly effective at resisting wave overtopping onto the railway tracks or onto trains; after a 2008 study by RSSB into climate change impacts Network Rail planned to design replacement infrastructure for the railway during CP5 (2014 – 2019) with a construction planned for CP6 (2019 – 2024) (RSSB 2008) (Network Rail 2014a).

The RSSB study determined that in the baseline year (2006) the line would be affected by climate change related closures on a 1 in 5 year basis. By the 2080s this would become 1 in 1 year probability (RSSB 2008).

Heathrow Airport has carbon reduction targets and is regularly reviewing ways to minimise its environmental impact. The way Heathrow has chosen to heat and cool their buildings using a district heating and cooling approach with networks fed by centralised boilers or chillers as opposed to individual buildings having their own heating and cooling plant allows Heathrow to plug in alternative greener energy sources and helps future proof opportunities to introduce alternative energy sources more simply.

In terms of economic factors, one of the most significant is trying to future proof against changes in airline ownership e.g. purchase of British Midland by British Airways in 2012. Changes in ownership are far easier to accommodate when operating from large terminal buildings that host a larger number of airlines hence the gradual move to an airport operating with fewer larger terminals.

6.3 Identify and analyse futureproofing considerations

The next step is to identify possible future disruptions, develop a set of futureproofing criteria, and conduct futureproofing assessment.

6.3.1 Identify and analyse future scenarios of possible disruptions in infrastructure management

Infrastructure operating environments are subject to a range of potential future changes. A number of events might occur in future, therefore it is important to identify possible event scenarios e.g. flood, snow, and wind. Potential usage changes / upgrades also need to be considered early on. Evaluating possible future scenarios in advance will help asset owners to make informed decisions to prepare the infrastructure to cope with disruptions and impacts of future events and changes.

The future operating environment through climate change was shown to be disruptive to the economy of the south west and for rail operations generally; delays and closures south of Exeter can have impacts across the network. Annual closures and frequent speed restrictions and single-line working procedures would mean an unacceptable level of resilience for the *Dawlish Railway*.

This knowledge of possible future scenarios does help to prepare the owners, operators and Government for likely decisions to futureproof this important part of the railway system. Dawson (2012) has shown a relationship between sea-level change and maintenance activity along the sea defences on the London – Penzance railway line.

The predictions for how the climate will change have led to *Heathrow Airport* changing their asset design standards for building services and drainage to reflect predicted increases in temperature and increases in rainfall. New facilities are designed in accordance with the new standards and existing facilities have been reviewed so that they understand where the operation might be at risk.

6.3.2 Identify and contextualise criteria for futureproofing assessment

It is crucial to understand and assess the fitness for the future of the infrastructure based upon the current infrastructure state, future scenarios (e.g. in the light of environmental change, future events or usage change), performance targets and a set of robust futureproofing criteria. This is in line with identifying and assessing specific risks as well as impacts of not futureproofing a particular infrastructure. This will help in identifying gaps and taking further actions to enable futureproofing of infrastructure as well as developing and analysing future business cases.

The following set of futureproofing criteria is proposed:

- **(C1) Resilience** is the ability to withstand shocks and recover quickly. The UK Government's approach to building infrastructure resilience is based on its definition as "the ability of assets and networks to anticipate, absorb, adapt to and recover from disruption", where resilience is secured through a combination of principal components i.e. resistance, reliability, redundancy and response & recovery (Cabinet Office 2015; Cabinet Office 2013a; Cabinet Office 2013b; Cabinet Office 2011).

- **(C2) Adaptability** is the ability of infrastructure to readily adapt or reconfigure if understanding of risks or requirements change over time. Adaptability is often defined as having different dimensions: extension, internal, use, planning (Cowee and Schwehr 2012).

- **(C3) Replaceability** is the ability to be replaced during or at the end of infrastructure life or use, assuming the infrastructure has a finite life.

- **(C4) Reusability** is the ability of the infrastructure to be reused or extended at the end of its life. Even though extension is partially used in adaptability as well it is executed during operation phase there while in reusability, extension is meant to be at the end of asset life.

- **(C5) System stability** is the ability of infrastructure assets to work for an overall balanced or positive effect, ensuring stability of a system or systems during or after future change(s). This could also mean that systems should work with rather against natural processes (McBain 2014).

Information futureproofing is very important for decision makers, for a 'system of systems' view, for future owners, operators, the environment and society. Hence, it is important to identify through-life information requirements at earlier life cycle stages of infrastructure and ensure availability of information at all stages by planning and taking appropriate actions for its collection, retention and reuse in long term (Masood et al 2013). The principles outlined here deserve a lot more emphasis due to their importance and should be considered as a criterion for infrastructure futureproofing; however these are not included in detail as this paper is focussed on futureproofing of physical infrastructure. Masood et al (2013; 2015) may be referred for further details on information futureproofing.

To successfully incorporate futureproofing into asset management processes, organisations would need to consider the above elements in their strategies to plan, design, construct, maintain and retire infrastructure. Organisations need to interpret these guiding criteria for a particular infrastructure, identify their importance to their organisations and assets (in some cases, some of these criteria may not be important at all), assess the current state and then work to achieve required futureproofing goals. The key criteria for futureproofing were allocated weightings during one of the project workshops, where the participants from 17 companies prioritised the criteria in terms of relevance to futureproofing in their organisations (see acknowledgements for the list of companies involved). The polling results are presented in Figure 5.

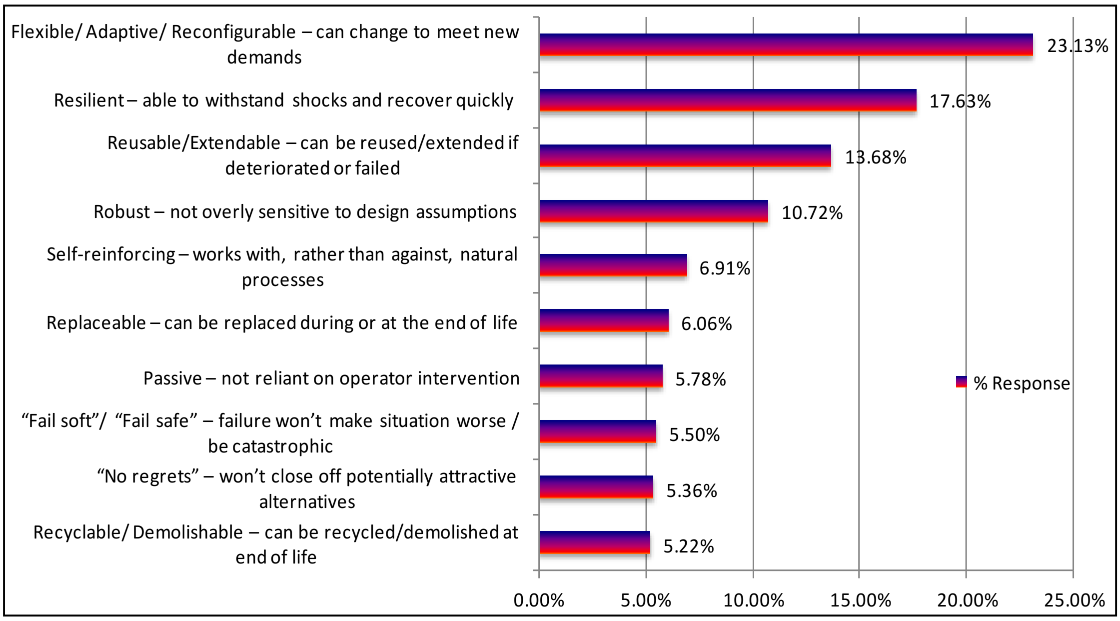

Figure 5: Infrastructure futureproofing criteria – responses from participants of futureproofing project workshop

The order of futureproofing criteria elements presented in Figure 5 may change from organisation to organisation. This would serve as a guide as to where it is important for an organisation to focus attention. It should be noted that the aim is not to achieve 100% against all of the criteria. This should be examined on a case-by-case basis and the 'desired' level against each criterion must be identified.

Once futureproofing criteria are contextualised according to a specific infrastructure, various possible future scenarios for the infrastructure are assessed against the futureproofing criteria, prior to consideration of appropriate futureproofing strategies.

6.4 Identify and analyse key issues related to a futureproofing strategy

It is vital to identify and analyse key issues to be addressed as part of a futureproofing strategy. Following questions will help in identifying and analysing such issues related to a futureproofing strategy:

- What futureproofing models and strategies are relevant for an infrastructure?
- What are the options for futureproofing?
- What future technologies are relevant and going to impact on an infrastructure?
- Why invest in such technologies?
- How can such technologies be used in futureproofing the infrastructure?
- How are asset lives being affected?
- What is the best timing for futureproofing?
- What is the whole life value in futureproofing?
- Would the organisation have right resources and skills in place when futureproofing actions are required?

Dawlish Railway had to undertake an extensive work over the last year to restore the south west's rail connection and make the line more resilient for the future. This was accomplished by following (Network Rail 2014b):

- Cliff stabilisation work between Teigmouth and Dawlish;
- Fully restoring signalling and electronic equipment; and
- Restoring and improving the public footpath on the sea wall to enable residents to use it at high tide, which was not possible before.

This work was in response to the severe damage caused by very strong winds and high seas, during February 2014, to the railway line that runs through Dawlish washing away a section of the sea wall, 80 metres of track, platforms at Dawlish station and sections of the coastal path.

Where *Heathrow Airport* can anticipate that there will be changes in types of technology or changes in the amount of demand they can consider futureproofing for this. Two examples of this are firstly Heathrow's hold baggage screening systems, where it is known that the technology will continue to evolve and become more sophisticated, so Heathrow designs its baggage handling facilities with sufficient flexibility in terms of space, access, service capacity to allow upgrades of screening machines easily.

Secondly Heathrow recognised early on that the demand for wireless technology would increase dramatically and that this would impact both airport operational services and the quality of service for passengers if allowed to develop without strict controls. Futureproofing to ensure an efficient use of limited radio spectrum through the use of shared infrastructure for wireless systems such as phones and wireless devices ensures that the spectrum that is available at the airport is used most effectively by all.

Futureproofing at the airport is undertaken in number of ways, responding to diverse factors that shape how the airport will operate and be used by airlines and passengers in the future.

Based on the aforementioned steps, it is important to form a model for futureproofing-considered infrastructure management. This is discussed in the following section.

6.5 Develop a model for futureproofing-considered infrastructure management

Based on the process described in sections 6.1-6.4, a model for futureproofing-considered infrastructure management is developed (see Figure 6). Based upon previous steps of the futureproofing framework, assessment of infrastructure futureproofing is conducted via futureproofing criteria. The model reviews possible future scenarios against future proofing criteria to see if the current infrastructure capabilities are adequate or need to be enhanced. This informs as well as helps improve existing infrastructure management practices.

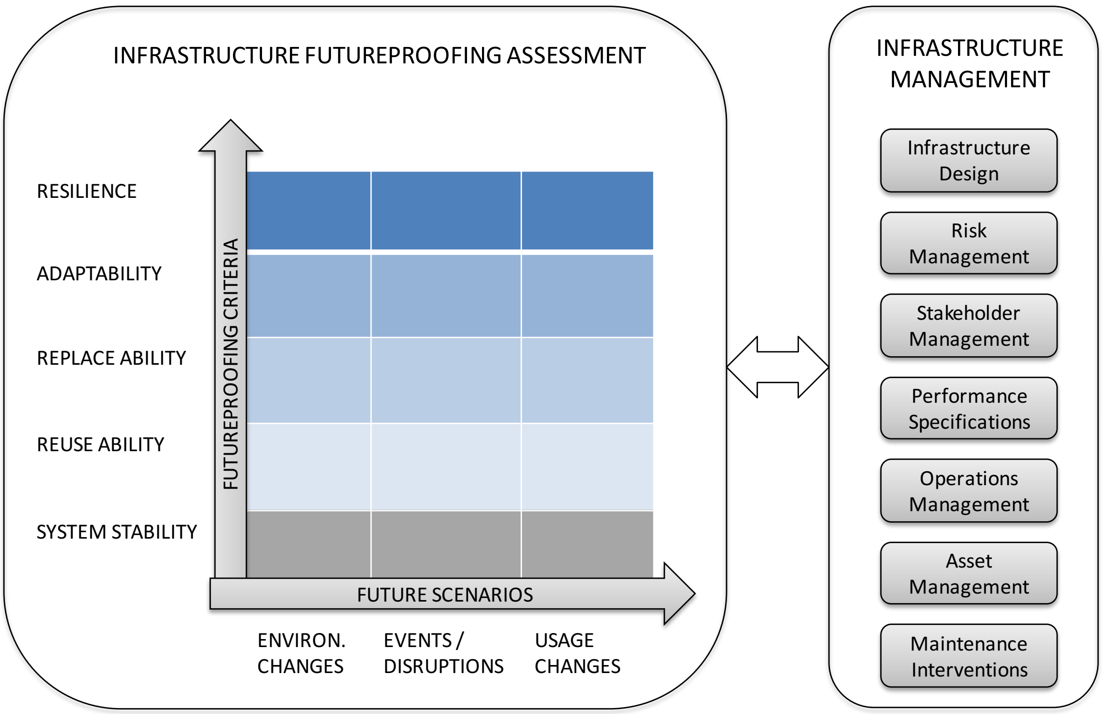

Figure 6: Model for futureproofing-considered infrastructure management

Some examples of what infrastructure futureproofing assessment vs. infrastructure management would contain are included in the following:

- To what extent is an underground railway infrastructure resilient in the face of environment changes e.g. increasing heat on tracks?
- To what extent is a rail infrastructure resilient in the face of disruptions due to e.g. flood, snow, wind, etc?
- To what extent are underground stations in London adaptable in the face of increasing usage demands?
- To what extent are current (sub) assets replace able in the face of (the pose of) significant failures necessitating such replacements.
- To what extent are piles reusable when converting an office block to a large residential building or vice versa, in a congested place in London?
- To what extent are other transport related systems going to be affected if changes to underground station systems are made in response to increase in user demands?
- To what extent are current asset management practices applicable in the face of (the pose of) significant disruptions / future scenarios.
- To what extent are current performance targets for key infrastructure applicable in face of environment changes / future scenarios?

The following are the key criteria to form a model for futureproofing-considered infrastructure management in *Dawlish Railway*:

- *Resilience* - The Dawlish railway needs to withstand increased stormy weather and sea level rise to afford reliable railway traffic. The damage caused to the Dawlish Railway during February 2014 due to stormy weather and the extensive restoration work in response provides an example of the importance of building resilience in overall futureproofing of this railway section.
- *Adaptability* - If affordability is a concern, the sea wall complex could be rebuilt with a height commensurate with wave heights expected until say the 2050s, and then it could be raised higher. Passive provision could be made economically by constructing foundations large enough to accommodate a higher and / or wider wall.
- *Replaceability* - The wall could be constructed in a modular way allowing extension or replacement with less difficulty than its traditional, masonry construction currently allows. Indeed there is talk in the railway industry long term planning process of widening (triple- or quadruple-tracks) the railway – a modular approach could permit this to happen at a future date.
- *Reusability* - This is the ability of the infrastructure to be reused or extended if deteriorated or failed – again a modular approach can aid reusability.

- *System stability* - A rock-armour protection approach can help this but is likely to be unappealing to the local community wing to its harsh visual impact on an amenity coastline famous for its beaches.

It is also considered at *Heathrow Airport* that a model for futureproofing-considered infrastructure management should include key criteria elements of resilience, adaptability, replaceability, reuse ability and system stability, as discussed in the following:

- *Resilience* - The changes in hold baggage system and wireless technology at the airport in advance provide examples of the role of key futureproofing criteria in Heathrow's model. It is important to consider how resilient the hold baggage system would be in the face of various disruptions in future e.g. power cuts affecting the baggage system, and leaving thousands of passengers having to fly without their luggage.
- *Adaptability* - Another example is from Heathrow's long-term planning for new terminals incorporating a model that considers key futureproofing elements e.g. adaptability and resilience.
- *Replaceability* – Adopting modular approach for baggage handling system is one of the approaches to consider for enabling replaceability of some components in case of failure.
- *Reusability* – Again, modular approach helps in reusing some of the components where possible.
- *System stability* - How a new airport terminal could affect other transportation networks e.g. road and rail networks is also an important consideration to be made part of a model for futureproofing-considered infrastructure management of an airport organisation.

The model for futureproofing-considered infrastructure management can be further enhanced to map impacts of future scenarios and potential futureproofing strategies against performance, operations, asset management or maintenance of infrastructure assets.

An integrated approach to dealing with futureproofing considerations and asset management practice is vital for success. This is further discussed in the following.

7. Integrating futureproofing considerations with asset management practice

Futureproofing should be integrated with asset management practice to gain the most value. Treating futureproofing as a standalone requirement leads to marginalisation of the issue and ultimately to futureproofing becoming an add-on consideration. Hence, it is important that futureproofing concepts are aligned with asset management practice and standards. Here we identify some steps towards integrating futureproofing into a broader infrastructural asset management agenda.

Based on discussions during the futureproofing project workshops with industry, the following actions will help in integrating futureproofing considerations with asset management practice:

- Addressing stakeholder requirements at an early stage
- Adopting standardised approaches to futureproofing
- Establishing and implementing criteria for futureproofing infrastructural assets across asset life cycle stages to help assess current state of futureproofing and take necessary actions to keep on futureproofing agenda.
- Planning for change earlier on, allowing for future growth across life cycle stages and managing change in operations to help in building resilience and adaptability.
- Keeping futureproofing goals at core of organizational policies, strategies, tactics and operations during whole life cycle of infrastructure.

Integration can also be supported by developing (non-prescriptive) standards, establishing benchmarks and codes of practice, understanding the value of futureproofing, defining / identifying impact (benefits for funding and costs for not funding). Government input can be critical here, through legal and regulatory standards and guidance. Key stakeholders in this process include - but not limited to - the public, asset owners/operators/maintainers, organisations e.g. utility companies, all industry bodies, interdependent / mutually benefited companies and Infrastructure UK.

There are synergies between futureproofing concepts and asset management standard, ISO 55001:2014 (ISO 2014). The following clauses of ISO 55001 can be extended to include requirements for futureproofing (Shetty 2014):

- *Clause 4.1* (Understanding the organization and its context) can include futureproofing requirements and futureproofing criteria.
- *Clause 4.2* (Understanding the needs and expectations of stakeholders) can also include futureproofing requirements and futureproofing criteria.
- *Clause 6.1* (Actions to address risks and opportunities) can include futureproofing requirements and long term risks and opportunities.
- *Clause 6.2* (Asset management objectives and plans to achieve them) can include futureproofing criteria and a model for futureproofing-considered infrastructure management.

Finally, when considering how futureproofing might be integrated into current asset management practices, it is worth noting that futureproofing will impact differently at different stages in an asset's lifecycle. The greatest value of futureproofing is created at earlier asset lifecycle stages, however that value is usually accrued at later stages in the asset's life. The following describes the value accrued at different asset lifecycle stages and the futureproofing actions which can be taken at each stage:

- *Requirements and planning stage* - can provide value in terms of greater certainty, answers to more questions, more long-term options, attractive financial proposition and greater rates of return. Actions can include defining asset life and specifying future requirements.
- *Designing / Building / Installing stages* - futureproofing provides negligible value gain for this stage in an asset's life cycle. However, actions taken at this stage can provide significant value later on. Actions include adding capacities, functionalities, and redundancies to assets; tailor designing, building and installing to asset life.
- *Operating stage* - can provide value in terms of reliable performance of infrastructure and cheaper infrastructure operations.
- *Maintaining / Renewing / Upgrading stages* - can provide value in terms of less reactive maintenance, safer planning and scheduling. Actions can incorporate predicting and preventing failures; predicting and proposing interventions.
- *Decommissioning/Reusing stages* - can provide greater residual value. Actions at this stage include improving ability to decommission safely and in an environmental friendly way; extracting or extending maximum effective life based on evidence.

8. Conclusions

Due to long lifetimes and service requirements of infrastructure assets, developing an effective strategy to futureproof infrastructure ensuring long-term sustainability and value delivery is essential. This paper has highlighted the key issues surrounding the issue of infrastructure futureproofing, explaining its importance, the major challenges, and strategies that can be considered to futureproof infrastructure assets.

The paper describes two major dimensions of infrastructure futureproofing – developing resilience to unexpected / uncontrollable events and circumstances; and ensuring the capability to adapt or respond to changing needs, uses or capacities.

Infrastructure futureproofing is challenging due to following issues: recognizing increased levels of investment in economic infrastructure and demands for value for money, developing and delivering best practice and innovation, identifying appropriate time horizons, identifying key stakeholders and decision makers, balancing 'long term risks' against 'near term need', identifying sponsors, capacity building, and making a business case.

The paper finds that the most value of futureproofing is accrued in Maintain/Renew/Upgrade lifecycle stages of the infrastructure, while other lifecycle stages can support accrual of value during these stages. This highlights the importance of including long-term needs and disruptions when designing infrastructure assets, as the extra investment put in at the design stage may pay off later during usage, especially in cases where changes to the assets may become more costly and involve heavy user disruptions. Nevertheless, a good business case needs to be made to ensure that the right amount (and the right kind) of investment is made.

In order to support this analysis, the paper presents a framework for infrastructure futureproofing, which includes a set of criteria that can be used to assess each asset in terms of its level of futureproofing. It is however important to note that each organisation needs to evaluate these criteria against the needs of each asset (or asset type), and identify the level of achievement that is necessary against each criteria. Even though this research has considered a wide spectrum of industries, it is worth investigating whether additional criteria need to be included as part of this analysis as needs of individual organisations and assets might differ.

Most importantly, the paper recommends that futureproofing considerations must be included as part of the organisation's asset management system. Futureproofing and Asset Management are not separate functions – it must be an integrated approach. The role of key stakeholders including governments, regulators and standards organisations is vital in addressing most of the challenges and integrating futureproofing in asset management practices.

Acknowledgements

The authors would like to acknowledge the Centre for Smart Infrastructure & Construction, EPSRC (Grant EP/K000314/1), Innovate UK and the industrial partners, which collectively funded this project. The authors are thankful to the CSIC industrial partners involved in the futureproofing project. The authors are also thankful to the speakers and delegates from London Underground, Costain, UCL, IBM, Crossrail, John Dora Consulting, Heathrow, Cementation Skanska, CIRIA, Network Rail, Arup, Highways Agency, Atkins, Halcrow/CH2M, Lang O' Rourke, Lend Lease, Infrastructure UK, Committee on Climate Change and CSIC, who attended the CSIC workshop(s) on infrastructure futureproofing. The authors are also thankful to the following companies who responded to our questionnaire on futureproofing strategies for industrial assets and systems: ABB, BAE Systems, Boeing, Caterpillar, EA Technology, Exxon Mobil, Finning, Hitachi, IBM and Rolls-Royce.

References

Atkins, UCL and DFID (2012) Futureproofing Cities – Risks and opportunities for inclusive urban growth in developing countries, London, 20 November.

Avery, K (2014) Climate change adaptation and rail, 1st CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 23 January, pp. 1-24.

Barbau, R, Lubell, J, Rachuri, S and Foufou, S (2014) Towards a reference architecture for archival systems: use case with product data, *Journal of Computing and Information Science in Engineering*, **14(3)**, September, 031005, pp. 1-12, DOI: 10.1115/1.4027150.

Cabinet Office (2015) *National Risk Register of Civil Emergencies*, Cabinet Office, London, UK, March, pp. 1-54. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf (accessed 15/4/2015).

Cabinet Office (2013a) *A Summary of the 2013 Sector Resilience Plans*. Cabinet Office, London, UK, November, pp. 1-18. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271370/SRP_Public_Summary_2013.pdf (accessed 22/12/2014).

Cabinet Office (2013b) *Resilience in society: infrastructure, communities and business*, Guidance, Cabinet Office, London. See https://www.gov.uk/guidance/resilience-in-society-infrastructure-communities-and-businesses (accessed 22/12/2014).

Cabinet Office (2011) *Keeping the Country Running: Natural Hazards and Infrastructure*, Cabinet Office, London, October, pp. 1-98. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61342/natural-hazards-infrastructure.pdf (accessed 22/12/2014).

CCSDS (Consultative Committee for Space Data Systems) (2012) OAIS: Reference Model for an Open Archival Information System, Recommendation for Space Data System Practice, CCSDS 650.0-M-2, Magenta Book, June, NASA Headquarters, Washington, pp. 1-135. See http://public.ccsds.org/publications/archive/650x0m2.pdf (accessed 14/8/2013).

Committee on Climate Change (2014) Managing climate risks to well-being and the economy, Adaptation Sub-Committee Progress Report, London, 8 July, pp. 1-202. See https://www.theccc.org.uk/wp-content/uploads/2014/07/Final_ASC-2014_web-version.pdf (accessed 28/10/2014).

Cowee, NP and Schwehr, P (2012) The Typology of Adaptability in Building Construction, Lucern School of Engineering & Architecture, Competence Centre for Typology & Planning in Architecture, vdf Hochschulverlag AG on der ETH Zurich, Zurich, pp. 1-110, ISBN 978-3-7281-3515-5.

Crossrail (2015) Crossrail in numbers. See http://www.crossrail.co.uk/news/crossrail-in-numbers (accessed 20/01//2015).

Dawson, DA (2012) The Impact of Sea-level Rise on the London-Penzance Railway Line, PhD Thesis, University of Plymouth, pp. 1-317, February. See http://hdl.handle.net/10026.1/912 (3/5/2014).

DEFRA (2011) Climate Resilient Infrastructure: Preparing for a Changing Climate, pp 1-76. See www.defra.gov.uk/environment/climate/sectors/infrastructure-companies/ (accessed 21/1/2015).

DfT (2014a) Transport Resilience Review – a review of the resilience of the transport network to extreme weather events, Department for Transport, July, pp. 1-168. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf (accessed 22/1/2015).

DfT (2014b) "Great Western Specification Consultation", Department for Transport, Rail Executive, May, pp. 1-53. See

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/309926/gw-consultation-document.pdf (accessed 25/1/2015).
Dora, J (2014) Futureproofing and Asset Management, 2nd CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 2 April, pp 1-20.
Ellis, A (2014) Heathrow – Future Proofing of Infrastructure, 1st CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 23 January, pp 1-20.
Environment Agency (2009) Flooding in England: A National Assessment of Flood Risk, Bristol.
Hargrave, J (2013) It's Alive! – Can you imagine the urban building of the future?, ARUP Foresight & Innovation, London, January, pp 1-12.
Fawcett, W (2011) Investing in Flexibility: The Lifecycle Options Synthesis, *Projections – The MIT Journal of Planning*, Special Issue on 'Designing for Growth and Change', Vol. 10, pp. 13-29.
HM Government (2011) Climate Resilient Infrastructure: Preparing for a Changing Climate, presented to the parliament by the Secretary of State for Environment, Food and Rural Affairs, May, pp. 1-76. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69269/climate-resilient-infrastructure-full.pdf (accessed 10/1/2015).
HM Treasury (2014) National Infrastructure Plan, December, pp. 1-140. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/381884/2902895_NationalInfrastructurePlan2014_acc.pdf (accessed 05/01//2015).
HM Treasury (2013) National Infrastructure Plan, December, pp. 1-152. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263159/national_infrastructure_plan_2013.pdf (accessed 24/10//2014).
HM Treasury (2010) National Infrastructure Plan, October, pp. 1-52. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/188329/nip_2010.pdf (accessed 24/10/2014).
House of Commons (2014) Infrastructure Investment: the impact on consumer bills, Fifth Report of Session 2014-15, Committee of Public Accounts, London, 1 July, pp. 1-74. See http://www.publications.parliament.uk/pa/cm201415/cmselect/cmpubacc/406/406.pdf (accessed 28/10/2014).
ICE (2014) The State of the Nation Infrastructure 2014, London, pp 1-28. See https://www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/Media/Policy/State-of-the-Nation-Infrastructure-2014.pdf (accessed 6/1/2015).
IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC (2014) Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32. See https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf (accessed 26/10/2014).

ISO (2014) ISO 55001: Asset Management -- Management systems -- Requirements, ISO, 9 January.

ISO (2012) ISO 22301: Business Continuity Management Systems - Requirements, ISO, 15 May.

Koren, Y, Hu, SJ, Gu, P and Shpitalni, M (2013) Open-architecture products, *CIRP Annals – Manufacturing Technology*, **62**, pp. 719-729.

Masood, T, McFarlane, D, Schooling, J and Parlikad, AK (2014) The role of future proofing in the management of infrastructural assets, International Symposium for Next Generation Infrastructure, Vienna, 30 Sep - 1 Oct, pp. 147-152. See http://discovery.ucl.ac.uk/1469416/1/Final%20Proceedings.pdf (accessed 3/8/2015).

Masood, T, Cuthbert, R, McFarlane, DC and Parlikad, AK (2013) Information futureproofing for large-scale infrastructure. In *Proceedings of the IET/IAM Asset Management Conference*, London, 27-28 November, DOI: 10.1049/cp.2013.1945.

Masood, T, Yilmaz, G, McFarlane, DC and Parlikad, AK (2015) An Information Futureproofing Approach for Large-scale Infrastructure, University of Cambridge, September.

McBain, W (2014) Futureproofing infrastructure for disruptive events: Flooding, 1st CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 23 January, pp 1-34.

Network Rail (2009) Route 12 – Reading to Penzance, Route Plans 2009, pp. 1-27. See www.networkrail.co.uk (accessed 16/12/2014).

Network Rail (2010) Network Rail Interim Climate Change Adaptation Report, pp 1-22, 30 September. See http://www.climatesoutheast.org.uk/images/uploads/Network_Rail_ARP_report.pdf (accessed 16/12/2004).

Network Rail (2014a) Network Rail's Delivery Plan for Control Period 5, 31 March 2014, updated 30 April 2014, pp 1-211. See http://www.networkrail.co.uk/publications/delivery-plans/control-period-5/cp5-delivery-plan/ (accessed 15/12/2014).

Network Rail (2014b) Dawlish. See http://www.networkrail.co.uk/timetables-and-travel/storm-damage/dawlish/ (accessed 16/12/2014).

Paris, R (2011) Crossrail-Climate Change Adaptation, Crossrail presentation.

Romero Rojo, FJ (2011) Development of a framework for obsolescence resolution cost estimation, PhD Thesis, Cranfield University, March, pp 1-473. See http://dspace.lib.cranfield.ac.uk/handle/1826/6854 (accessed 5/12/2014).

Romero Rojo, FJ, Roy, R, Shehab, E and Wardle, P J (2009) Obsolescence challenges for product-service systems in aerospace and defence industry. In *Proceedings of the 1st Industrial Product-Service Systems (IPS2) Conference*, Cranfield University, 1-2 April, 2009. See http://hdl.handle.net/1826/3845 (accessed 5/12/2014).

RSSB (2008) Impact of climate change on coastal rail infrastructure, T643 Research Brief, Rail Safety & Standards Board, June, pp. 1-6. See http://www.rssb.co.uk/library/research-development-and-innovation/research-brief-T643.pdf (accessed 7/12/2014).

RSSB (2011) Operations and Management: Adapting to extreme climate change (TRaCCA) - Phase 3 report – Tomorrow's railway and climate change adaptation (T925 Report), Rail Safety & Standards Board. See http://www.rssb.co.uk/Pages/research-catalogue/T925.aspx (accessed 2/12/2014).

Shetty, N (2014) ISO 55001 Framework for Futureproofing, 2nd CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 2 April 2014, pp 1-24.

TfL (2015a) Providing Transport Services Resilient to Extreme Weather and Climate Change – 2015 Update Report following last report to government in 2011, Transport for London, pp. 1-35. See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/466602/climate-adrep-tfl.pdf (accessed 20/10/2015).

TfL (2015b) Improving the Tube - What we're doing, Transport for London. See https://tfl.gov.uk/campaign/tube-improvements/what-were-doing (accessed 20/1/ 2015).

UK Parliament (2011) Impact on transport of recent adverse weather conditions – written evidence from British Airways (AWC 31), prepared 11 March 2011. See http://www.publications.parliament.uk/pa/cm201011/cmselect/cmtran/uc794-ii/awc31.htm (accessed 20/10/2014).

Waller, K (2014) Futureproofing in Asset Management, 2nd CSIC Workshop on Infrastructure Futureproofing, Centre for Smart Infrastructure & Construction and Institute for Manufacturing, University of Cambridge, Cambridge, 2 April 2014, pp 1-16.